Calorimetric Measurements of AC losses in HTS tapes in a Stator Environment

Cryogenics Engineering Conference/
International Cryogenic Materials Conference
Tucson Arizona
June 29, 2015

John P Murphy
UDRI Contractor
Propulsion Directorate
Air Force Research Laboratory
CO-AUTHORS, ACKNOWLEDGEMENTS

• **Air Force Research Laboratory – Aerospace Systems Directorate**
  - T.J. Haugan
• **Univ. of Dayton Research Institute (@ AFRL)**
  – J.P. Murphy
• **The Ohio State University**
  – M.D. Sumption
  – M. Majoros
  – E.W. Collings
• **UES Inc.**
  – N. Gheorghiu

Support by the
**Air Force Office of Scientific Research (AFOSR) and**
**The Air Force Research Laboratory. (AFRL/RQ)**
AC Loss in Superconductors

• Critical factor, sometimes considered at the end of machine design, instead of at the beginning
• AC Loss in Motors/Generators typically 3-4x higher than theory

\[ Q = Q_{\text{Hysteresis}} + Q_{\text{Coupling}} + Q_{\text{Eddy-current}} + Q_{\text{Transport}} + Q_{\text{Interaction (eg. Dynamic)}} \]

For motor/generator – the loss induced by external fields (blue terms) are dominant, and can be denoted \( Q_{\text{magn}} \)

\[ Q_{\text{magn}} = Q_{\text{Hysteresis}} + Q_{\text{coupling}} + Q_{\text{Eddy-current}} \]

YBCO Tape Loss

\[ Q = Q_{\text{Hysteresis}} + Q_{\text{Coupling}} + Q_{\text{Eddy-current}} \]

\[
Q_{h,v} = \mu_0 J_c w H_a \left[ 2 \frac{H_c}{H_a} \ln \left( \cosh \left( \frac{H_a}{H_c} \right) \right) - \tanh \left( \frac{H_a}{H_c} \right) \right]
\]

(Brandt / Müller)

Where \( Q_{h,v} \approx \mu_0 J_c w H_m \)

\[
\frac{Q_h}{L} = B_a w J_c w t = B_a w I_c
\]

\[
P/L = B_a f w I_c
\]

\[ Q \propto w : \text{minimize filament diameter to decrease } Q \]

Heat due to AC loss must be removed, with cryocooler penalty

Hysteretic Loss

Normal Metal Eddy Current

\[
\frac{P}{L} = B_a f w I_c + \frac{\pi^2}{6\rho} w^3 t (B_a f)^2
\]

AC Loss

\[
\left( \frac{P}{L} \right) \left( \frac{1}{B_a f} \right) = w I_c + \frac{\pi^2}{6\rho} w^3 t + (B_a f)^2
\]

Intercept

Slope
YBCO Tape Loss

\[ Q = Q_{\text{Hysteresis}} + Q_{\text{Coupling}} + Q_{\text{Eddy-current}} \]

\[ Q_{h,v} = \mu_0 J_c w H_a \left[ 2 \frac{H_c}{H_a} \ln \left( \cosh \left( \frac{H_a}{H_c} \right) \right) - \tanh \left( \frac{H_a}{H_c} \right) \right] \]

(Brandt / Müller)

Where \( Q_{h,v} \approx \mu_0 J_c w H_m \)

\[ Q_{h}/L = B_a w J_c w t = B_a w l_c \]

\[ P/L = B_a f w l_c \]

Heat due to AC loss must be removed, with cryocooler penalty

\[ P \quad \text{(Hysteresis)} \quad \text{Normal Metal} \]

\[ Eddy \quad \text{Current} \]

\[ \frac{P}{L} = B_a f w l_c + \frac{\pi^2}{6 \rho} w^3 t (B_a f)^2 \]

AC Loss

\[ \frac{P}{Bf} \]

Intercept

Slope

Hysteresis

Eddy Loss

\[ \left( \frac{P}{L} \right) \left( \frac{1}{B_a f} \right) = w l_c + \frac{\pi^2}{6 \rho} w^3 t + (B_a f)^2 \]
Need for high B and dB/dt Testing

- Windings in a motor/generator see high $dB/dt$ like no other superconducting machine (e.g., 500 Hz and 0.5-1 T).
- Extrapolate to high $dB/dt$ in principle, need actual tests to make predictions reliable
- Easy to imagine a magnet which can reach these values of $B$ and $dB/dt$, but
  - such a magnet would need to be SC to reach the needed fields without Fe
  - The losses would require a SC of the kind we wish to develop
  - Would require high voltage (10s of kV).

Alternative: Move sample and field relative to each other
Effectively -a motor simulator- “mock” motor/generator!
Reduced loss expression plotted against reduced magnetic field for frequency of 171 Hz for (a) … (b) 40-filament sample. Dashed lines are approximate copies of weak field measurements published by Levin et al, and solid lines calculated from strong field results given here. From Carr et al, Supercond. Sci Technol. 20, 168 (2007).

