Minimizing the heat losses of a self-switching kA-class rectifier flux pump

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Superconducting coil magnets are normally working in driven model with thick current leads.

- Generating considerably heat load
- Complicating thermal insulation
- Enlarging footprint
- Higher cost

Magnetisation of HTS ring magnets using field cooling.

- Requires high external magnetic field
- Cryogenic temperature should be maintained to keep HTS magnet alive
- Magnets decay over time

HTS flux pumps can inductively generate DC voltage in a closed superconducting loop, avoiding the current lead problems.

- Flux pumping is a promising technology for HTS DC magnets, in motor/generator, MRI/NMR, high field magnets, etc.
Joule heating and heat leakage due to copper at 77K

To calculate the resistance of the copper lead we use equation 1, where $R$, $\rho$, $l$, $A$ are resistance, electrical resistivity, length of lead and cross-sectional area.

$$R = \rho \left( \frac{l}{A} \right) \quad (1)$$

Joule loss ($P$) can be calculated using Equation no 2.

$$P = i^2 R \quad (2)$$

For the heat leakage or heat flux/power we can use equation no 3, where $Q$, $\kappa$, $T_H$, $T_L$ are heat flux, thermal conductivity.

$$Q = i \sqrt{2} \kappa r (T_H - T_L) \quad (3)$$

Table 1. gives the values used in calculations $^{1,2}$.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>2.00E-9</td>
<td>$\Omega m$</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>781</td>
<td>Wm$^{-1}$K$^{-1}$</td>
</tr>
<tr>
<td>$T_H$</td>
<td>273</td>
<td>K</td>
</tr>
<tr>
<td>$T_L$</td>
<td>77</td>
<td>K</td>
</tr>
</tbody>
</table>

Table 1. Parameters values used in this analysis

2. Le, Conceptual design of current lead for large scale high temperature superconducting rotating machine. https://doi.org/10.9714/PSAC.2014.16.2.054
Comparison of instantaneous heat losses in copper

<table>
<thead>
<tr>
<th>1- Conventional HTS coil</th>
<th>2- HTS flux pump</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Copper Terminals</strong></td>
<td><strong>Bifilar Bridge</strong></td>
</tr>
<tr>
<td><strong>Load Coil</strong></td>
<td><strong>Load Coil</strong></td>
</tr>
<tr>
<td><strong>Charging secondary</strong></td>
<td></td>
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<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Target current in coil</td>
<td>100A</td>
<td>100A</td>
</tr>
<tr>
<td>Applied current (i)</td>
<td>100A</td>
<td>3A</td>
</tr>
<tr>
<td>Copper lead length x2</td>
<td>0.2m</td>
<td>500 Nturns</td>
</tr>
<tr>
<td>Copper lead diameter</td>
<td>φ30mm</td>
<td>φ1.5mm</td>
</tr>
<tr>
<td>Joule Heating</td>
<td>0.0056W</td>
<td>Joule Heating</td>
</tr>
<tr>
<td>Heat Flux/Power</td>
<td>1.18W</td>
<td>Heat Flux/Power</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td>1.1856W</td>
<td><strong>Sum</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.64W</td>
</tr>
</tbody>
</table>

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Applied current signals

As mentioned previously the conventional HTS coil magnets are operated in driven mode, so a constant DC supply is connected to the ends of the coil. Whereas the HTS flux pump is operated inductively by a non symmetric signal.

Fig 1: Applied signal for conventional HTS coil

Fig 2: Applied signal for Flux pump
Joule heating in the HTS coil and flux pump plotted over one cycle. In case of flux pump the peak current is applied in a fraction of a second and only during this time instant we see a comparatively high loss, for the rest of the cycle the losses are less than 0.001W.

By integrating the total joule heating will come as:

- P = 5.6W
- P = 3.4W
Current in the load coil

The current waveforms for both conventional HTS coil and flux pump operated HTS coil.

Fig 1: Current in conventional HTS coil

Fig 2: Current in coil pumped by using flux pump
Conclusion and further studies

- This study is performed at lower scale as a fraction of the 1kA level target to give a brief insight of the importance of flux pump to reduce the heat losses in the cryogenic systems.

- A quantitatively study is performed to estimate the total heat losses in the copper for conventional HTS coil magnets and comparison is presented with the promising flux pump technology.

- The study proved that the heat losses will be minimized to a 60% and has a potential to go further down with optimal topology, as well as reducing the footprint of the whole HTS magnet.

- In this study only copper losses are considered, joule heat and heat leaking. It is well kept in mind there is another kind of source present in the flux pump system in the form of iron core. Heat loss due to iron core is kept for future study, since there is an ongoing study on different core materials and their performance in cryogenic systems.
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