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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 / r20201119

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Permanent Magnet Losses

Permanent Magnet Losses

- The permanent magnets are often presented as losless source of a permanent magnetic field
- But they have certain conductivity

  => it is possible to induce some voltage into them
- By laing the permanent magnet into time-variable magnetic field induction of voltage is allowed and it leads to generation of eddy currents

  => permanent magnet losses

Permanent Magnet Losses

- In case of synchronous machines the permanent magnets move in synchronous speed together with the stator magnetic field
- The losses are therefore generated by higher order harmonic components
  - Time harmonic components
  - Spatial harmonic components

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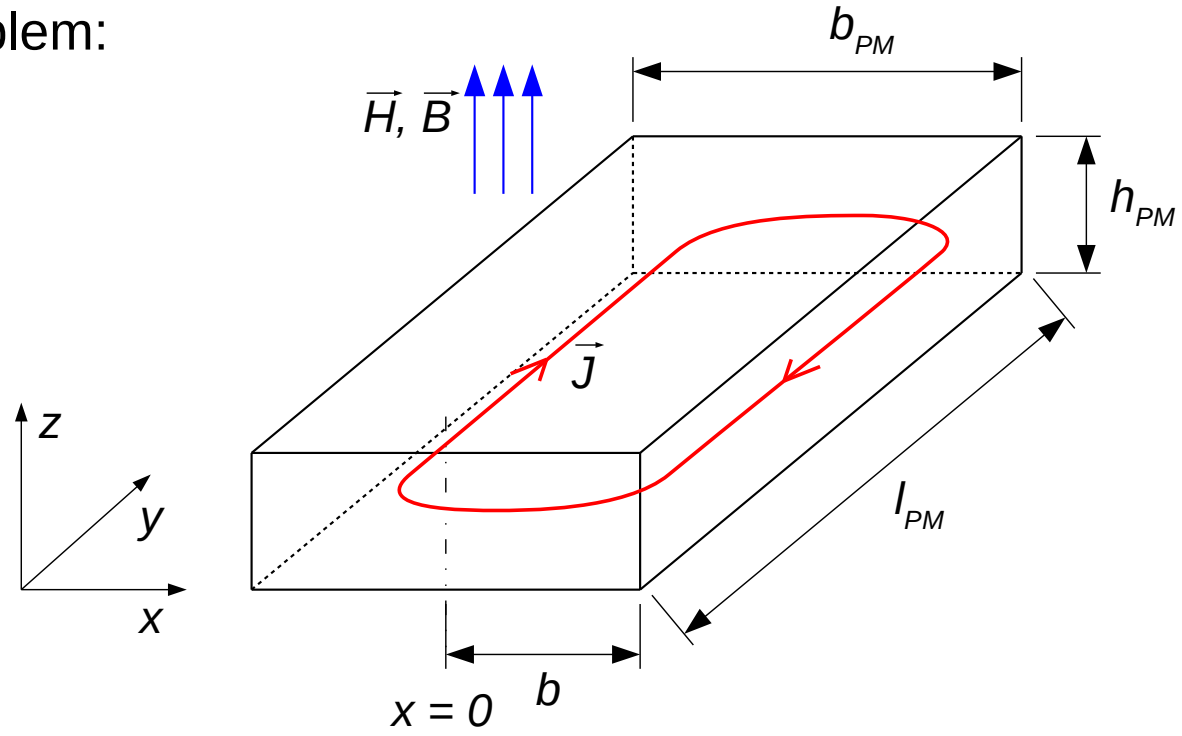
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Calculation of Permanent Magnet Losses

Calculation of Permanent Magnet Losses

- Results from one-dimensional solution of Maxwell equations
- Solved problem:



Calculation of Permanent Magnet Losses

- The time varying magnetic field strength leads to rotation of the electric field strength:

$$\operatorname{curl} \hat{E} = -\mu \frac{\partial \hat{H}}{\partial t}$$

Calculation of Permanent Magnet Losses

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- The electric field strength may be, based on Ohm's law, substituted by current density:

$$\hat{J} = \gamma_{PM} \hat{E}$$

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$$\hat{J} = \gamma_{PM} \hat{E}$$

- The asising current then generates its own magnetic field according to

$$\operatorname{curl} \hat{H} = \hat{J}$$

Calculation of Permanent Magnet Losses

- Now it is possible to substitute the current density, or the electric field strengt respectively

$$\operatorname{curl}\operatorname{curl}\hat{H} = -\mu_{PM}\gamma_{PM}\frac{\partial \hat{H}}{\partial t}$$

Calculation of Permanent Magnet Losses

- Now it is possible to subsitute the current density, or the electric field strengt respectively

$$\operatorname{curl}\operatorname{curl}\hat{H} = -\mu_{PM}\gamma_{PM}\frac{\partial \hat{H}}{\partial t}$$

- Which may be written as

$$\Delta\hat{H} = \mu_{PM}\gamma_{PM}\frac{\partial \hat{H}}{\partial t}$$

Calculation of Permanent Magnet Losses

- Presuming harmonic time-variables, we may use the complex numer notation, thus the time derivation of $\overline{H}$ is $j\omega\overline{H}$

