Core Losses in Co-rich Inductors with Tunable Permeability

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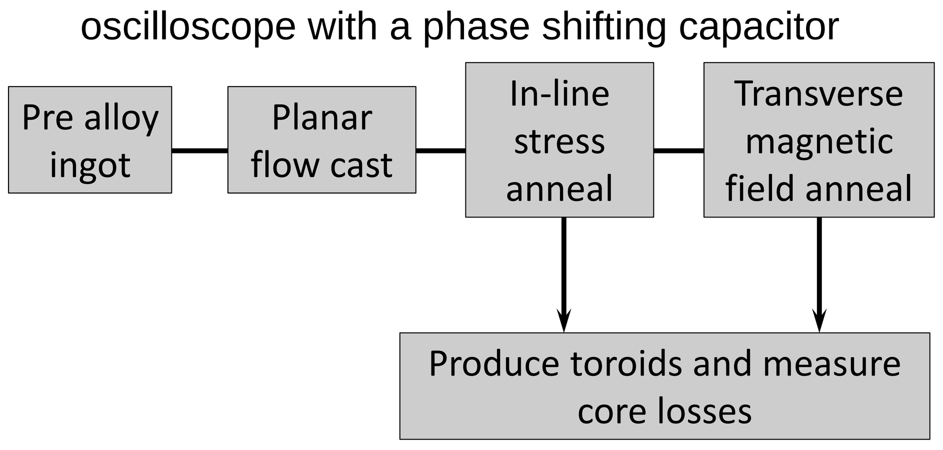
BACKGROUND

High frequency, low loss power systems enable electrified aircraft propulsion. Filter inductors that reduce noise in high current systems can account for 50% of the motor drive mass. Efficient inductor cores with tunable permeability reduce system mass by producing less heat, that removes heat sink mass. Requirements for filter inductors vary based on the chosen topology, but all inductor cores must operate below saturation levels. As the saturation flux density is limited (less than ~2 T), high differential current applications require cores with low relative permeabilities. The large induced anisotropies possible in Co-rich metal amorphous nanocomposite materials enables gapless inductors with relative permeabilities down to ~20. These materials have a nanocomposite close packed structure with high fault density [1]. Scalable processing methods have been demonstrated to produce graded permeability cores [2]. The impact of different processing methods on core losses are presented along with comparison to other low permeability soft magnetic materials.

