Optimising Rotor Speed and Geometry for an Externally-Mounted HTS Dynamo

A.E. Pantoja, C.W. Bumby, A. Barnes, Zhenan Jiang, J.G. Storey, R.A. Badcock

1 Robinson Research Institute, Victoria University of Wellington, 69 Gracefield Road, Lower Hutt 5046, New Zealand

Contact e-mail: chris.bumby@vuw.ac.nz

Dynamo-type flux pump

- HTS magnet coils cannot be operated in persistent mode.
- Require DC current injection from external current supply via metal current leads.
  - Conducting current leads bridge between room temperature and cryogenic environment
- Alternative approach: HTS flux pump
  - Enables quasi-persistent current operation by developing a small (∼ 18 mV) time-averaged DC driving voltage which compensates for resistive losses
- Dynamos-type HTS flux pump employs mechanically-rotating permanent magnets to generate an AC emf, which is partially rectified as magnet passes over coated conductor tape
  - Behaves like a DC voltage source with internal resistance
  - Minimise parasitic heat load by placing all moving parts OUTSIDE of cryogenic environment

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Excites HTS circuit through the cryostat wall

Origin of DC output

A DC open circuit voltage arises due to time-averaging of the voltage waveform across the stator wire, i.e.

\[ V_\text{oc} = \frac{1}{\pi} \int_0^{\pi} V_s(t) \sin(\omega t) \, dt = \frac{1}{\pi} \int_0^{\pi} \sin(\omega t) \, dt \]

Here \( V_s(t) \) is the flux enclosed by the loop formed by the stator wire, its connecting leads, and the load (or measurement unit), and \( \Delta V_s(t) \) is the change in output voltage measured in the superconducting state (i.e. compared to the normal-conducting state). This can be re-expressed as an integral over the rotor angle, \( \theta \),

\[ V_\text{oc} = \frac{1}{\pi} \int_0^{\pi} \Delta V_s(t) \sin(\omega t) \, dt \]

Furthermore:

\[ \Delta V_s(t) = \Delta V_{s0} \cos \omega t \Rightarrow f_\text{oc} = \frac{\Delta V_{s0}}{\pi \omega} \]

where \( f_\text{oc} \) is the crossing frequency of magnets across the stator wire, \( \omega \) is the rotor speed (in rpm), and \( n \) is number of magnets on the rotor.

Therefore we expect:

\[ V_\text{oc} = \frac{n \Delta V_{s0}}{\pi \omega} \]

AC waveforms

Plots of the time-dependent open-circuit voltage waveforms \( V(t) \), shown as function of rotor angle \( \theta \), data was obtained at 77 K, and is shown for each rotor geometry across a range of rotor speeds. Note that the sharp (negative) voltage peaks correspond to angle at which a rotor magnet is centered directly above the single stator wire.

Frequency ramping

Open-circuit DC voltage measured during frequency ramp. Normalising the voltage by magnet number collapses all data onto single linear relationship. (Ramp rate = 4.75 rpm s⁻¹)

Output I-V performance:

Time-averaged DC output from HTS dynamo. 1-V curves obtained using a programmable current source (source-measure unit) [4]. Data shown for ‘generator’ quadrant in which dynamo acts as a current & voltage source.

DC output parameters as a function of rotor speed and magnet number. Short-circuit current \( I_{\text{sc}} \) is maximum current that can be delivered by dynamo, \( R_\text{L} \) is effective internal resistance due to AC losses.

Summary

- Through-wall excitation of HTS magnet coil by dynamo-type HTS flux pump enables injection of large currents into an HTS circuit, without penetration of the cryogenic envelope.
- This type of flux pump behaves as a DC voltage source with open-circuit voltage \( V_\text{oc} \) and an internal resistance, \( R_\text{L} \), (due to dissipative losses arising from time-varying field interacting with DC current).
- DC output arises from time-averaging of a partially-rectified AC waveform voltage (see [6]).
- DC output voltage is directly proportional to frequency at which magnets cross stator, \( f = \frac{V_{\text{oc}}}{R_\text{L}} \)
- At rotor speeds below 1000 rpm, \( I_{\text{sc}} \) is independent of number of rotor magnets or speed.

References