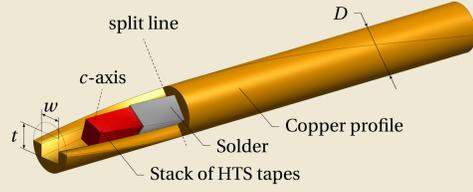


Design description

Symbol Description

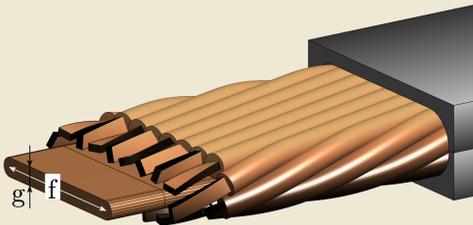
w	Width of the strand's slot (width of the tape)
t	Height of the strand's slot
n	Number of tapes in the strand
h	Twist-pitch of the strand
D	Diameter of the strand



$Q_{strand} \approx Q_{hyst} + Q_{intra}$, where
 Q_{hyst} – hysteresis loss in stacks
 Q_{intra} – intra-strand coupling loss

Symbol Description

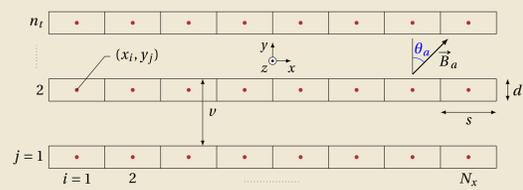
N	Number of strands in the cable
g	Thickness of the cable core
f	Width of the flat part of core
θ	Twist-angle of the cable
L	Twist-pitch of the cable



$Q_{cable} \approx NQ_{strand} + Q_{inter}$, where
 Q_{inter} – inter-strand coupling loss

Hysteresis loss in the stack of tapes

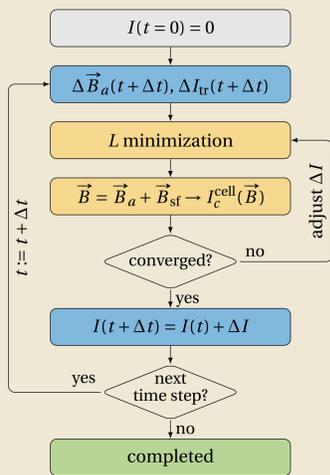
Numerical analysis: variational method



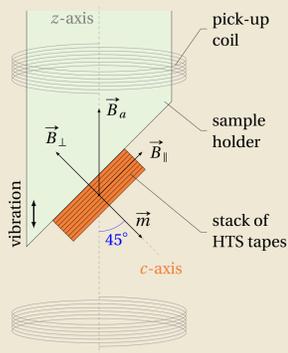
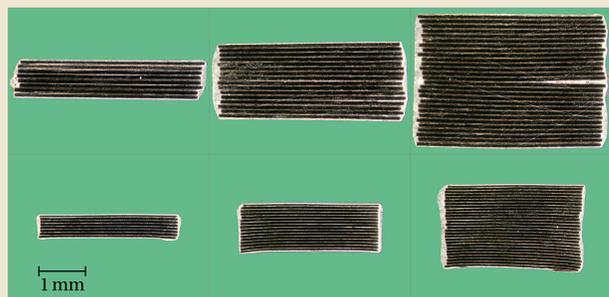
$$L(\Delta I) = \sum_{i=1}^N \left(\sum_{j=1}^N \frac{1}{2} C_{ij} \Delta I_j \Delta I_i + \Delta A_{a_i} \Delta I_i + \frac{E_c J_{c_i}}{n+1} \left(\frac{|I + \Delta I|}{I_{c_i}^{cell}} \right)^{n+1} \right)$$

$$m(t) = \sum_{k=1}^N x_k I_k(t) \quad P(t) = \sum_{k=1}^N E_k(t) I_k(t) = \sum_{k=1}^N E_c I_k(t) \left(\frac{|I(t)|}{I_{c_i}^{cell}} \right)^n$$

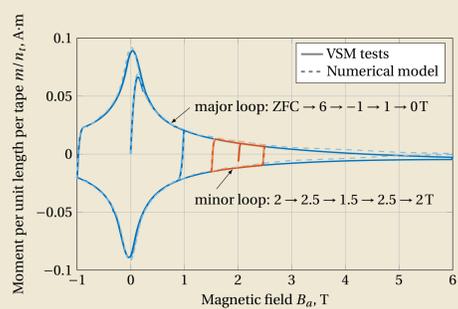
$$Q = \oint P(t) dt \quad \text{in general, or also} \quad Q = \oint m dB_a \quad \text{if } I_{tr} = 0$$