Calculation of Permanent Magnet Losses

- Presuming harmonic time-variables, we may use the complex numer notation, thus the time derivation of $\overline{H}$ is $j\omega\overline{H}$
- The distribution of the magnetic field strength along the x-axis may be written as

$$\frac{d^2\bar{H}_z}{dx^2} - \bar{k}^2\bar{H}_z = 0$$

where

$$\bar{k}^2 = j\,\omega\,\mu_{PM}\,\gamma_{PM}$$

Calculation of Permanent Magnet Losses

- Thus it is a solution of differential equation of second order

Calculation of Permanent Magnet Losses

- Thus it is a solution of differential equation of second order
- Presuming that the layout of the current density in the permanent magnet is symmetric along the y-axis, the solution has a form of counter-running exponential functions:

$$\bar{H}_z(x) = \bar{H}_{1z} e^{\bar{k}x} + \bar{H}_{2z} e^{-\bar{k}x}$$

with symmetrical maxima on both ends of the permanent magnet (coordinates $x = -b$ a $x = b$)

$$\bar{H}_z(-b) = \bar{H}_z(b) = \bar{H}_{0z}$$

Calculation of Permanent Magnet Losses

- After substitution of presumed solution to the equation we obtain

$$\bar{H}_{1z} = \bar{H}_{2z} = \frac{\bar{H}_{0z}}{2\cosh \bar{k}\, b}$$

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- And the general layout of the magnetic field in the magnet is

$$\bar{H}_z = \bar{H}_{0z} \frac{\cosh \bar{k}\, x}{\cosh \bar{k}\, b}$$

Calculation of Permanent Magnet Losses

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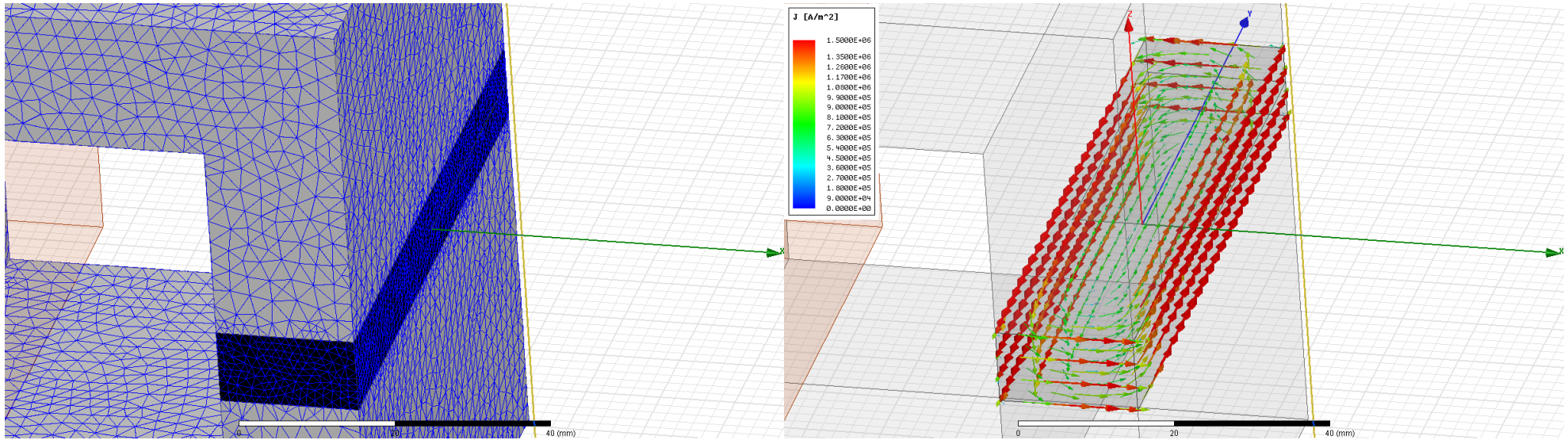
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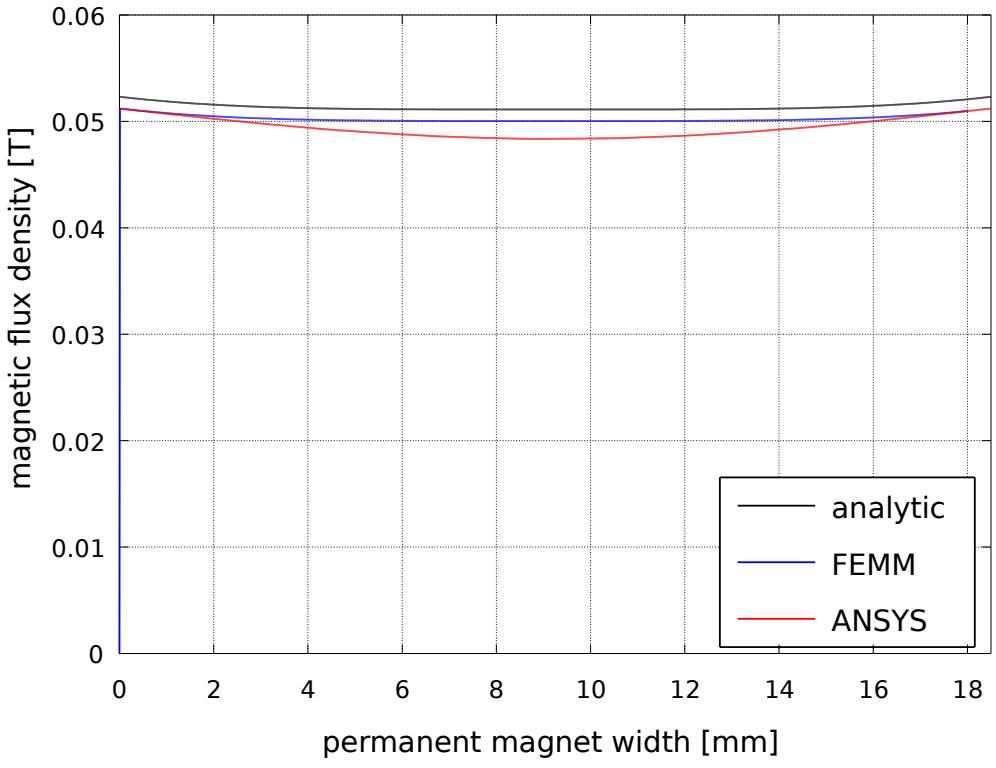
$$\bar{H}_z = \bar{H}_{0z} \frac{\cosh \bar{k}\, x}{\cosh \bar{k}\, b}$$

...which is, in fact, a catenary...

