EM modeling and power cables

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2nd SSF workshop on Optimal and Automated Design of Electromagnetic Structures, Lund, 14 January, 2015.

Outline

Research activities

Electromagnetic losses in three-phase power cables

On the natural modes of helical structures

Previous and planned research activities

Previous research activities

- VR-ABB-PhD: Electromagnetic dispersion modeling and analysis for power cables. Broadband pulse propagation on HVDC power cables, for fault localization, length estimation, etc.

Current and planned research activities within the SSF-project: *Complex analysis and convex optimization for EM design*

- SSF-ABB-PhD: Electromagnetic losses in cable armour. Characterization, measurements and estimation of the induced conduction and hysteresis losses in the cable steel armour.
- SSF-ABB-mobility: Electromagnetic losses in three-phase power cables. On the natural modes of helical structures.

Outline

Research activities

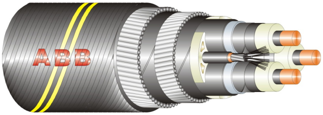
Electromagnetic losses in three-phase power cables

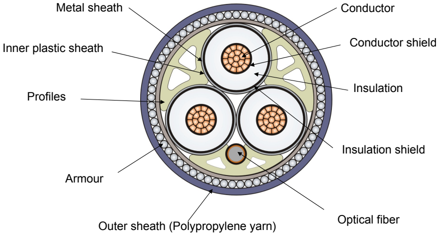
On the natural modes of helical structures

Electromagnetic losses in three-phase power cables

There is a great potential of accurate electromagnetic modeling, analysis, and optimization (design) of three-phase power cables, with regard to

- conductor losses, skin-effect
- induced conduction losses in metal sheaths and armour
- iron losses in armour (hysteresis losses)





Images from: Workshop on Mathematical Modelling of Wave Phenomena 2013, Linnæus University.

Presentation by Danijela Palmgren: http://lnu.se/polopoly_fs/1.85931!Palmgren.pdf

Armour loss measurement: Armoured cable

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ABB

Images from: Workshop on Mathematical Modelling of Wave Phenomena 2013, Linnæus University.

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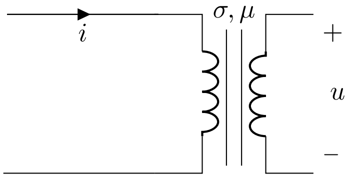
Estimation of electromagnetic losses in cable armour

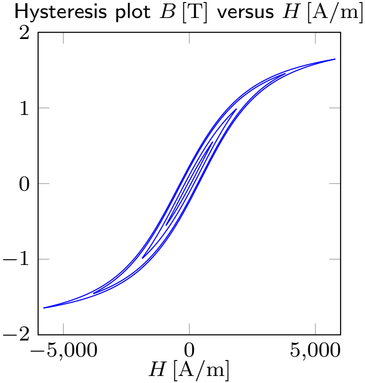
- Build and model a transfomer based on the cable steel
- Conduction losses (eddy currents) $J = \sigma E \Rightarrow D = \epsilon_0(\epsilon_\mathrm{r} + \mathrm{i}\frac{\sigma}{\omega\epsilon_0})E$
- Iron losses (hysteresis effect) $B = \mu_0\mu(H)$
- How to estimate, simultaneously, the conduction losses as well as the (non-linear) hysteresis losses in the cable steel?
  - Linear model, proximity effects
  - Micromagnetic models: Jiles-Atherton model (1984-1986)
  - Variational models based on thermodynamics (1997-2011)
- Identify model (material) parameters based on measurements. EM-theory, estimation theory, convex optimization.

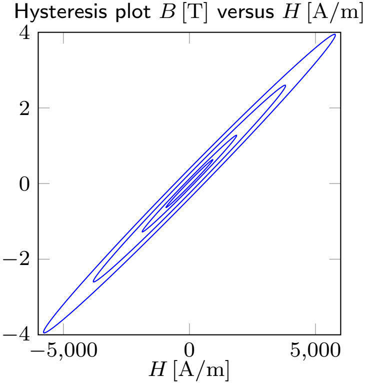


Estimation of electromagnetic losses in cable armour

Modeling of magnetic hysteresis losses in steel

Left: Classical non-linear Jiles-Atherton model. Right: Linear model.





