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VICTORIA UNIVERSITY OF WELLINGTON TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI | Robinson Research Institute

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

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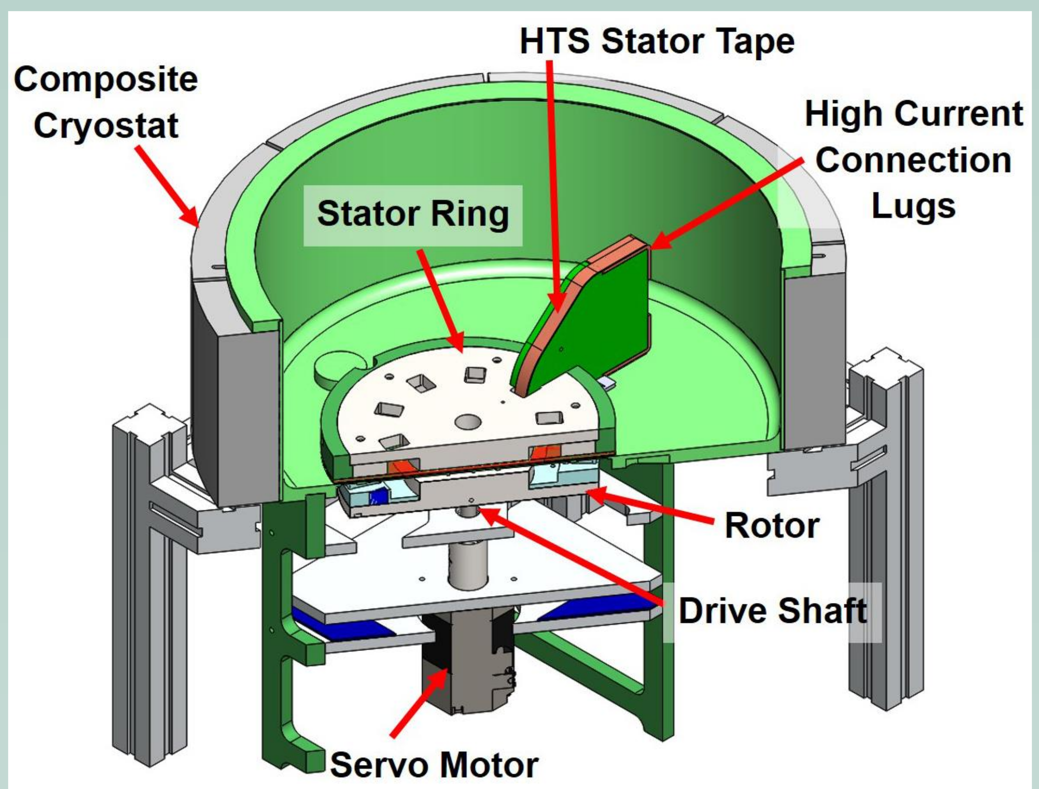
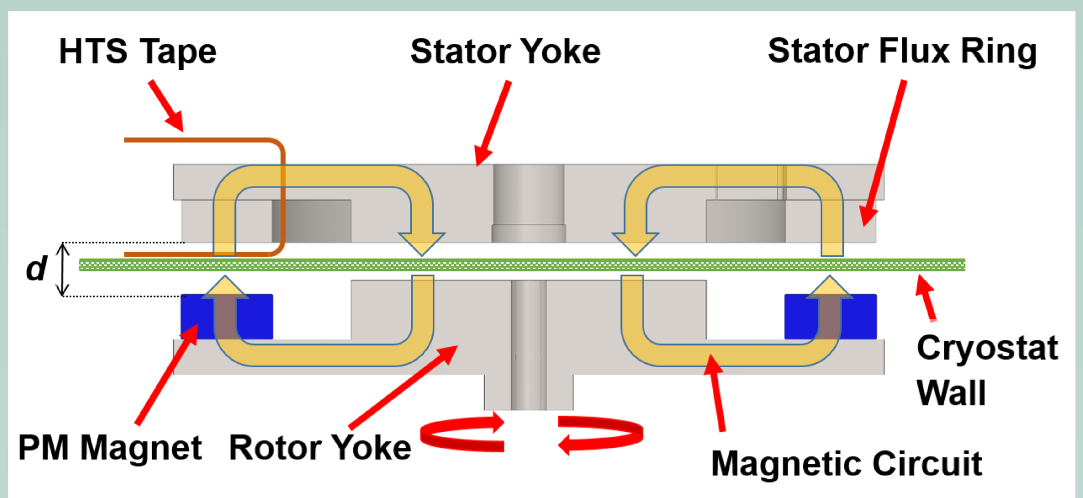
Dynamo-type flux pump