Calculation of Permanent Magnet Losses



Calculation of Permanent Magnet Losses



Calculation of Permanent Magnet Losses

- The total magnetic flux through the permanent magnet generated by the eddy currents is then an integral of the magnetic flux density over the area of the permanent magnet:

$$\bar{\Phi} = \int_{S_{PM}} \bar{B}_z \, dS = \int_{-b}^{b} \int_{0}^{l_{PM}} \bar{B}_z \, dy \, dx$$

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where

$$\bar{B}_z = \mu_{PM} \bar{H}_z = \mu_{PM} \bar{H}_{0z} \frac{\cosh \bar{k} \, x}{\cosh \bar{k} \, b}$$

Calculation of Permanent Magnet Losses

- To make the integration possible it is suitable do divide the real and imaginary part by introduction

$$\bar{k} = \frac{1 + j}{a}$$

Calculation of Permanent Magnet Losses

- To make the integration possible it is suitable do divide the real and imaginary part by introduction

$$\bar{k} = \frac{1+j}{a}$$

where a is the eddy current penetration depth

$$a = \sqrt{\frac{2}{\omega \gamma_{PM} \mu_{PM}}}$$

Calculation of Permanent Magnet Losses

- After integration we obtain

$$\Phi_{PM} = \sqrt{2} \cdot \mu_{PM} H_{0z} a l_{PM} \sqrt{\frac{\cosh \frac{2b}{a} - \cos \frac{2b}{a}}{\cosh \frac{2b}{a} + \cos \frac{2b}{a}}}$$

Calculation of Permanent Magnet Losses

- After integration we obtain

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- This magnetic flux must be equal to the magnetic flux of a harmonic component, which has excited the eddy currents

$$\bar{\Phi} = \int_{S_{PM}} \bar{B} \, dS = \alpha \bar{B} b_{PM} l_{PM}$$

Calculation of Permanent Magnet Losses

- By comparison of both relations the magnetic flux density in the permanent magnet results

$$B = \sqrt{2} \cdot \frac{\mu_{PM} H_{0z} a}{\alpha 2b} \sqrt{\frac{\cosh \frac{2b}{a} - \cos \frac{2b}{a}}{\cosh \frac{2b}{a} + \cos \frac{2b}{a}}}$$

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which may be further simplified by introduction of the proportional penetration depth

$$\zeta = \frac{2b}{a}$$

Calculation of Permanent Magnet Losses

- After expression if the magnetic field strength its magnitude results

$$H_{0z} = \frac{1}{\sqrt{2}\,\mu_{PM}}\,\alpha\, B\,\zeta \sqrt{\frac{\cosh\zeta + \cos\zeta}{\cosh\zeta - \cos\zeta}}$$

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and we can insert it into previously calculated expression

$$\bar{H}_z = \bar{H}_{0z} \frac{\cosh \bar{k}\, x}{\cosh \bar{k}\, b}$$

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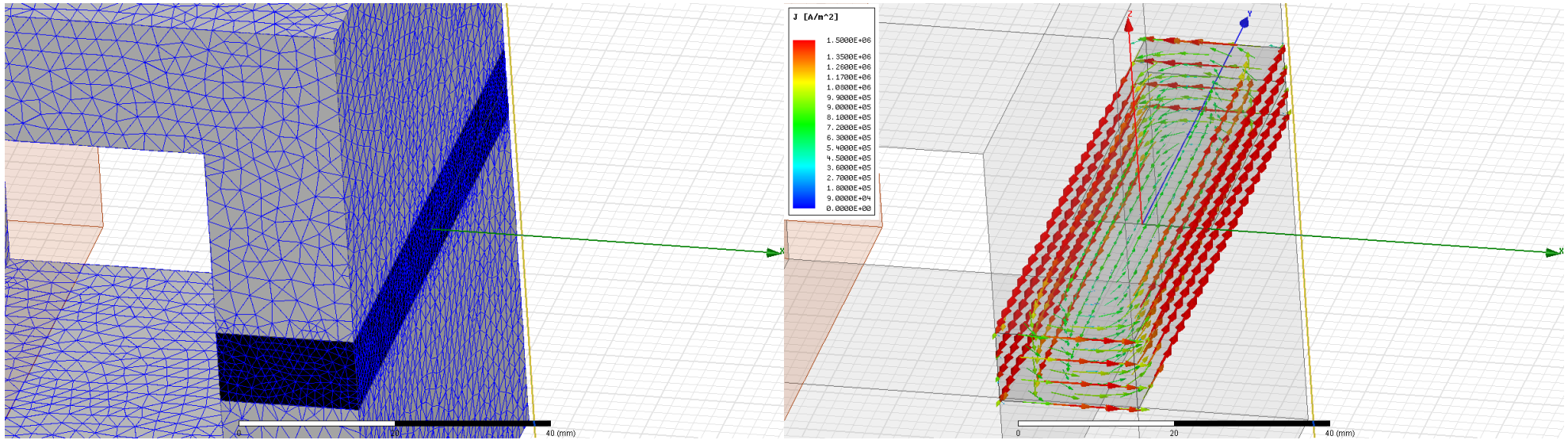
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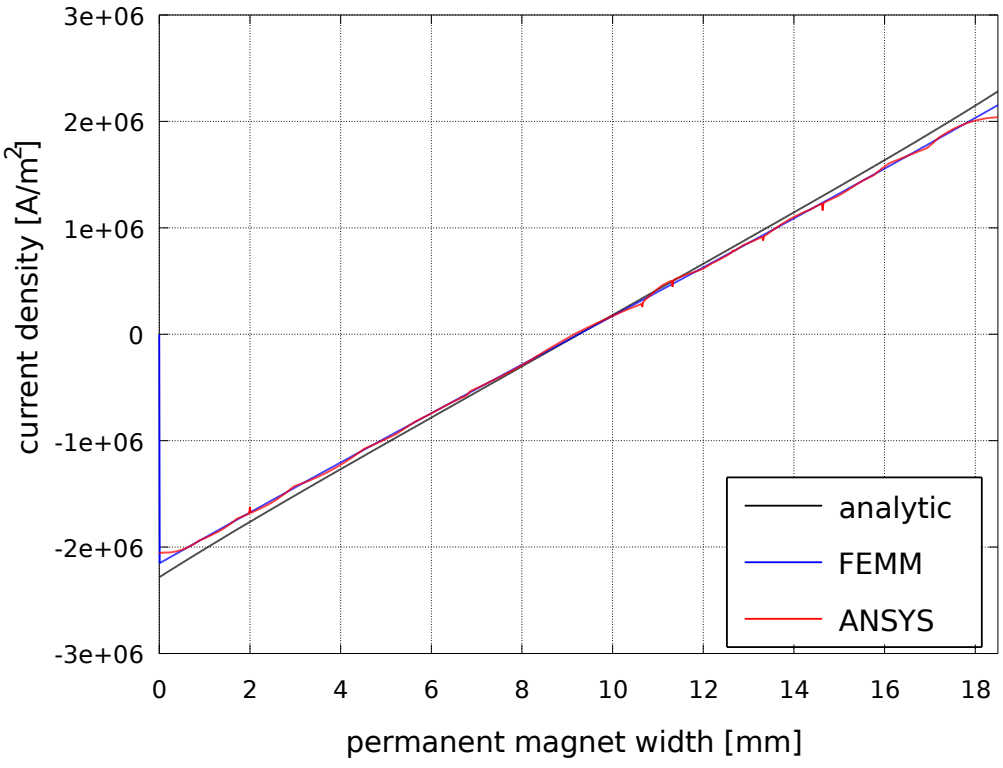
- The current density in the permanent magnet then results