Samples for the VSM measurements



Magnetization loss

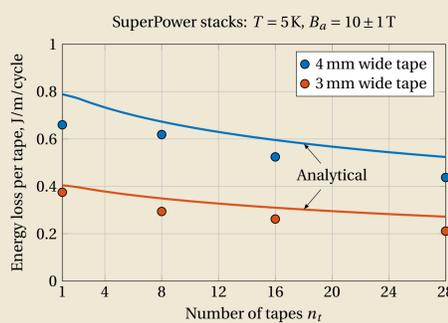


$$Q_{brandt} = w j_c B_c q_1(B_a/B_c)$$

$$q_1(x) = 2 \ln(\cosh x) - x \tanh x$$

$$Q_{mawatari} = w j_c B_c q_\infty(B_a/B_c, 2v/\pi w)$$

$$q_\infty(x, a) = a^2 \int_0^x (x-2\xi) \ln \left(1 + \frac{\sinh^2(1/a)}{\cosh^2 \xi} \right) d\xi$$



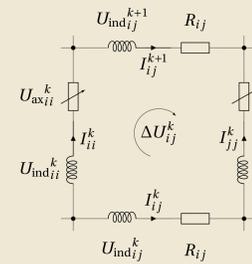
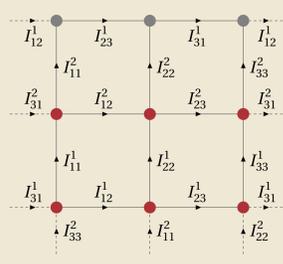
$$Q_{n_r} = w j_c B_c q_n(B_a/B_c, 2v/\pi w)$$

$$q_n(x, a) \approx q_\infty \left(x, a + \frac{0.25}{n^{0.77} - 1} \right)$$

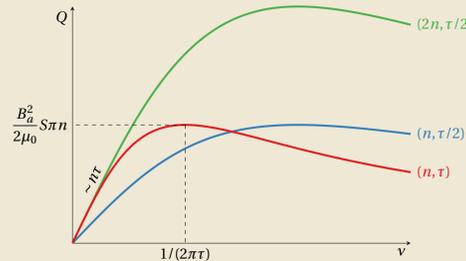
$$B_c = \frac{\mu_0 j_c d}{\pi}$$

Coupling current loss

Numerical analysis: network model



- Kirchhoff's current law: $\sum I = 0$ for every node
- Kirchhoff's voltage law: $\sum U = \Delta U$ for every circuit, where ΔU due to the Faraday's law
- Current conservation: $\sum_k I_{kk}^k = I_{tr}$



General formula for electrical-circuit models (Campbell'82):

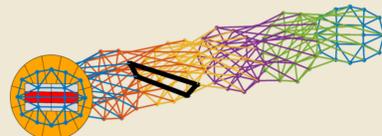
$$Q_{coupling} = \frac{B_a^2}{2\mu_0} \cdot S \cdot \frac{4\pi^2 n \tau v}{1 + 4\pi^2 \tau^2 v^2} \quad [J/m/cycle]$$

n – shape factor, τ – time constant

$$P \approx B_a^2 S n \tau / \mu_0 \quad [W/m] \quad \text{if } v \ll 1/\tau$$

S, n and τ are the only unknowns ...

Intra-strand loss

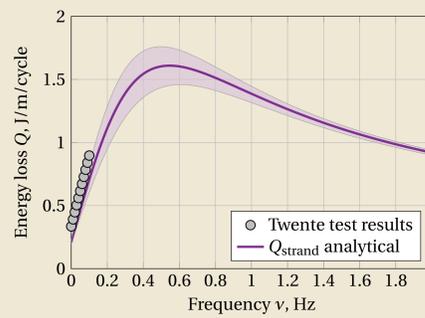


$$S = \pi D^2 / 4, \quad n \approx 0.2320$$

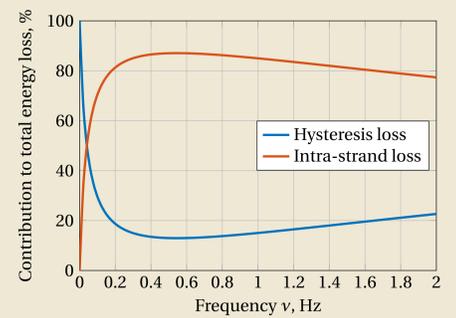
$$\tau = (p_1 D + p_2) \left(1 - \frac{d}{D} \right)^{p_3 + p_4} \left(1 - \exp \left(- \left(\frac{h}{D} \right)^{p_5} \right) \right)$$