- 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
    → Parasitic heat load (conduction + dissipation)
- Alternative approach: HTS flux pump
  - Enables quasi-persistent current operation by developing a small (≲10 mV) time-averaged DC driving voltage which compensates for resistive losses
- Dynamo-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

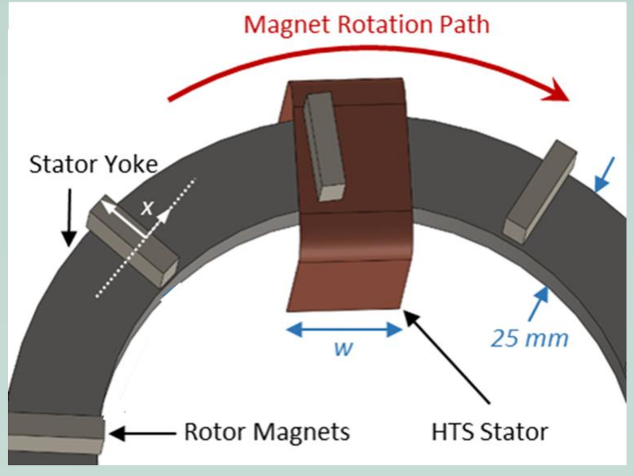
→ Excite HTS circuit through the cryostat wall



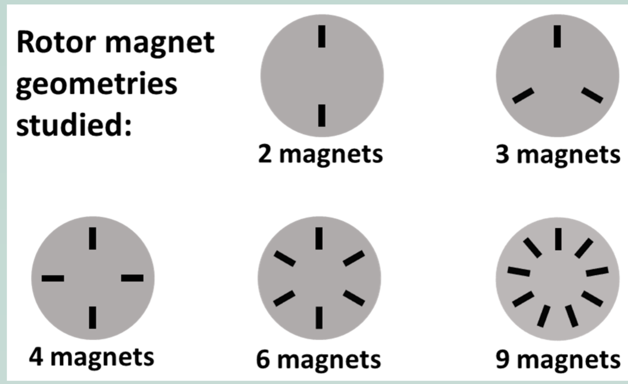
Cut-away diagram of experimental HTS dynamo test rig, showing stator yoke within composite LN2 bath and arrangement of external rotor. HTS stator tape is 12 mm REBCO coated-conductor wire (Superpower).
For this work: stator width, w = 12 mm; Flux gap, d =7.5 mm. Magnet dimensions were 25 mm x 12.5 mm x 6.3 mm, and radial length to centre of magnets, r = 63 mm.



Cross-section of Flux pump showing iron rotor yoke, stator yoke and cryostat wall.



Schematic of magnet path across stator wire. (Cryostat wall and rotor yoke omitted for clarity)



Different arrangements of equally-spaced Nd-Fe-B permanent magnets on rotor yoke.

Origin of DC output

A DC open-circuit voltage arises due to time-averaging of the voltage waveform across the stator wire, ie:

$$\overline{V}_{oc} = f\int_0^{1/f} V_{oc}(t)dt = \underbrace{f\int_0^{1/f}\frac{d\Phi(t)}{dt}dt}_{=0} + \underbrace{f\int_0^{1/f}\Delta V_{oc}(t)dt}_{\neq 0}$$

Here $\Phi(t)$ is the flux enclosed by the loop formed by the stator wire, its connecting leads, and the load (or measurement unit), and $\Delta V_{oc}(t)$ is the change in output voltage measured in the superconducting state (ie compared to the normal-conducting state).