$$\operatorname{curl} \hat{H} = \hat{J}$$

Calculation of Permanent Magnet Losses



Calculation of Permanent Magnet Losses



Calculation of Permanent Magnet Losses

- Using the current density the volumetric permanent magnet losses result from Poynting vector

$$\Delta p = \frac{J_z^2}{\gamma_{PM}} = \frac{1}{4} \cdot \frac{\alpha^2}{\gamma \mu_{PM}^2} B^2 \frac{\zeta^2}{a^2} \left(\frac{\cosh \frac{2x}{a} - \cos \frac{2x}{a}}{\cosh \zeta - \cos \zeta} \right)$$

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and the total losses are

$$\Delta P = \oint_{V_{PM}} \Delta p \, dV = \frac{1}{16} \cdot \frac{\alpha^2}{\zeta} B^2 \gamma_{PM} \omega^2 b_{PM}^2 \left(\frac{\sinh \zeta - \sin \zeta}{\cosh \zeta - \cos \zeta} \right) b_{PM} l_{PM} h_{PM}$$

Calculation of Permanent Magnet Losses

- Thus the permanent magnet losses may be obtained as

$$\Delta P = \frac{1}{16} \cdot \frac{\alpha^2}{\zeta} B^2 \gamma_{PM} \omega^2 b_{PM}^2 \left(\frac{\sinh \zeta - \sin \zeta}{\cosh \zeta - \cos \zeta} \right) b_{PM} l_{PM} h_{PM}$$

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- But this relation is valid for a single permanent magnet and for a single harmonic component only

Calculation of Permanent Magnet Losses

- Thus the permanent magnet losses may be obtained as

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- But this relation is valid for a single permanent magnet and for a single harmonic component only
- For a whole machine we have to make a sum over the amount of permanent magnets and time and spatial harmonic components

$$\Delta P_{PM} = 2 p n_B n_L \left(\sum_{\nu} \Delta P_{\nu} + \sum_{\mu} \Delta P_{\mu} \right)$$

Calculation of Permanent Magnet Losses

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permanent magnet volume

Calculation of Permanent Magnet Losses

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permanent magnet volume

permanent magnet width

Calculation of Permanent Magnet Losses

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permanent magnet volume

permanent magnet width

Except generally known dependency of the eddy current losses on squares of magnetic flux density and frequency,
there is a dependency on the thir power of the permanent magnet width.

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Spatial Harmonic Components

Spatial Harmonic Components

- For the purpose of calculation of permanent magnet losses, it is necessary to know the relative speed of the permanent magnets against field of ν-th harmonic component
- The higher order harmonic components move slowly in comparison to the stator field according to

$$\omega_\nu = \pm \frac{\omega_1}{\nu}$$

- But, in the area of one pole they form ν waves, moving this fast

Spatial Harmonic Components

- The relative speed of these waves against rotor may be then expressed as the difference of their speed against rotor and their speed against stator

$$\omega_{\nu r} = \nu\,\omega_1 \pm \frac{\omega_1}{\nu}$$

… where waves with lower order in pair move against the stator magnetic field, thus their speed adds to the rotor speed

