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AC loss calculation on a 6.5 MVA/25 kV HTS traction transformer with hybrid winding structure

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Introduction

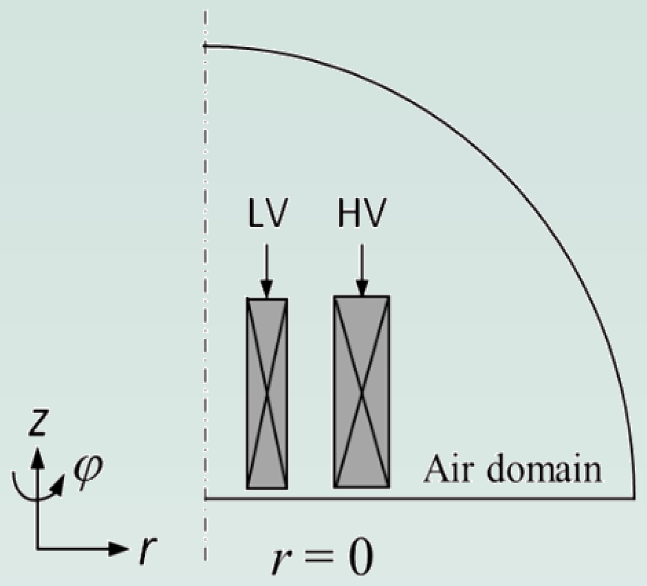
- Traction transformers are key components for the Chinese high speed trains [1-2].
- Since 2018 Beijing Jiaotong University has been leading a six-party project to develop a single-phase 6.5 MVA HTS traction transformer.
- Specifications for the traction transformer

	HV	LV
Frequency (Hz)	50	50
Rated capacity (kVA)	6433	4 × 1608
Rated voltage (V)	25000	4 × 1900
Rated current (A)	257	4 × 846
Short circuit impedance (%)	43	
Efficiency (%)	95 ⟶	>99%
Weight (kg)	5920 ⟶	<3000

- 2 kW AC loss in the HTS windings is critical to achieve both efficiency and system weight.
- HTS wire cost is one of major obstacles preventing commercialization of HTS machines.
- Wire costs might be minimized without significantly increasing AC loss by introducing hybrid winding structure [3].

Calculation method

Calculations have been carried out in a 2D axisymmetric modelling using *H* formulation [4-7].



$$E_\varphi = \rho J_\varphi \quad (1)$$

$$\rho_{HTS} = \frac{E_c}{J_c(B)}\left(\frac{J_\varphi}{J_c(B)}\right)^{(n-1)} \quad (2)$$

$$J_c(B) = \frac{I_{c0}}{S}\left(1 + \frac{k^2 B_{\text{para}}{}^2 + B_{\text{perp}}{}^2}{B_0{}^2}\right)^{-\alpha} \quad (3)$$

$$\nabla \times \boldsymbol{E} = -\partial \boldsymbol{B}/\partial t \quad (4)$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} \quad (5)$$

$$\boldsymbol{B} = \mu_0 \mu_{re} \boldsymbol{H} \quad (6)$$

$$\partial(\mu_0 \mu_{re} \boldsymbol{H})/\partial t + \nabla \times \rho(\nabla \times \boldsymbol{H}) = 0 \quad (7)$$

$$\begin{cases} \mu_0\mu_{re}\dfrac{\partial H_r}{\partial t} - \dfrac{1}{r}\dfrac{\partial\left(r\rho\left(\dfrac{\partial H_r}{\partial z} - \dfrac{\partial H_z}{\partial r}\right)\right)}{\partial z} = 0 \\ \mu_0\mu_{re}\dfrac{\partial H_z}{\partial t} + \dfrac{1}{r}\dfrac{\partial\left(r\rho\left(\dfrac{\partial H_r}{\partial z} - \dfrac{\partial H_z}{\partial r}\right)\right)}{\partial r} = 0 \end{cases} \quad (8)$$

References

[1] R. Schlosser, *et al.*, *IEEE Trans. Appl. Supercond.* **13**, 2325-2330, (2003).

[2] W. Song, *et al.*, *IEEE Trans. Appl. Supercond.*, **29**, 5501405 (2019).

[3] Z. Jiang, *et al.*, *Supercond. Sci. Technol.*, **29**, 095011, (2016).