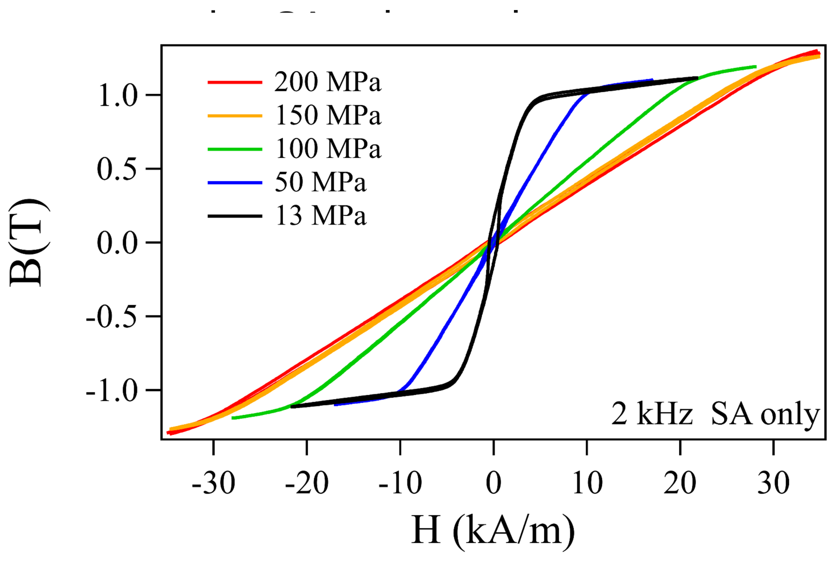
METHODS

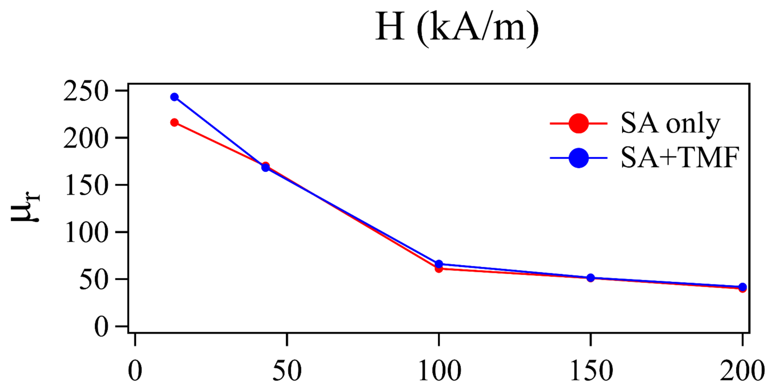
1. Produced amorphous ribbons from pre-alloyed ingots
2. Annealed amorphous ribbon under tensile stress (SA) followed by a transverse magnetic field (TMF) anneal
3. Measure core loss using a high accuracy power meter (Yokogawa WT5000) and an oscilloscope with a phase shifting capacitor

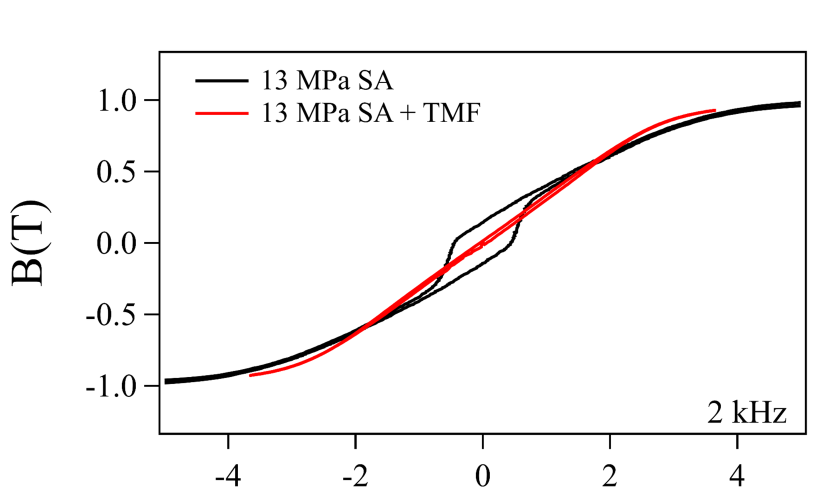


RESULTS

- Results presented for $Co_{75.4}Fe_{2.3}Mn_{2.3}Nb_4B_{14}Si_2$ alloy
- In-line stress varied between 13-200 MPa produces μ_r between 216-40
- Permeability is highly linear to saturation
- After annealing at low tensile stresses (<50 MPa), BH loops shows large coercivity H_c>300 A/m at 2 kHz. Following subsequent TMF, H_c decreases to ~50 A/m
- Permeability remains fairly constant between SA and SA+TMF processing
- SA+TMF anneal significantly lowers core loss