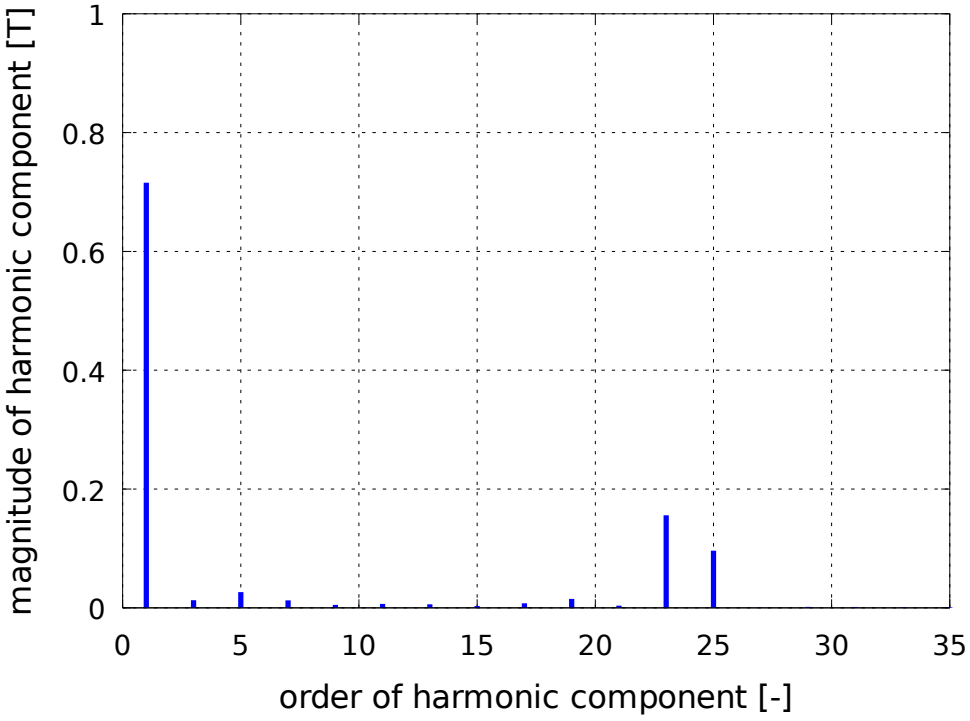
Spatial Harmonic Components

- The manitudes of harmonic components may be obtained from the analysis of the air gap magnetic field using
  - analytic
  - numeric

  approach and following Fourier analysis

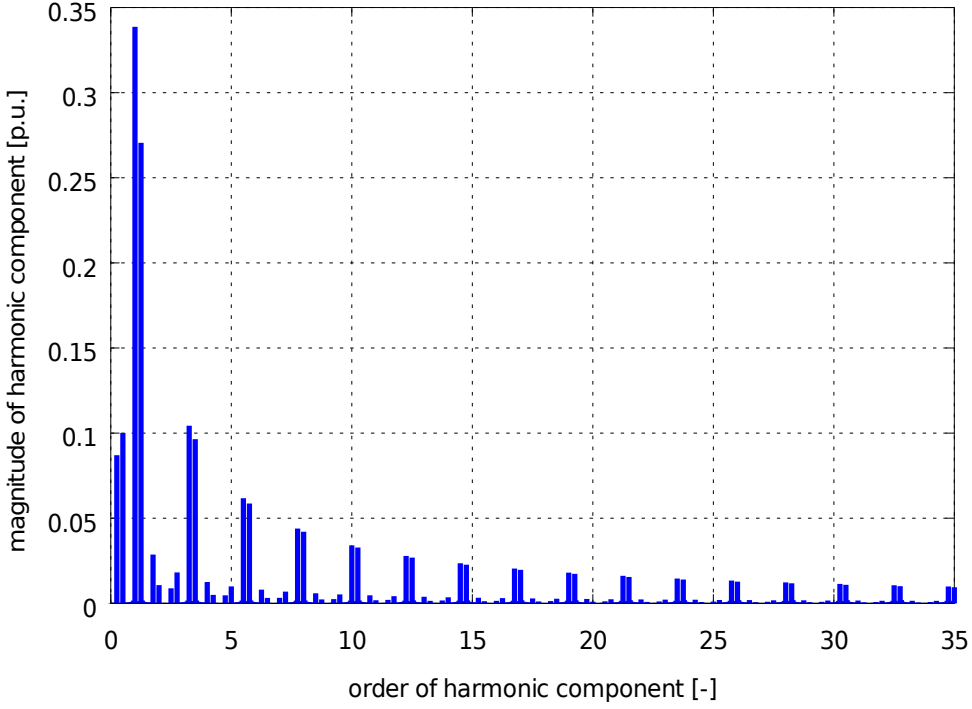
Spatial Harmonic Components

- Distributed windings:



Spatial Harmonic Components

- Tooth windings:



Spatial Harmonic Components

- Tooth windings have significantly richer spectrum
  => they generate higher permanent magnets losses
- Although they are often used in combination with the permanent magnets