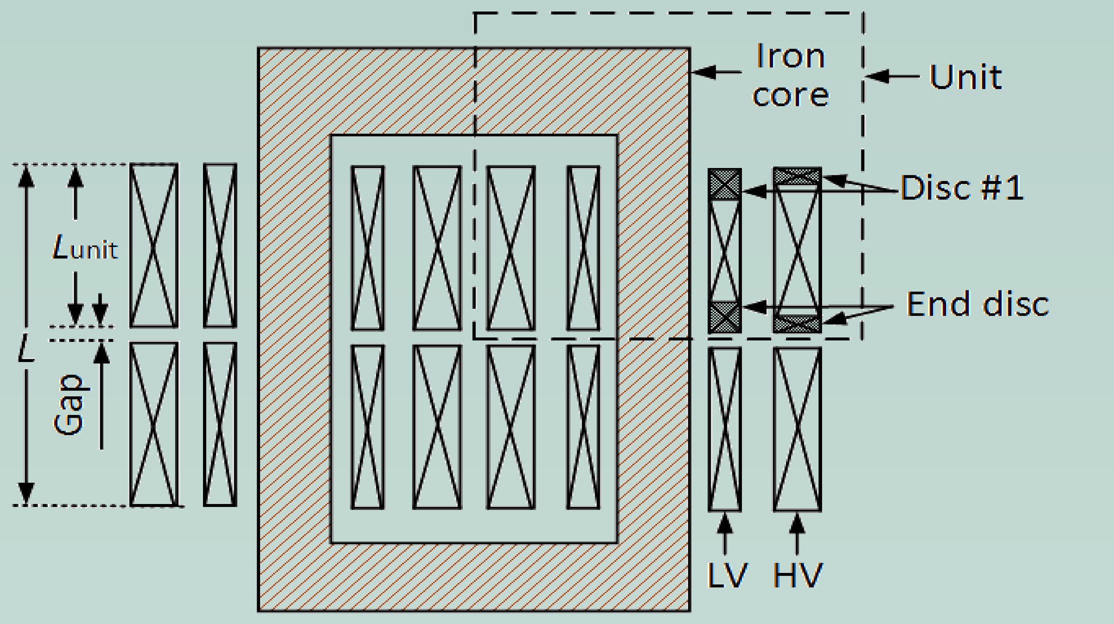
[4] W. Song, et al., *Cryogenics*, **94**, 14-21 (2018).

[5] Z. Hong, et al., *Supercond. Sci. Technol.*, **19**, 1246–1252 (2006).

[6] R. Brambilla, et al., *Supercond. Sci. Technol.*, **20**, 16–24, (2006).

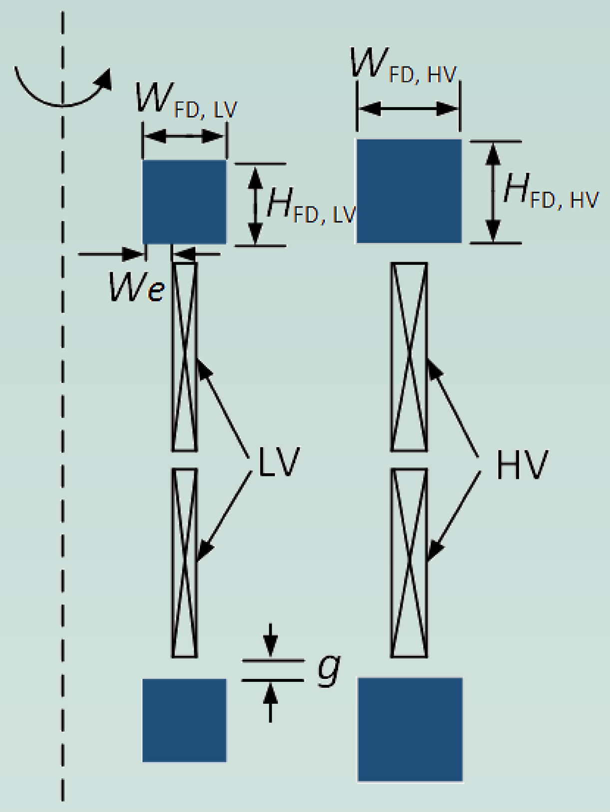
[7] M. Zhang, *et al.*, *J. Appl. Phys.*, **111**, 083902, (2012).