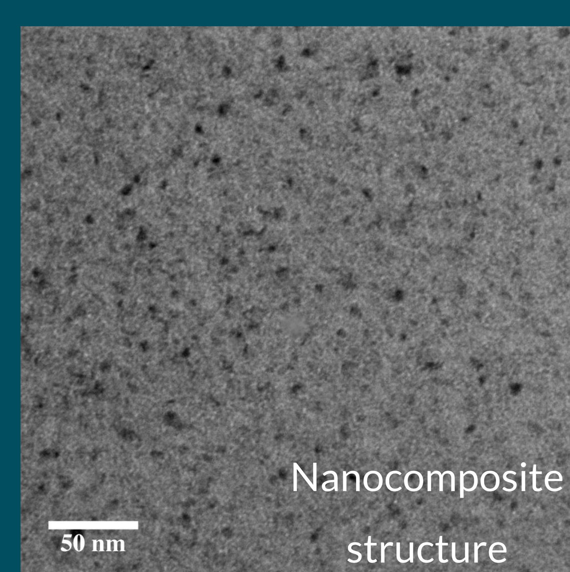


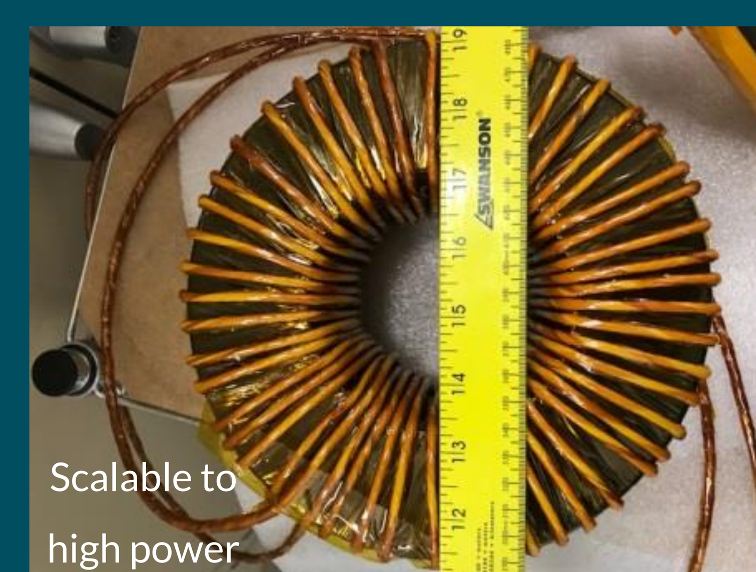




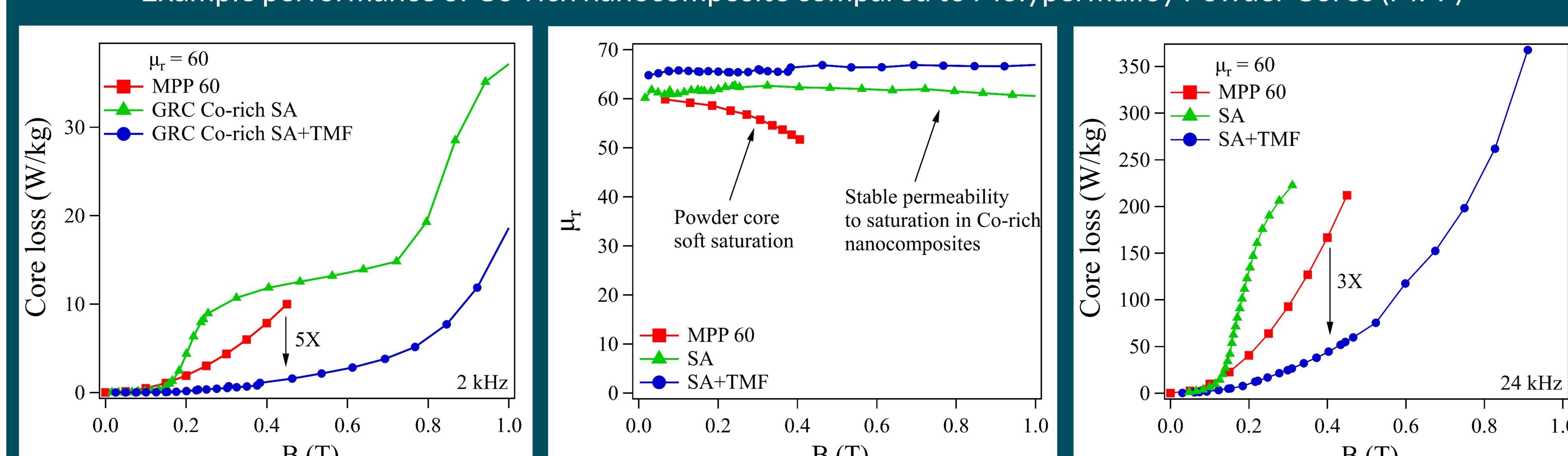
All electric X-57 Maxwell

More than **3X lower** core loss than the best commercial **powder cores**.