This can be re-expressed as an integral over the rotor angle, θ:

$$\overline{V}_{oc} = \frac{1}{2\pi}\int_0^{2\pi}\Delta V_{oc}(\theta)d\theta$$

Furthermore:

$$\Delta V_{oc}(\theta) \propto V_{oc}(t) \propto \frac{d\Phi(t)}{dt} \propto f = n\omega_{\text{rotor}}/60$$

where f is the crossing frequency of magnets across the stator wire, ω_{rotor} is the rotor speed (in rpm), and n is number of magnets on the rotor.

Therefore we expect:

$$\overline{V}_{oc} \propto n\omega_{\text{rotor}}$$

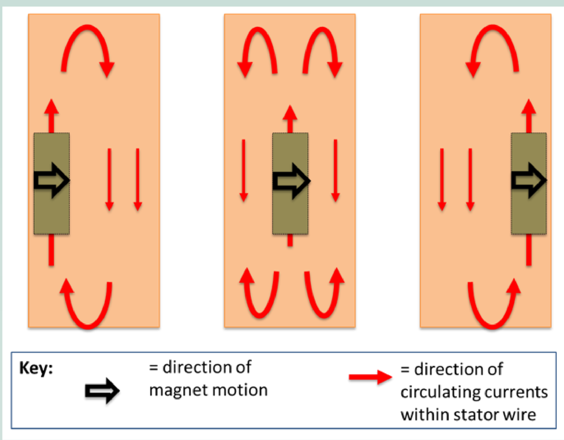
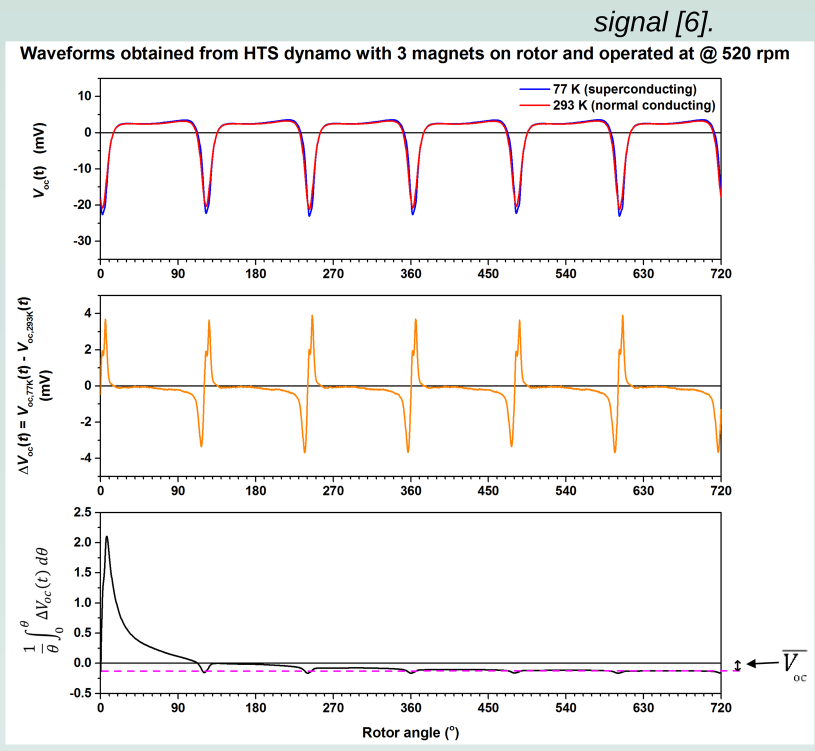