Transformer structure and design

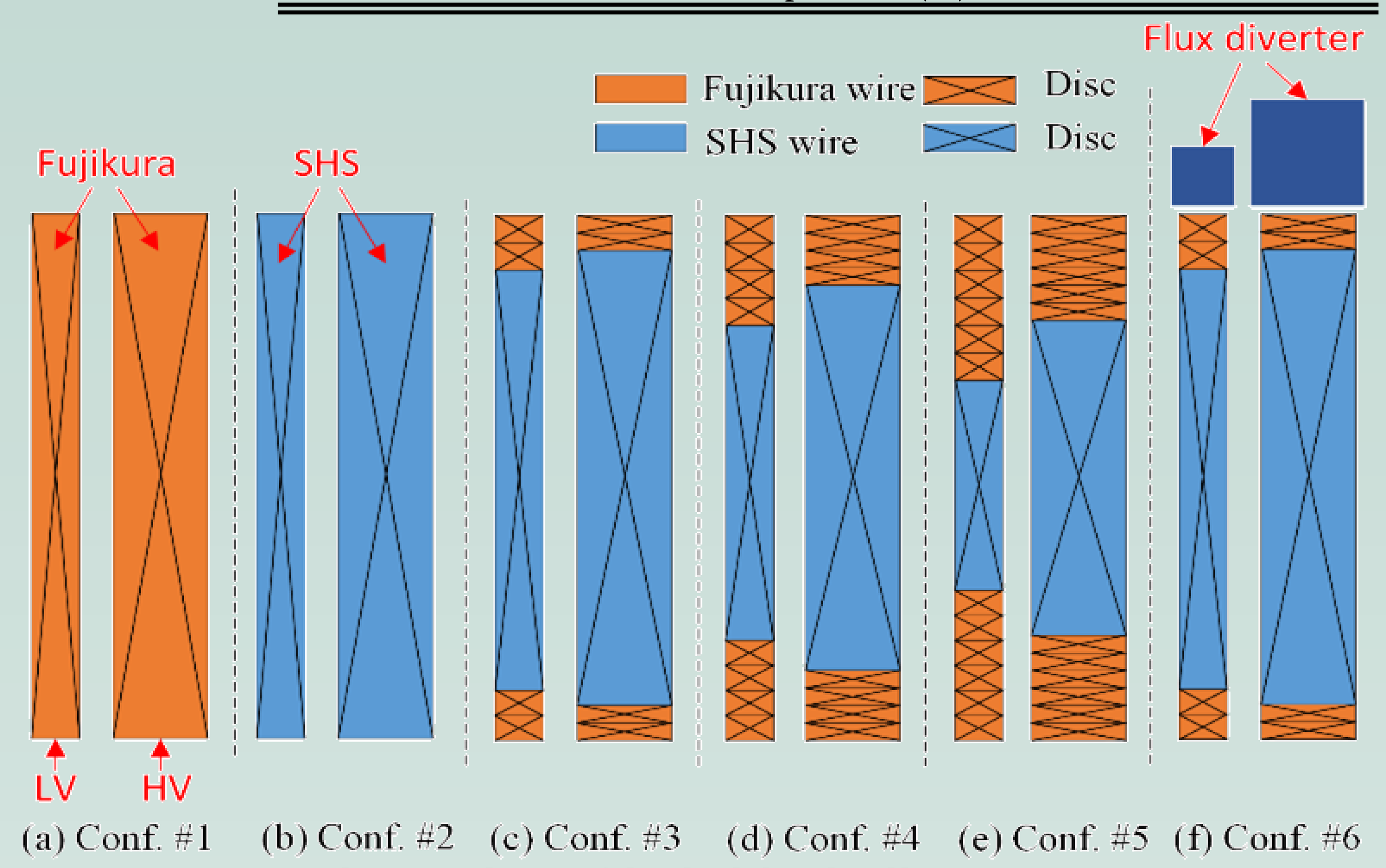


Schematic of transformer structure

Items	Value
Winding length *L* (m)	1
Number of turns in each HV winding disc	14
Number of discs stacked to make the HV winding per unit	116
Number of layers of 8-strand Roebel cable in LV winding	3
Number of turns in one layer in LV winding	40
Number of total turns per unit in HV winding	1624
Number of total turns per unit in LV winding	120
Inner diameter of HV winding (mm)	437
Inner diameter of LV winding (mm)	285
Axial gap between the two units on each leg of the core (mm)	20
Short-circuit impedance (%)	43