Estimation of electromagnetic losses in cable armour

Modeling of magnetic hysteresis losses in steel

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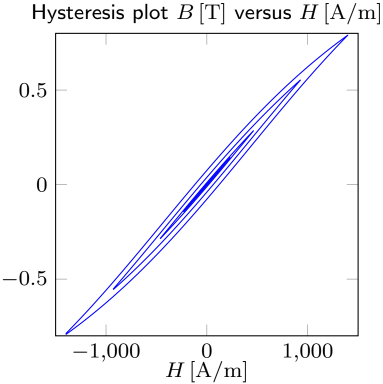
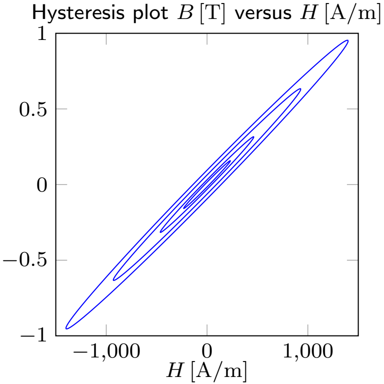




Outline

Research activities

Electromagnetic losses in three-phase power cables

On the natural modes of helical structures

On the natural modes of helical structures

Floquet wave number for periodic structures $\boldsymbol{J}(\boldsymbol{r}) = \widetilde{\boldsymbol{J}}(\boldsymbol{r})\mathrm{e}^{\mathrm{i}\beta z}$

Periodic electric Green's dyadic

$$\boldsymbol{E}(\boldsymbol{r}) = \mathrm{i}\omega\mu_0\mu \int_S \int_0^p \boldsymbol{G}_{\mathrm{ep}}(\boldsymbol{r}, \boldsymbol{r}', k, \beta) \cdot \boldsymbol{J}(\boldsymbol{r}') \, \mathrm{d}S' \, \mathrm{d}z'$$

Poisson summation formula

$$\begin{aligned} \boldsymbol{G}_{\mathrm{ep}}(\boldsymbol{r}, \boldsymbol{r}', k, \beta) &= \sum_{n=-\infty}^{\infty} \boldsymbol{G}_{\mathrm{e}}(\boldsymbol{r}, \boldsymbol{r}' + \hat{\boldsymbol{z}} np, k)\mathrm{e}^{\mathrm{i}\beta pn} \\ &= \frac{1}{p} \sum_{n=-\infty}^{\infty} \boldsymbol{G}_{\mathrm{e}}(\boldsymbol{\rho}, \boldsymbol{\rho}', k, \beta + n\frac{2\pi}{p})\mathrm{e}^{\mathrm{i}(\beta + n\frac{2\pi}{p})(z - z')} \end{aligned}$$

Spectral representation of the free-space electric Green's dyadic

$$\boldsymbol{G}_{\mathrm{e}}(\boldsymbol{r}, \boldsymbol{r}', k) = \{\boldsymbol{I} + \frac{1}{k^2}\nabla\nabla\} \frac{\mathrm{e}^{\mathrm{i}k|\boldsymbol{r} - \boldsymbol{r}'|}}{4\pi|\boldsymbol{r} - \boldsymbol{r}'|} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \boldsymbol{G}_{\mathrm{e}}(\boldsymbol{\rho}, \boldsymbol{\rho}', k, \alpha)\mathrm{e}^{\mathrm{i}\alpha(z - z')} \, \mathrm{d}\alpha$$

On the natural modes of helical structures

- Periodic volume integral equation for the electric field, based on the Floquet mode $\mathrm{e}^{\mathrm{i}\beta z}$