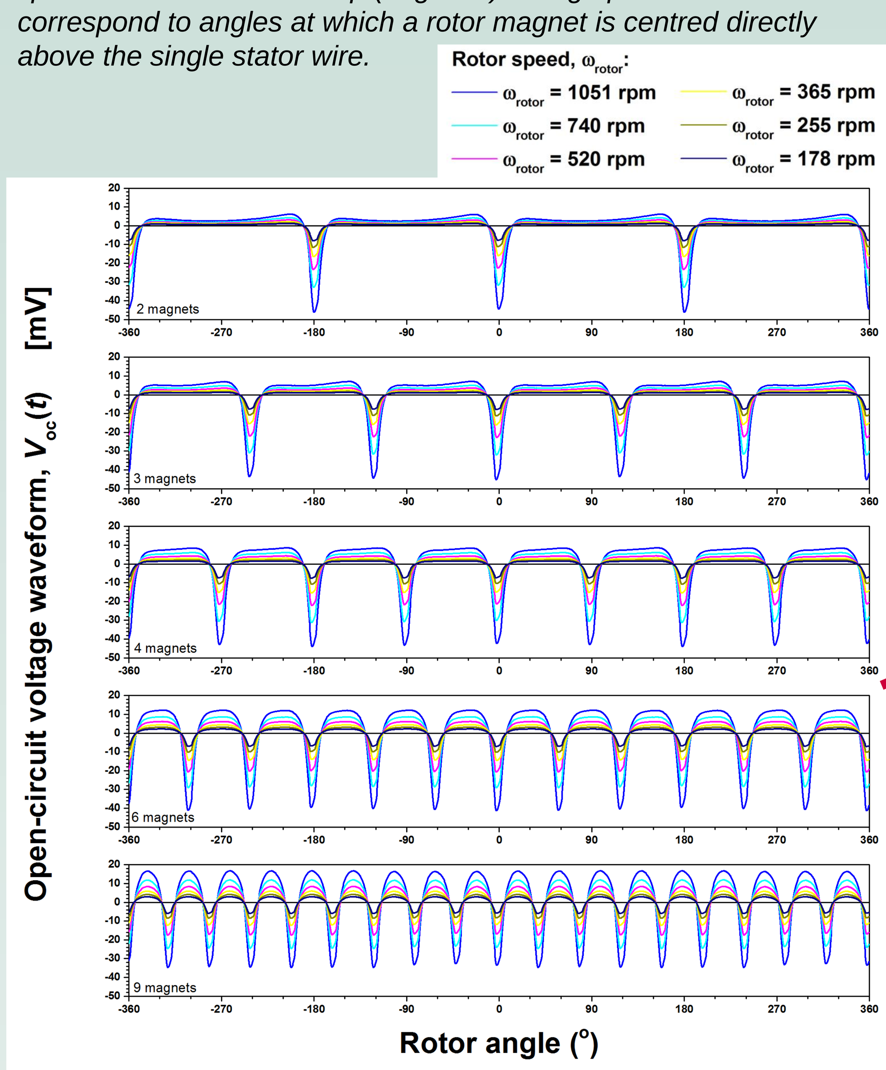
Diagram showing circulating eddy currents flowing around rotor magnet as it passes over coated conductor wire. Non-linear resistivity of eddy current path acts as a potential divider during this period of cycle causing partial rectification of ac signal [6].