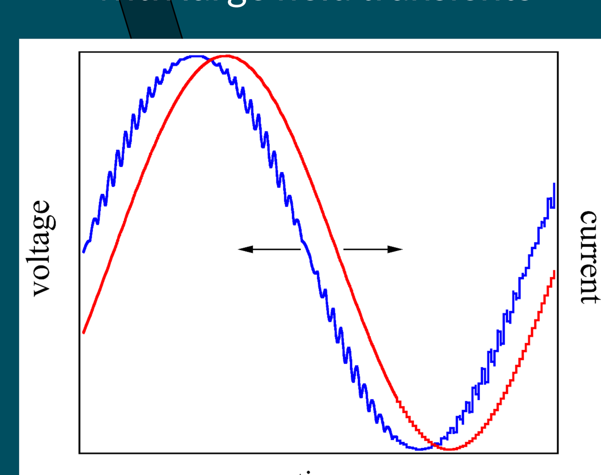


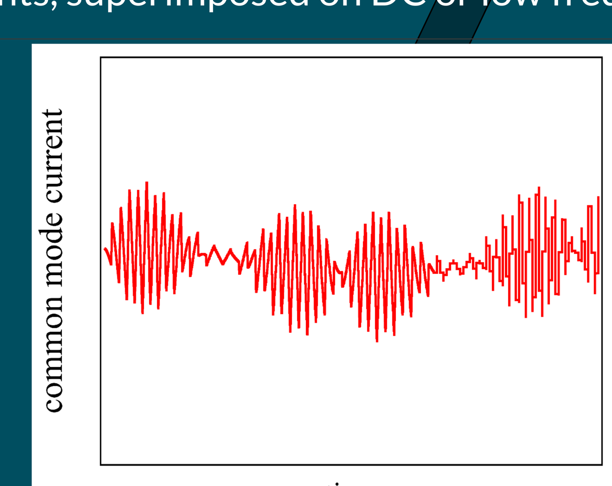
Example performance of Co-rich nanocomposite compared to Molypermalloy Powder Cores (MPP)



Phase frequency typically <5kHz with large field transients

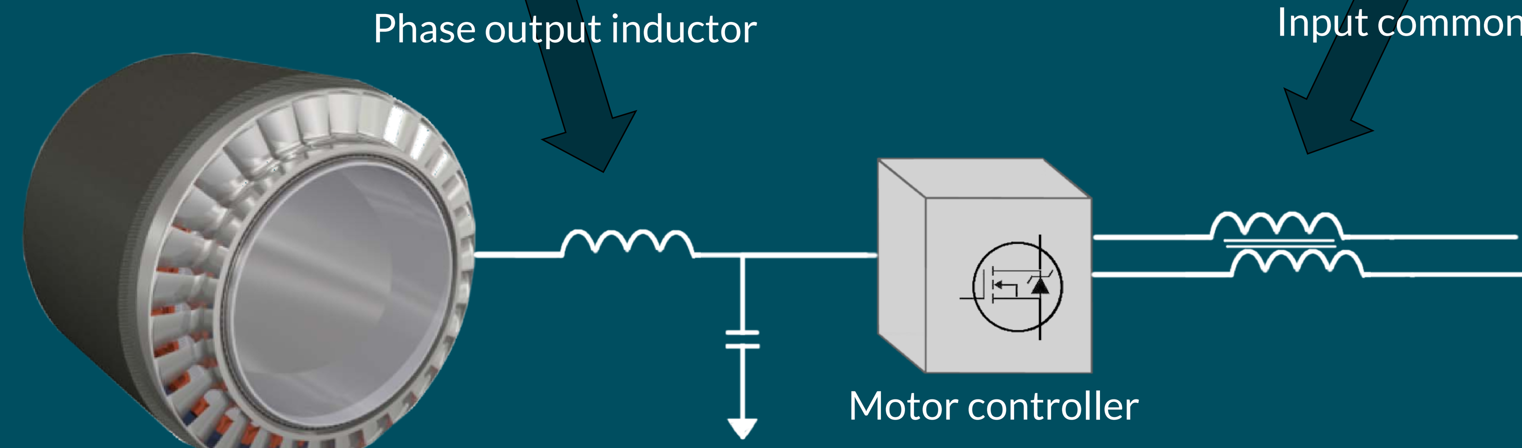
Ripple currents typically >10kHz with small field transients, superimposed on DC or low frequency AC