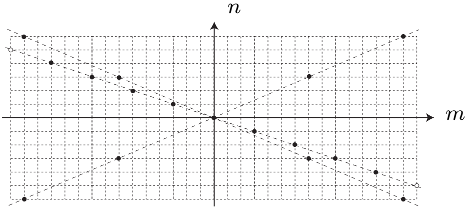
$$[\boldsymbol{I}+\hat{\boldsymbol{\rho}}\hat{\boldsymbol{\rho}}\cdot\boldsymbol{\chi}(\boldsymbol{r})]\cdot\boldsymbol{E}(\boldsymbol{r})-k^2\int_S\int_0^p \boldsymbol{G}_{\mathrm{ep}}^0(\boldsymbol{r},\boldsymbol{r}',k,\beta)\cdot\boldsymbol{\chi}(\boldsymbol{r}')\cdot\boldsymbol{E}(\boldsymbol{r}')\,\mathrm{d}S'\,\mathrm{d}z'=\boldsymbol{0}$$

- Expansion of the periodic dyadic Green's function $\boldsymbol{G}_{\mathrm{ep}}^0(\boldsymbol{r},\boldsymbol{r}',k,\beta)$ in cylindrical vector waves.
- A two-dimensional Fourier series expansion yields an infinite system of coupled one-dimensional integral equations

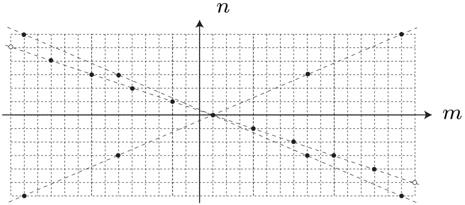
$$\begin{aligned}&\boldsymbol{E}_{mn}(\boldsymbol{\rho})+\hat{\boldsymbol{\rho}}\hat{\boldsymbol{\rho}}\cdot\sum_{m'}\sum_{n'}\boldsymbol{\chi}_{m-m',n-n'}(\boldsymbol{\rho})\cdot\boldsymbol{E}_{m'n'}(\boldsymbol{\rho})\\ &-k^2 2\pi\int_0^a \boldsymbol{a}_m(\boldsymbol{\rho},\boldsymbol{\rho}',k,\beta+n\frac{2\pi}{p})\cdot\sum_{m'}\sum_{n'}\boldsymbol{\chi}_{m-m',n-n'}(\boldsymbol{\rho}')\cdot\boldsymbol{E}_{m'n'}(\boldsymbol{\rho}')\rho'\,\mathrm{d}\rho'\\ &=\boldsymbol{0}\end{aligned}$$

On the natural modes of helical structures

Material twist-modes $\boldsymbol{\chi}_{mn}$ in Fourier space



Azimuthal Floquet mode $\boldsymbol{E}_{mn}$ containing the "excitation" factor $\mathrm{e}^{\mathrm{i}\phi}$
Quasi-static assumption: The mode shapes of $\boldsymbol{E}$ is the same as for $\boldsymbol{\chi}$



On the natural modes of helical structures

Issues

- Proper treatment of the source point (here in cylindrical coordinates)

$$\boldsymbol{G}_{\mathrm{e}}(\boldsymbol{r},\boldsymbol{r}',k)=\{\boldsymbol{I}+\frac{1}{k^2}\nabla\nabla\}\frac{\mathrm{e}^{\mathrm{i}k|\boldsymbol{r}-\boldsymbol{r}'|}}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|}=\boldsymbol{G}_{\mathrm{e}}^{0}(\boldsymbol{r},\boldsymbol{r}',k)-\frac{1}{k^2}\hat{\boldsymbol{\rho}}\hat{\boldsymbol{\rho}}\delta(\boldsymbol{r}-\boldsymbol{r}')$$

- The volume integral formulation is known to be "strongly" singular.
- Each one-dimensional integral operator is only weakly singular (discontinuous kernel).
- Spectral theory, characterization of spectral properties similar to Fredholm theory?
- Analytic function theory view. Existence of modes (residues), radiation modes are the contributions from an integration along the branch-cut.