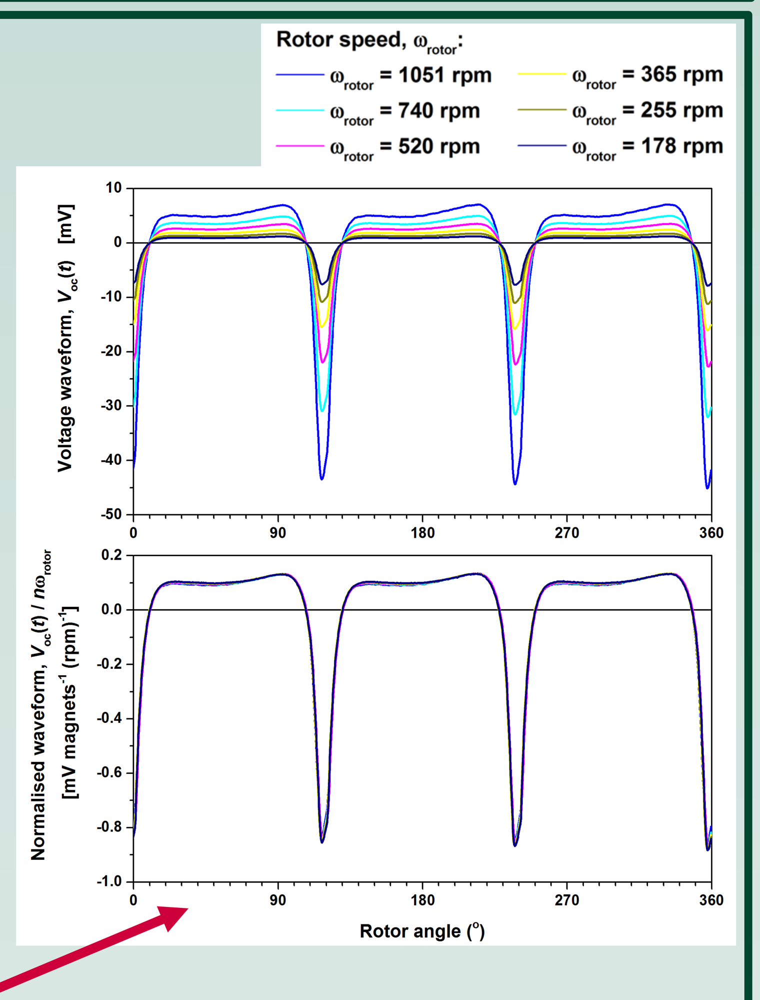


Plots showing waveforms obtained with normal-conducting stator (@ 293 K) and superconducting stator (@ 77 K). Normal conducting waveform is zero (as is induced ac emf). Time integral of superconducting waveform is non-zero due to partial rectification as magnet passes over stator wire [6].

AC waveforms

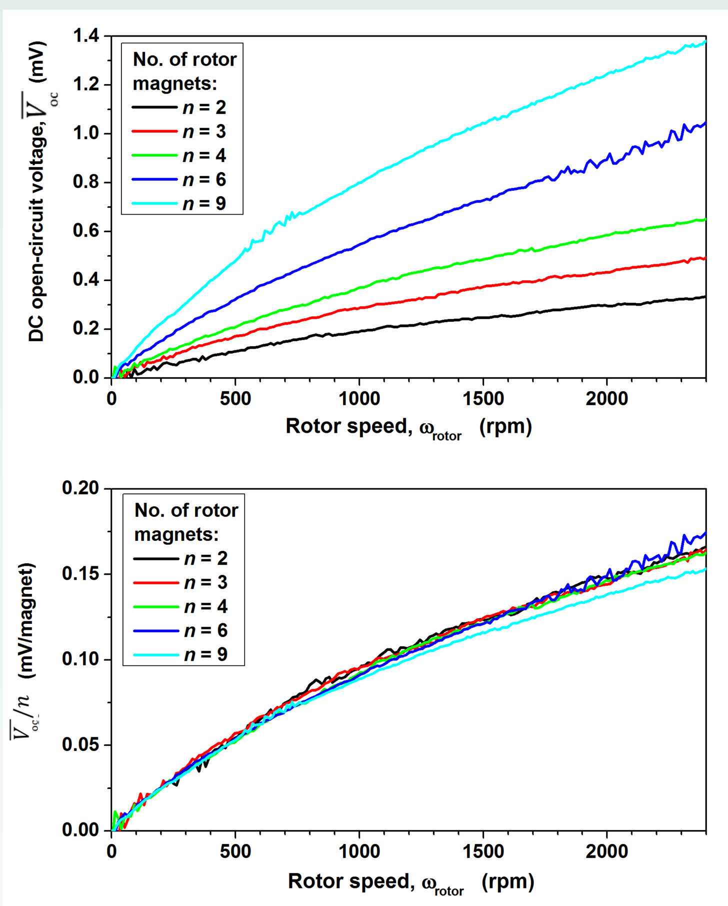
Plots of the time-dependent open-circuit voltage waveforms $V_{oc}(t)$, shown as function of rotor angle. Data was obtained at 77 K, and is shown for each rotor geometry across a range of rotor speeds. Note that the sharp (negative) voltage peaks correspond to angles at which a rotor magnet is centred directly above the single stator wire.





Normalising the voltage waveform by the factor $n\omega_{\text{rotor}}$ collapses all waveform curves onto a single line. (Data plotted for 3 magnet rotor only)