$$d = \sqrt{w^2 + t^2}$$

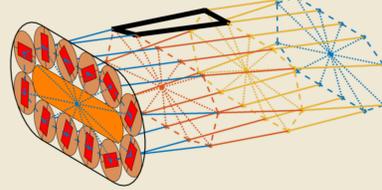
p_1 [s/mm]	0.2824
p_2 [s]	-1.0968
p_3 [-]	0.0883
p_4 [-]	0.1909
p_5 [-]	0.0226
p_6 [-]	1.4430



Intra-strand coupling loss is $\approx 80\%$ of the total loss



Inter-strand loss

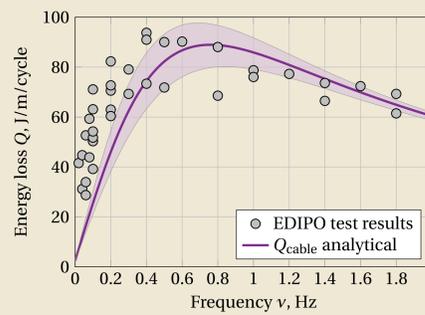


$$S = N S_{strand} + f g + \pi g^2 / 4$$

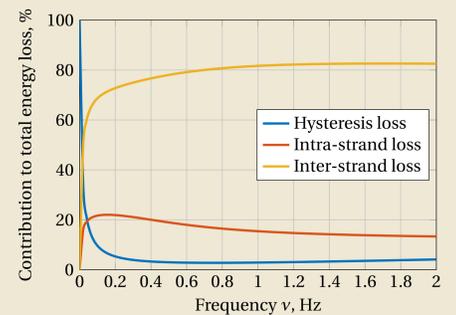
$$n = 0.1049 \frac{ND}{f + g + 2D} (1 + x)$$

$$\tau = 0.0143 \mu_0 L^2 \left(\frac{f + g}{D} \right)^{0.434} \left(\frac{1}{R_a} + \frac{8.283}{R_c} \right) \left(1 - \frac{0.773}{1 + x} \right)$$

$$x = f \cos^2 \theta_a / (g + 2D)$$

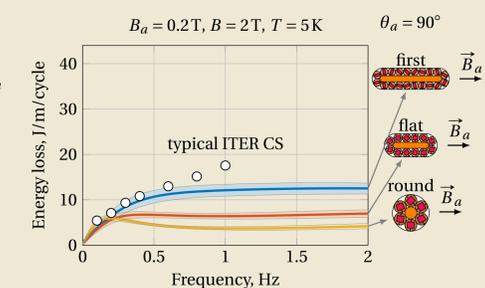
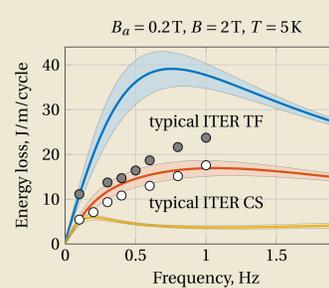
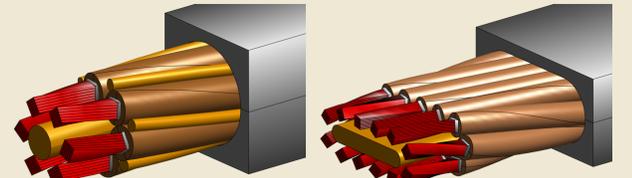


Inter-strand coupling loss is $\approx 80\%$ of the total loss



Next prototypes

Cable	Round	Flat
width of tape, mm	4.8	3.3
strand diameter, mm	10.0	7.0
number of tapes per strand	42	28
annealing of copper profiles	No	Yes
number of strands	6	12
thickness of core, mm	10	5
cable space, mm ²	710	750



Significant loss reduction is expected for the new prototypes, meant for CS coils