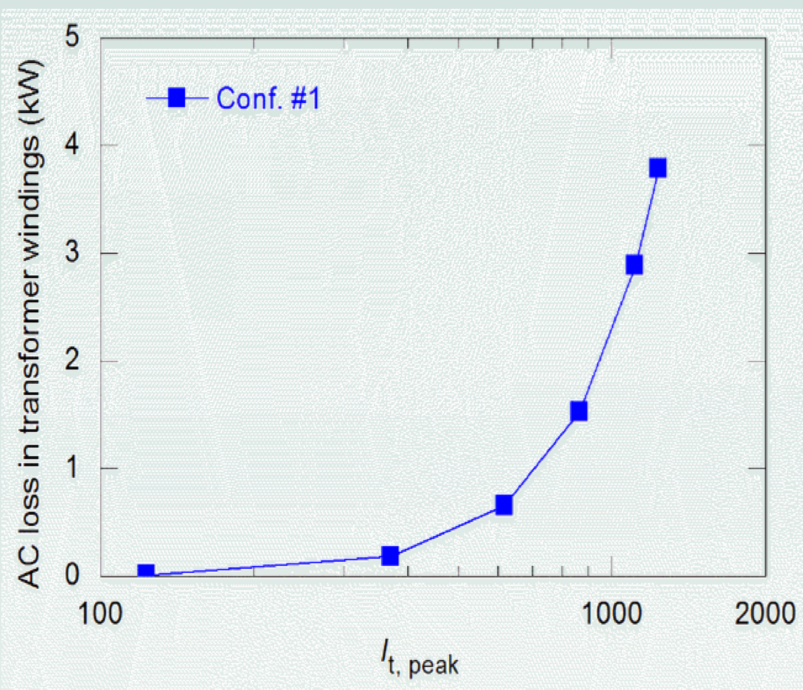


Schematic of flux diverter

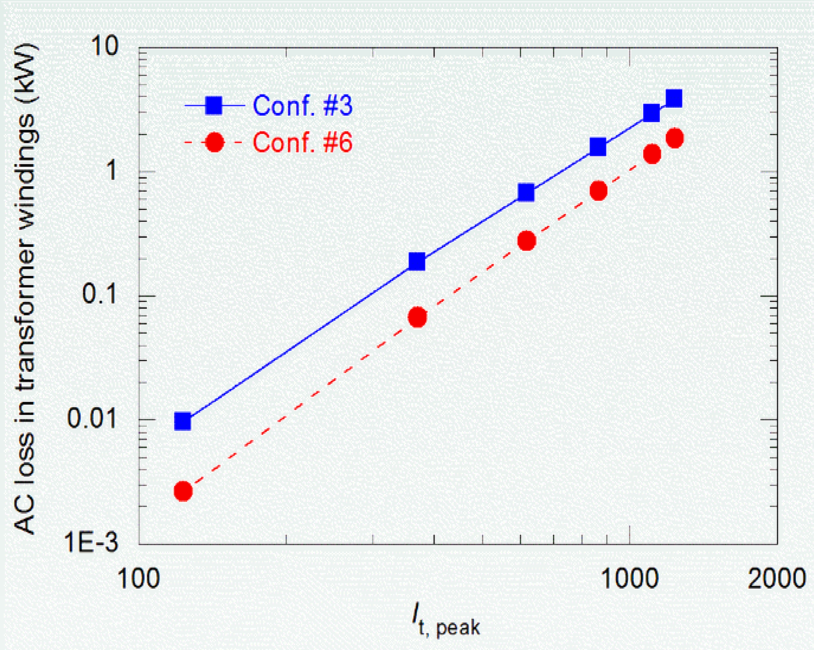


Schematics of hybrid winding structure

Results

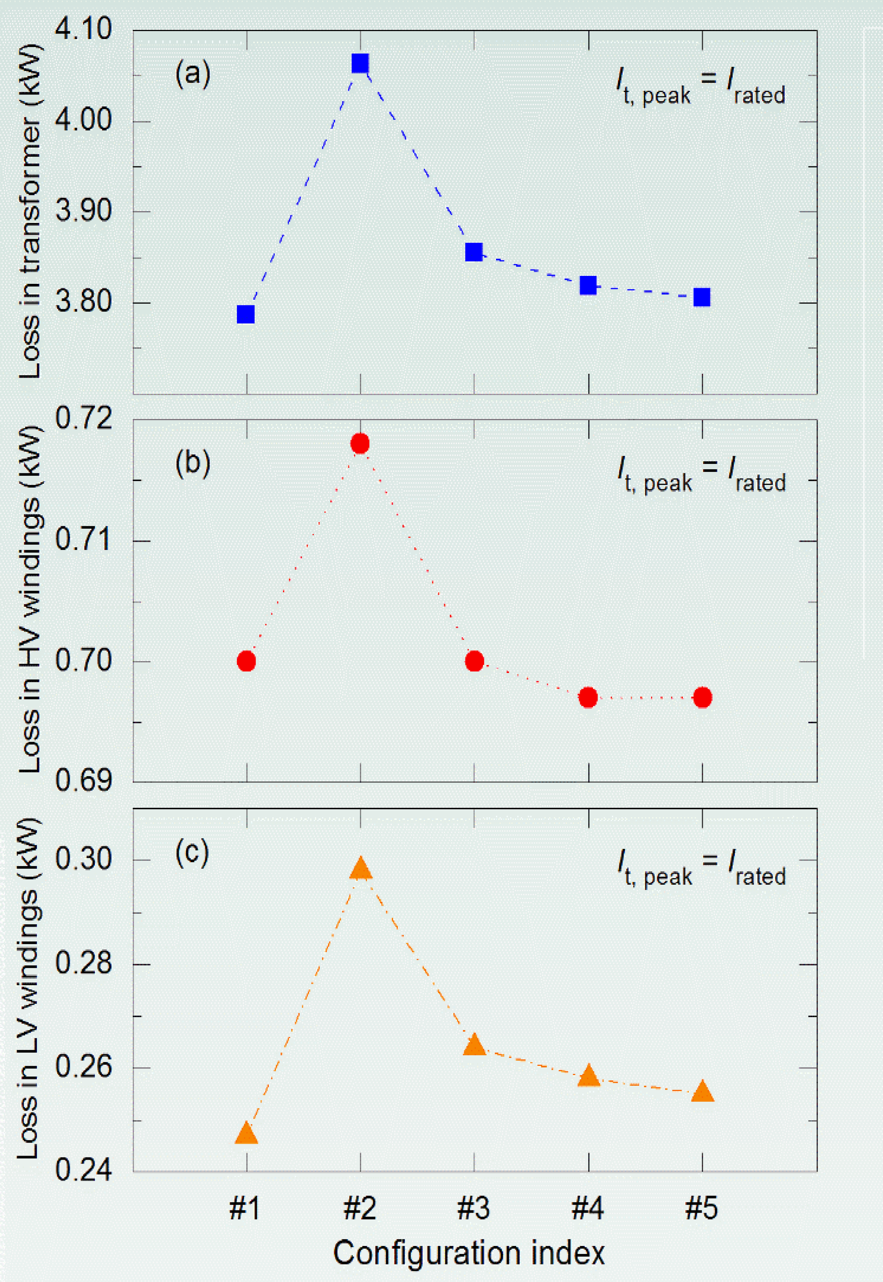


AC loss in Conf. #1 at different current



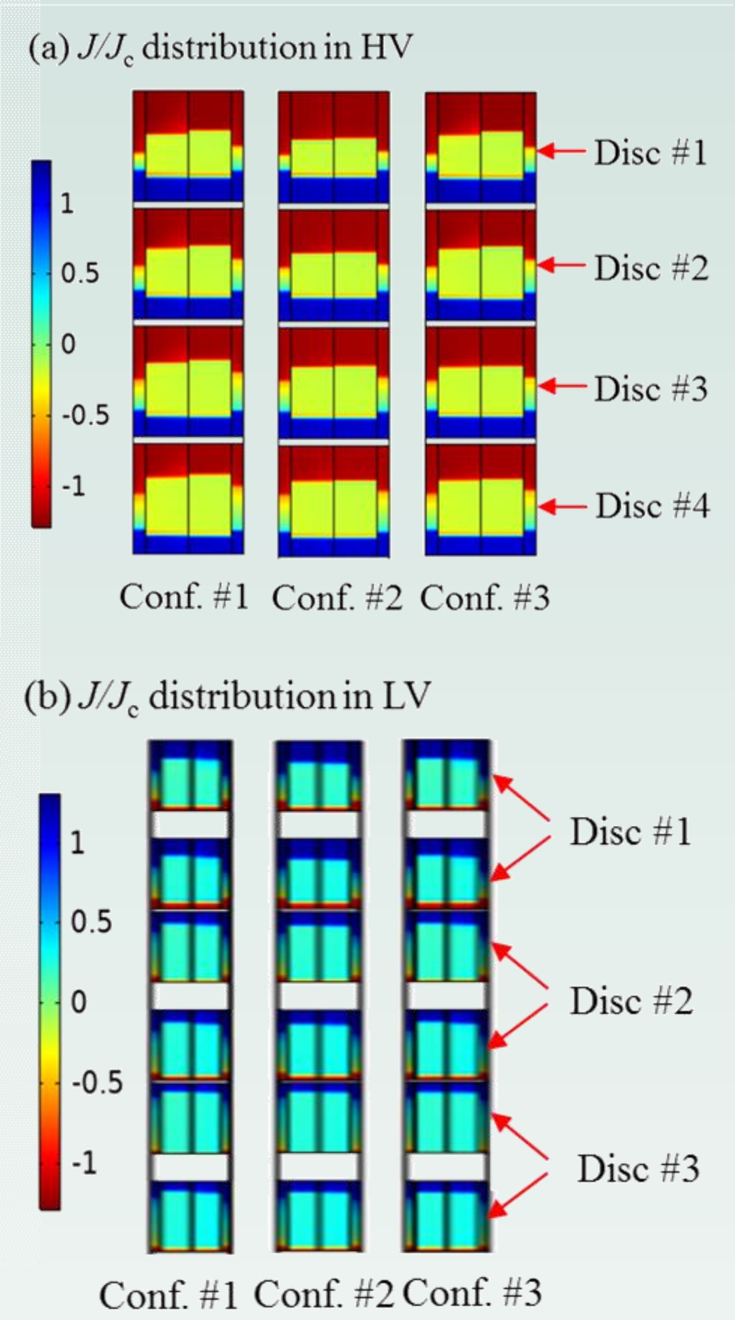
AC loss comparison between Conf. #3 and Conf. #6 at different current

- With flux diverters arranged around the outer ends of the windings, AC loss in windings has been reduced dramatically.
- At rated current, AC loss in Conf. #6 is 1.859 kW, which is less than our AC loss target for the project.



AC loss comparison in transformer windings, HV and LV winding under all configurations simulated at rated current

- The difference in AC loss values between Conf. #1 and Conf. #2 is 7.03%.
- The difference in AC loss values between Conf. #1 and Conf. #3 is only 1.78%, even though Conf. #3 uses only small portion of the Fujikura wires.
- Substantial cost reduction can be achieved by introducing hybrid winding structure by replacing majority of coil winding with low cost and low performance wires while keeping negligible AC loss.



- The region where $|J/J_c| > 1$ is bigger in Conf. #2 than in Conf. #1. This explains why the AC loss value in Conf. #2 is larger than that in Conf. #1.

Summary

- A hybrid transformer structure has been proposed for a 6.5 MVA/25 kV traction transformer, in order to reduce HTS wire cost while keeping low AC loss.
- We calculated and compared six winding configurations, which use different portions of Fujikura wires and SHS wires in HV and LV windings.
- By replacing two discs at the outer ends of HV and LV windings with Fujikura wire, while all other central discs are wound using SHS wire, we obtained similar AC loss value in the configuration (Conf. #3) as that in the configuration wound with the Fujikura wires (Conf. #1).
- With flux diverters arranged around the outer ends of the windings of the hybrid winding (Conf. #3), we can get 1.859 kW, which is less than our AC loss target for the project.