This experiment expands $B^*f$ to over 200 with extended options.
Time-Varying Magnetic Field in a Stator Environment
AC Loss Test Device - Spin-around-Magnet (SAM)

Unique AC Loss Test Device
- 8-pole Hallbach Array of NdFeB Magnets
- B-field = 0.62 T
- Frequency = 0 to 400 HZ (required for AF)
- Sweep Rate B*f = 800 T/s
  (~ 48x higher than standard world-wide)
- Calorimetry Measurement – very precise
- 77K with liquid N₂
- 4.2 K with liquid He ?
- 20 K with liquid Hydrogen ?
- Tapes, Cables, Coils
- AC loss in real stator environment, complex $B$ and $I$ varying in time and space


8 Pole Permanent Magnet Rotor Provides 0.62 Tesla
0 Hz to 400 Hz
AC Field Characteristics

In the 0.5 T sample plane (~ 14 mm from rotor)
At 1800 RPM (120Hz) sweep rate is 240 T/Sec
At 6000 RPM (400Hz) sweep rate is 800 T/Sec

High field harmonics contribute to waveform shape
There are four N and four S poles projecting out from the rotor. Thus, there are four complete field cycles as we go one time around the rotor.

Frequency of the AC field: \[ f = \text{RPM} \times \frac{1}{60} \times 4 \]
Assume 1800 RPM: \[ 1800 \times \frac{1}{60} \times 4 = 120 \text{ Hz} \]

Using the maximum field measured in the sample holder for the radial field in the center of the magnet space \((B_{\text{max}} = 0.5 \text{ T})\),
\[ 0.5 \text{ T} \times 120 \text{ Hz} = 60 \text{ T/s} \]

But, taking only the first quarter cycle,

\[
\frac{\Delta B}{\Delta t} = \frac{B_{\text{max}}}{\tau/4} = \frac{B_{\text{max}} f}{1/4} = 4B_{\text{max}} f = 240 \text{ T/s}
\]
Sealed Sample holder
LN$_2$ Filled via remote operated valve on top
Sample inserted through bottom port which is sealed with a plug
Contains resistors for heating and to indicate LN$_2$ level
All fiberglass except valve and resistors
Typical AC Loss Measurements and Resistive Heater Calibration

**Measured AC loss Cu tape**
- Fast accurate measurement (< 15 min!)
- Small or large tapes, cables, coils
- Sample geometry sufficient for calorimetry
- Tapes are best, good mass to surface area

**Resistive Heater 105.5 ohms (Calibration)**
- Calibration equation: $P = -1.4643x^2 + 3.8274x - 0.0343$  
  $R^2 = 0.9949$

**SLPM (mass flow) N2**

**SLPM (mass flow) N2 vs. Magnetic Field Frequency (Hz)**

**Measured AC loss HTS tape**

**SLPM (mass flow) N2 vs. 40-50 sec each step**
Direct resistivity measurements led to a RR = 7.355
Based on Ice point resistivity 1.553 \( \mu \Omega \text{cm} \) that gives
77K resistivity of 0.21 \( \mu \Omega \text{cm} \).
Graph at right slope is .002 Wsec/T giving
rho = 0.16 \( \mu \Omega \text{cm} \) which is 25% low,
defining our error bar.

\[
P_{\text{eddy}} / L = \frac{\pi^2}{6\rho_n} B_m^2 f^2 w^3 t
\]
REBCO Loss Measurements

Using calibrations to determine the hysteresis (Intercept) and eddy current (Slope) losses in HTS sample
Finding the Critical Current in an HTS Sample

\[ P_{\text{eddy}} / L = \frac{\pi^2}{6 \rho_n} B_m^2 f^2 w^3 t \]

\[ P = P_{\text{hysteresis}} + P_{\text{eddy}} \]
\[ P = \lambda_1 I_c B_f + \lambda_2 I_c (B_f)^2 \]
\[ \frac{P}{I_c B_f} = \lambda_1 + \lambda_2 B_f \]

\[ I_c = \text{Intercept}/Lw \]
\[ L = 0.1 \text{ m} \]
\[ w = 0.004 \text{ m} \]
Intercept (here) = 0.0179 Ws/T
\[ I_c = 45 \text{ A} \]

Slope/L = \( \pi^2 t w^3/6 \rho_n \)
\( \rho = 0.29 \mu \Omega \text{cm} \) is a bit high because of “shadowing” of magnetic field
Conclusions

- A new, High field, High ramp rate AC loss device operational which can reach 480 T/s!
- AC loss calibrations performed using (i) Standard resistor, (ii) Cu strip of known RR
- Measurements performed on YBCO tape. The Ic and sheath resistivity consistent with expectations
- Next samples: striated tapes, CORC cables, Roebel cables, and small Coils
- We have developed a new machine for testing HTS tapes, cables, and coils at high B-dB/dt in motor/generator-like environments