Phase output inductor

Input common mode choke

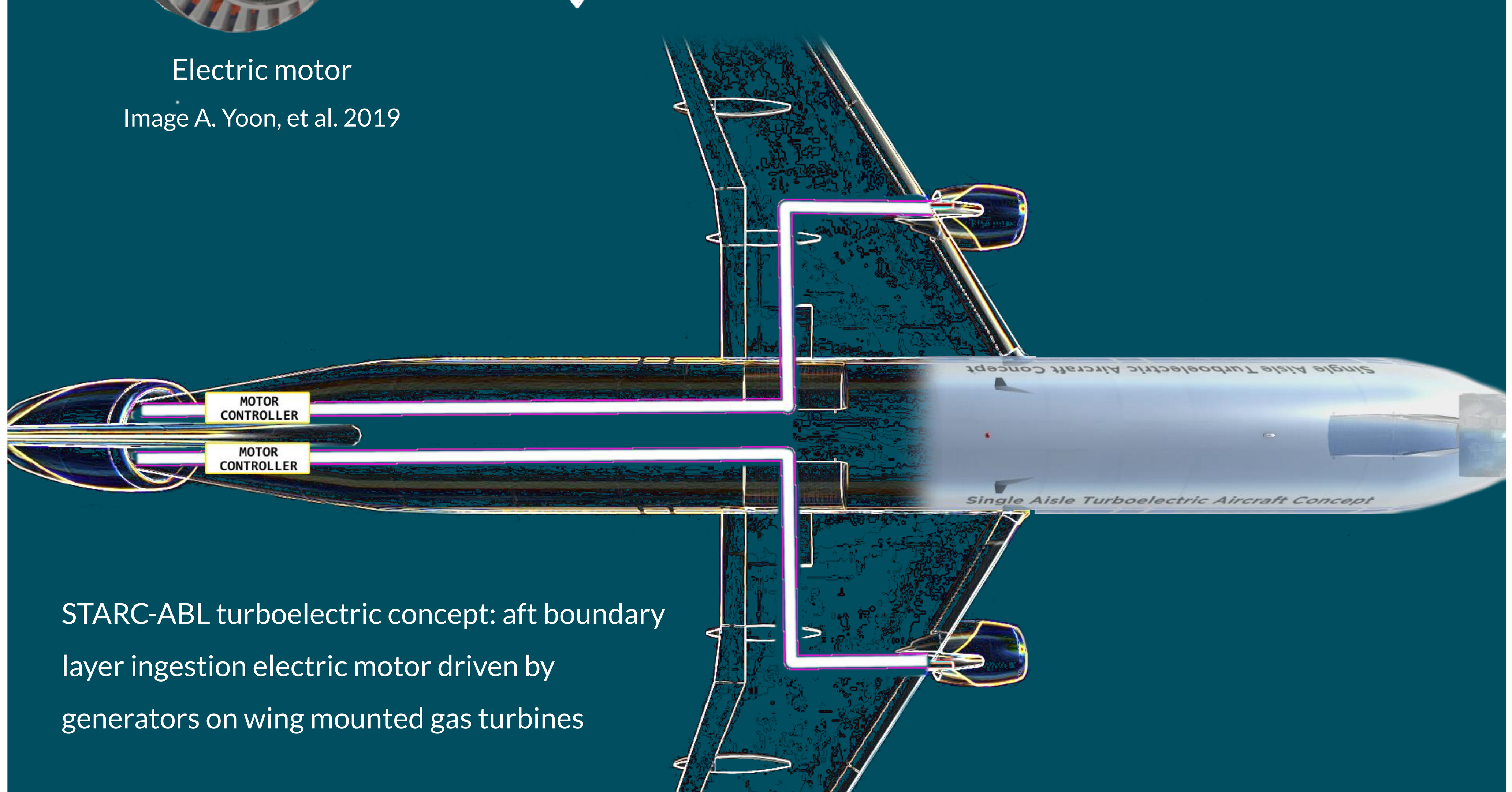


Engine driven generator output

Motor controller

Electric motor

Image A. Yoon, et al. 2019



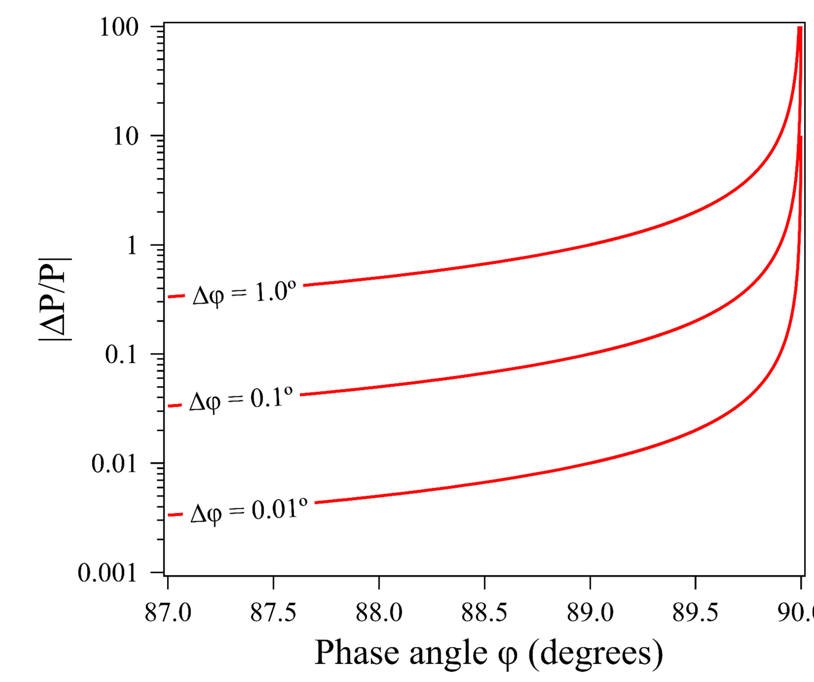
STARC-ABL turboelectric concept: aft boundary layer ingestion electric motor driven by generators on wing mounted gas turbines

MEASUREMENT DETAILS