Frequency ramping

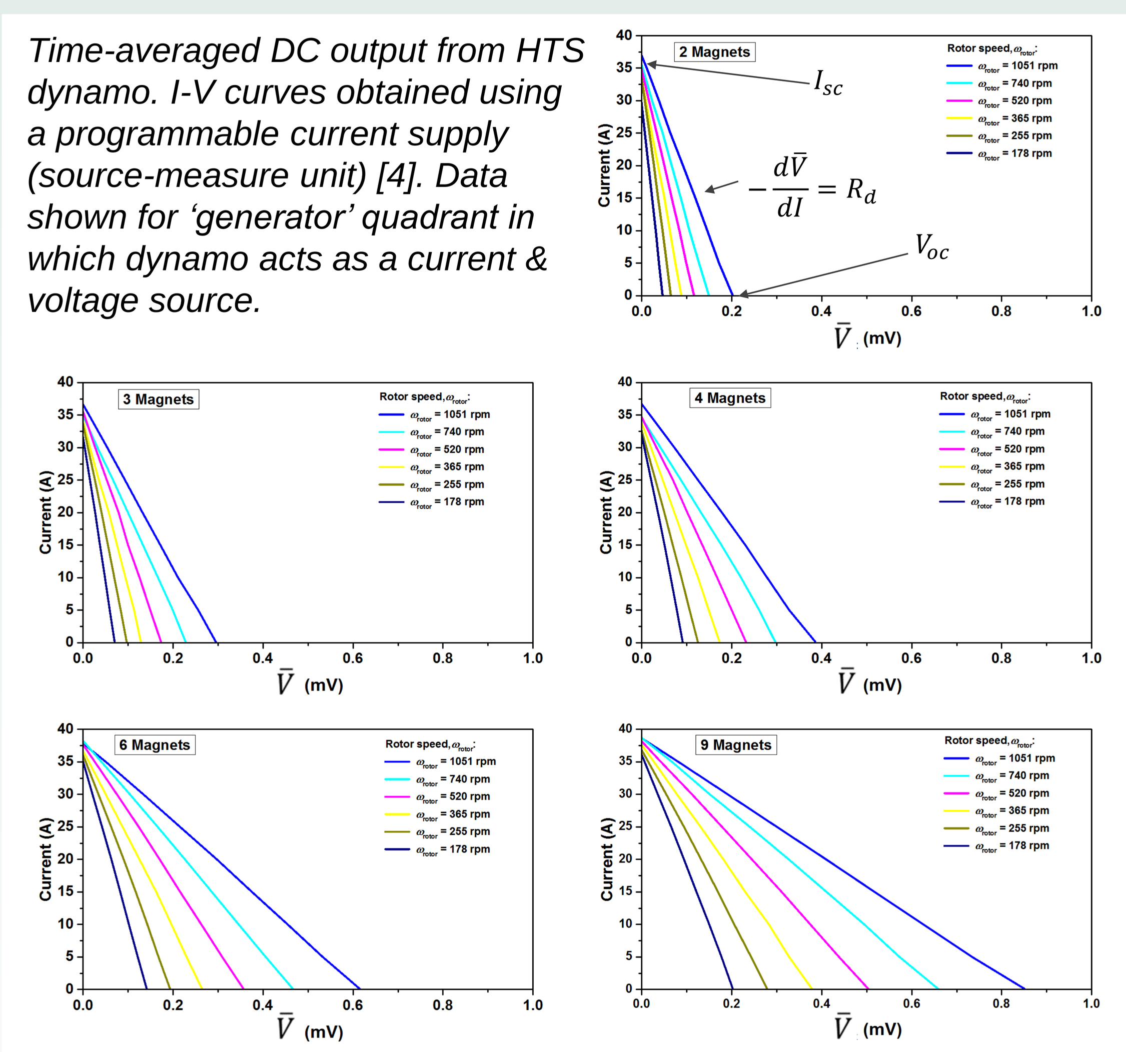


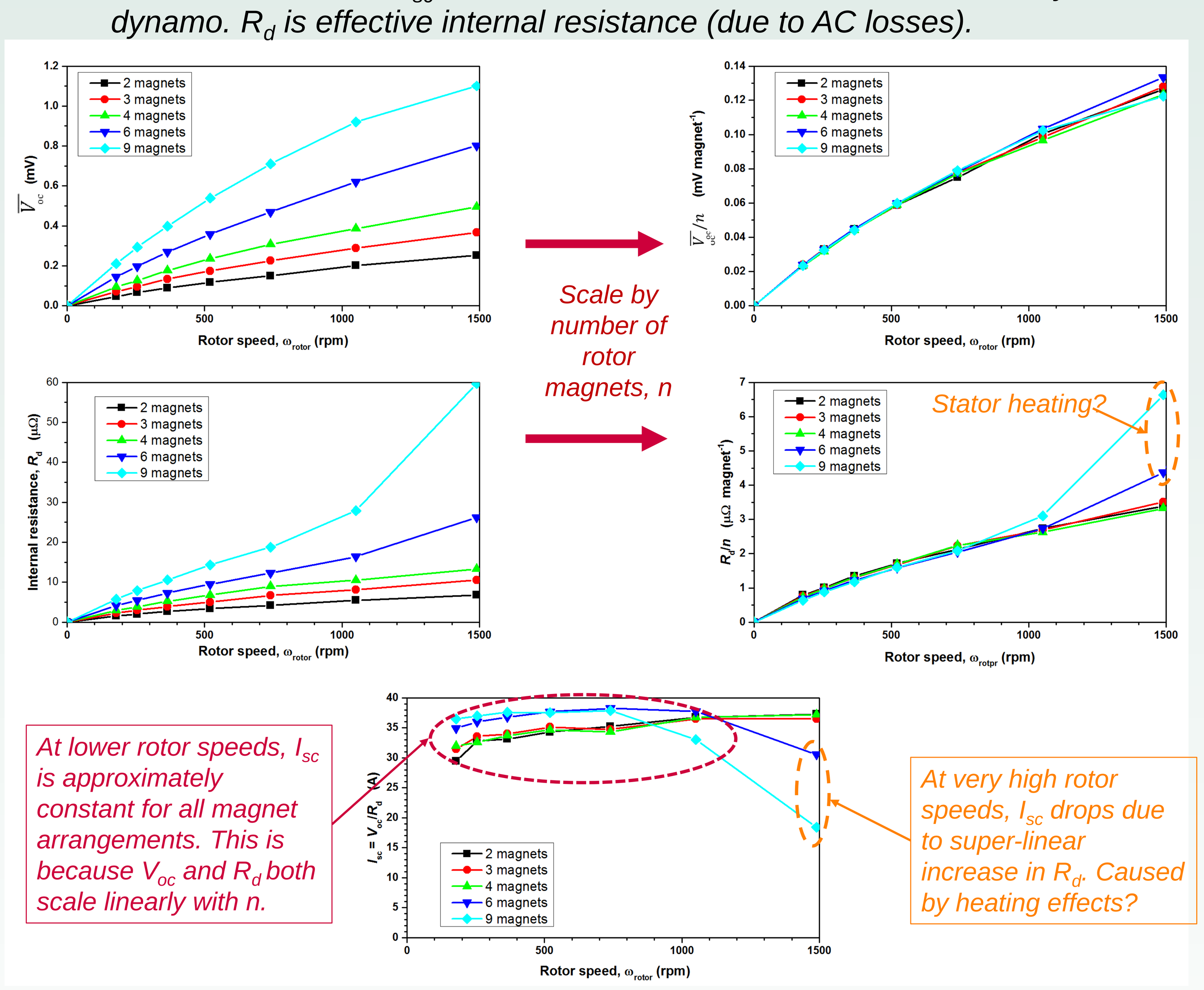
Open-circuit DC voltage measured during frequency ramp. Normalising the voltage by magnet number collapses all data onto single linear relationship. (Ramp rate = 4.75 rpm s⁻¹)

Output I-V performance:

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

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





References

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[7] A.E. Pantoja *et al.* "Impact of stator wire width on output of a dynamo-type HTS flux pump," *IEEE Trans. Appl. Supercond.* **26**, 4805208 (2016)

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, $\overline{V_{oc}}$ and an internal resistance, R_d (due to dissipative losses arising from time-varying field interacting with DC current).
- DC output arises from time-averaging of a partially-rectified AC voltage waveform (see [6]).
- DC output voltage is directly proportional to frequency at which magnets cross stator, $f = n\omega_{\text{rotor}}/60$
- **At rotor speeds below 1000 rpm, I_{sc} is independent of number of rotor magnets or speed.**

See also: [184] Tue-Af-Po2.11-02 'Impact of Stator Ring Width on Output of a Dynamo-type HTS Flux Pump'; [185] Tue-Af-Po2.11-03 'Frequency Ramping Effects on a Dynamo-type HTS Flux Pump'