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Time Harmonic Components

Time Harmonic Components

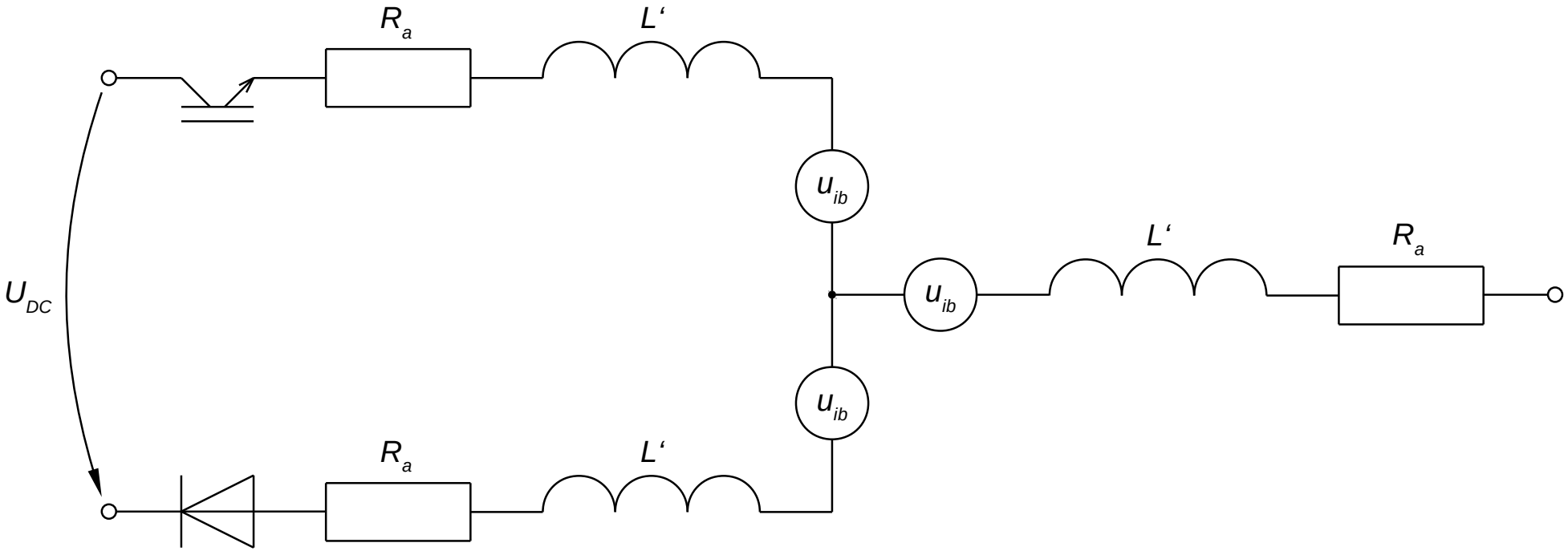
- Time harmonic components are introduced into the machine from the power electronic power supplies → PWM
- **Very** rich time-variable spectrum
- The important is in this case the current ripple
  - Projects into fluctuations of the magnetic flux density

Time Harmonic Components

- An exact analysis would require deep simulation of the current ripple and analysis of current harmonic components
  - Dependent on the control strategy (scalar control, direct torque control, control with variable switching frequency...)
- In a very simplified approach it is possible to solve the problem for 50% switching ratio
  - In theory greatest current ripple
  - Well known difference between converter voltage and motor induced voltage

Time Harmonic Components

- Equivalent circuit of one phase of the converter and the machine:



Time Harmonic Components

- The current time dependency may be written as:

$$i(t) = I\left[1 - e^{-\frac{t}{\tau}}\right]$$

Time Harmonic Components

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- Where I is the steady state value of the current:

$$I = \frac{\Delta U}{2R_a}$$

Time Harmonic Components

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- Where I is the steady state value of the current:

$$I = \frac{\Delta U}{2 R_a}$$

as it results from the voltage difference between the voltage of the DC circuit and induced voltage:

$$\Delta U = U_{DC} - \sqrt{6} U_{ib}$$

Time Harmonic Components

- The time constant of this phenomena is:

$$\tau = \frac{2L'}{2R_a} = \frac{L'}{R_a}$$

Time Harmonic Components

- The time constant of this phenomena is:

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and the duration of the transient phenomena will be equal to one half of the switching period:

$$t = \frac{T_{sw}}{2} = \frac{1}{2f_{sw}}$$

Time Harmonic Components

- The difference between current peaks then results

$$\Delta I = \frac{U_{DC} - \sqrt{6}\,U_{ib}}{2R_a}\left[1 - e^{-\frac{R_a}{2L'f_{sw}}}\right]$$

Time Harmonic Components

- The difference between current peaks then results

$$\Delta I = \frac{U_{DC} - \sqrt{6}\,U_{ib}}{2R_a}\left[1 - e^{-\frac{R_a}{2L'f_{sw}}}\right]$$

thus the current ripple is

$$i_{rip} = \frac{\Delta I}{2} = \frac{U_{DC} - \sqrt{6}\,U_{ib}}{4R_a}\left[1 - e^{-\frac{R_a}{2L'f_{sw}}}\right]$$

Time Harmonic Components

- For generally osed values of switching frequencies for a PMSM machine ($f_{sw} \geq 8\ kHz$) it is possible to consider the result as a saw signal

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- The fundamental harmonic of the sawtooth wave is then

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Time Harmonic Components

- For generally osed values of switching frequencies for a PMSM machine ($f_{sw} \geq 8\ kHz$) it is possible to consider the result as a saw signal
- The fundamental harmonic of the sawtooth wave is then

$$i_1 = \frac{8}{\pi^2} i_{rip}$$

- This value of current then causes the greatest magnetic field pulastions and it induces most of permanent magnet losses

Time Harmonic Components

- The magnetic flux linkage created by this current is then

$$\psi_{rip} = L' i_1$$

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and it corresponds with magnetic flux

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Time Harmonic Components

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$$\Phi_{rip} = \frac{\psi_{rip}}{N_s}$$

- The resulting magnetic flux pulsations are then

$$B_{rip} = \frac{\Phi_{rip}}{\alpha_\delta t_p l}$$

Time Harmonic Components

- After substitution the magnitude of pulsations of the magnetic flux density of μ-th harmonic component is $$B_{rip} = \frac{L' i_1}{\alpha_\delta N_s t_p l}$$