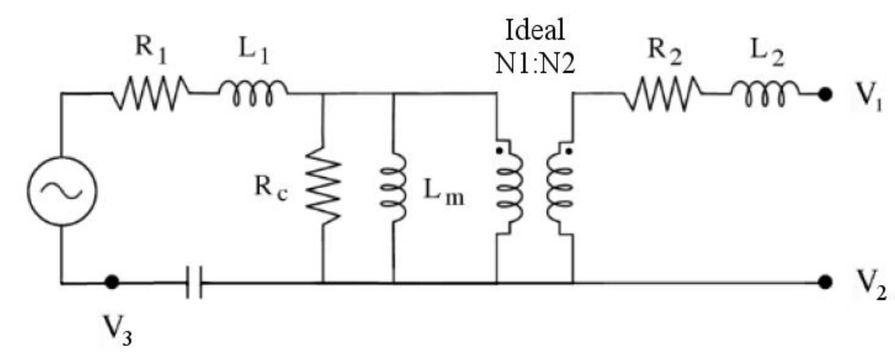
Core loss measurements of low permeability cores requires large output currents and excellent phase angle accuracy $\Delta\varphi$. Assuming small ΔV and ΔI, the power measurement error ΔP is described as:

$$\Delta P = \frac{\partial P}{\partial V}\Delta V + \frac{\partial P}{\partial I}\Delta I + \frac{\partial P}{\partial \phi}\Delta\phi.$$

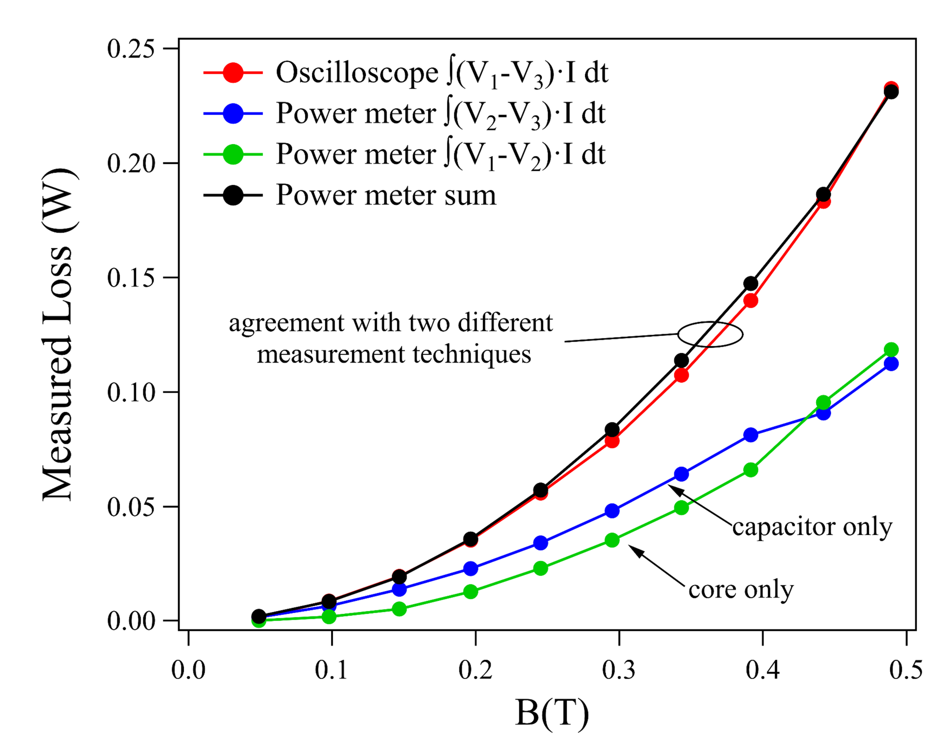
$$\left|\frac{\Delta P}{P}\right| = |\tan\phi||\Delta\phi|$$



Small phase angle errors lead to large power measurement errors when φ→90°. Measurements that rely on oscilloscope probes can have $\Delta\varphi$~0.5°, but power analyzers can improve accuracy. A series capacitor can be used to lower circuit impedance near the test frequency and to remove DC bias. Otherwise, the test circuit is similar to standard two winding core loss measurements.



Measurement accuracy was verified by comparing two different measurements; individual losses in the core and the capacitor with a power analyzer, and a second that measured the total loss (both core and capacitor) with an oscilloscope. The measurement frequency was chosen near the L_mC resonance so that the phase angle was far from 90°. There is good agreement between the two measurements.



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[1] Leary, A., Keylin, V., Devaraj, A., DeGeorge, V., Ohodnicki, P., & McHenry, M. E. Stress induced anisotropy in Co-rich magnetic nanocomposites for inductive applications. *JMR*, 31(20),3089–3107 (2016).

[2] Byerly, K., Ohodnicki, P. R., Moon, S. R., Leary, A. M., Keylin, V., Mchenry, M. E., … Bhattacharya, S. Metal Amorphous Nanocomposite (MANC) Alloy Cores with Spatially Tuned Permeability for Advanced Power Magnetics Applications. *JOM,* 70(6),879-891 *(2018)*.

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