Time Harmonic Components

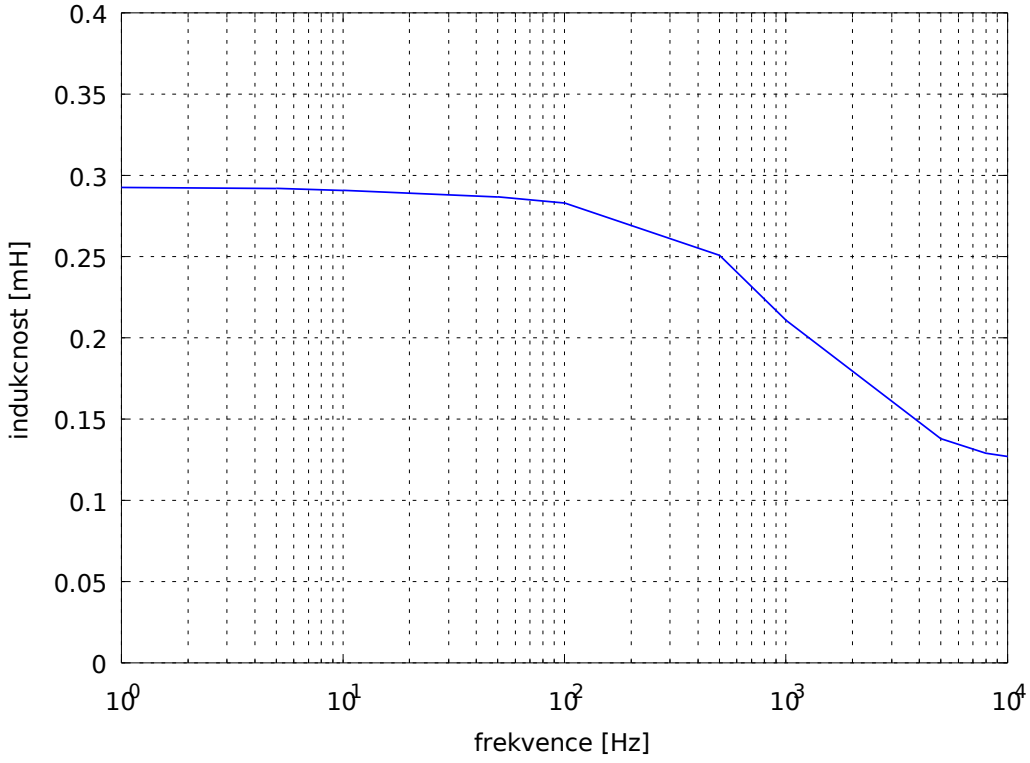
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  - This may not be, in general, equal to L_d

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- For correct calculation of the magnetic flux density ripple it is necessary to know the inductance of the machine at the switching frequency – L‘
  - This may not be, in general, equal to L_d
- The value of U_{ib} must then correspond with the actual value of U_{ib} in time moment, which corresponds to 50% voltage switch
  - i.e. considering machine torque angle

Time Harmonic Components

- The PMSM inductance frequency dependence may also look like this...



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Harmonic Component to Permanent Magnet Coverage Factor

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- For the purpose of calculation of permanent magnet losses, the harmonic component to permanent magnet coverage factor α was used:

$$\Delta P = \frac{1}{16} \cdot \frac{\alpha^2}{\zeta} B^2 \gamma_{PM} \omega^2 b_{PM}^2 \left(\frac{\sinh \zeta - \sin \zeta}{\cosh \zeta - \cos \zeta} \right) b_{PM} l_{PM} h_{PM}$$

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- This coefficient expresses a ratio between harmonic component wavelength and the width of the permanent magnet
  - For time harmonic components it is equal to 1 (they generate a quickly oscillating waves over the whole pole-pair)

Harmonic Component to Permanent Magnet Coverage Factor

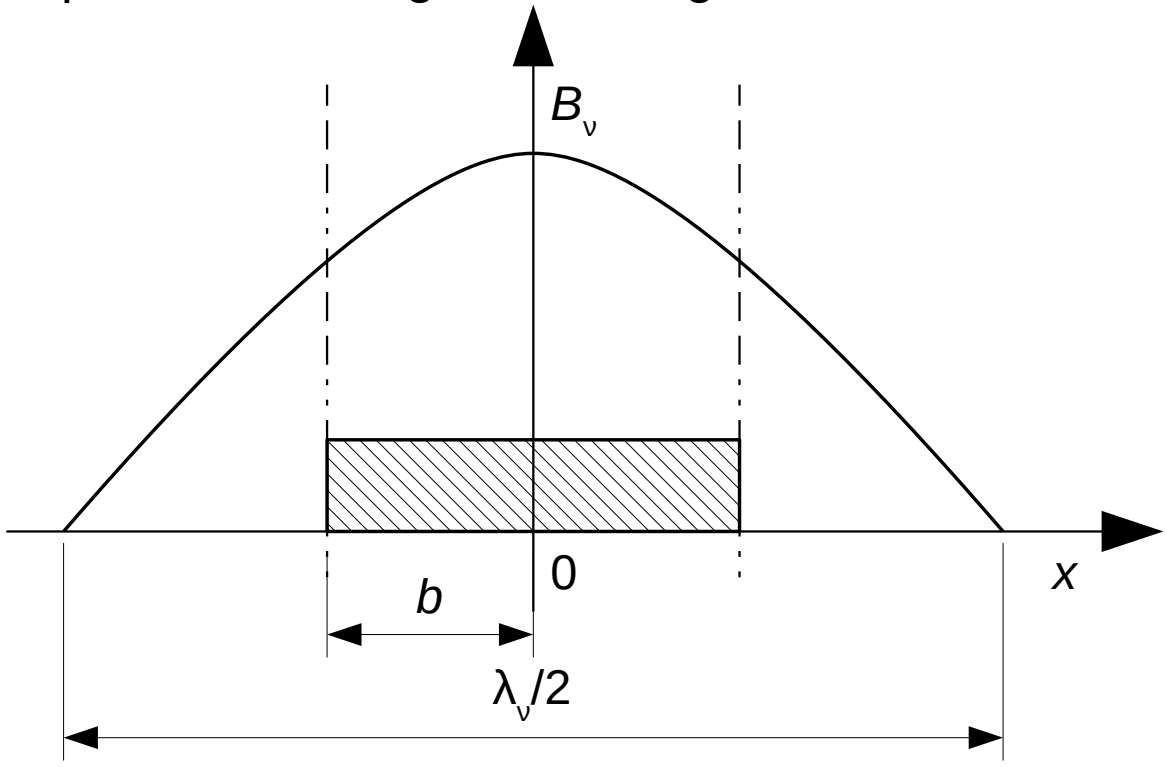
- For the purpose of calculation of permanent magnet losses, the harmonic component to permanent magnet coverage factor α was used:

$$\Delta P = \frac{1}{16} \cdot \frac{\alpha^2}{\zeta} B^2 \gamma_{PM} \omega^2 b_{PM}^2 \left(\frac{\sinh \zeta - \sin \zeta}{\cosh \zeta - \cos \zeta} \right) b_{PM} l_{PM} h_{PM}$$

- This coefficient expresses a ratio between harmonic component wavelength and the width of the permanent magnet
  - For time harmonic components it is equal to 1 (they generate a quickly oscillating waves over the whole pole-pair)
  - For time harmonic components they differ

Harmonic Component to Permanent Magnet Coverage Factor

- Determination of permanent magnet coverage factor:



Harmonic Component to Permanent Magnet Coverage Factor

- The wavelength of ν-th harmonic component may be obtained from the wavelength of the fundamental harmonic component:

$$\lambda_1 = 2 t_p = \frac{\pi D_1}{p}$$

Harmonic Component to Permanent Magnet Coverage Factor

- The wavelength of ν-th harmonic component may be obtained from the wavelength of the fundamental harmonic component:

$$\lambda_1 = 2 t_p = \frac{\pi D_1}{p}$$

- The wave of ν-th harmonic component is the ν-times shorter:

$$\lambda_\nu = \frac{\lambda_1}{\nu} = \frac{\pi D_1}{\nu p}$$

Harmonic Component to Permanent Magnet Coverage Factor

- Thus it may be described as

$$B_\nu(x) = B_\nu \cos \frac{2\pi}{\lambda_\nu} x$$

Harmonic Component to Permanent Magnet Coverage Factor

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$$B_\nu(x) = B_\nu \cos \frac{2\pi}{\lambda_\nu} x$$

whose average value is

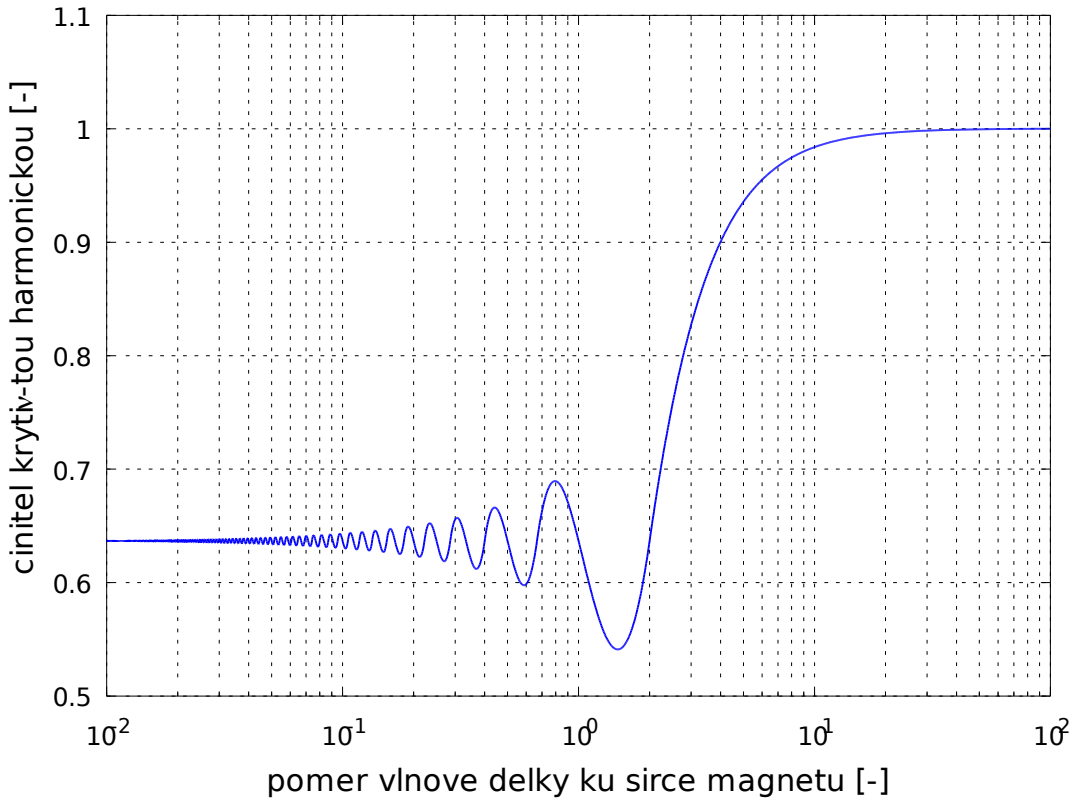
$$B_{s\nu} = \frac{1}{2b} \int_{-b}^{b} \left| B_\nu \cos \frac{2\pi}{\lambda_\nu} x \right| dx$$

Harmonic Component to Permanent Magnet Coverage Factor

- Resulting in harmonic factor to permanent magnet coverage factor for ν-th spatial harmonic component

$$\alpha_\nu = \frac{1}{2b}\int_{-b}^{b}\left|\cos\frac{2\pi}{\lambda_\nu}x\right|dx$$

Harmonic Component to Permanent Magnet Coverage Factor



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Thank You for Your Attention!

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