Experimental evaluation of a high-speed multi-megawatt SMPM machine

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Agenda

- Machine Description
- Testing
  - Stator-only
  - Open circuit
  - No-load
  - Short circuit
  - Partial load, full speed generating
- Analysis
- Conclusion
Frame 8 Product Family

- Highlighted area is capability envelope of product family
- Maximum electrical loading along constant torque line
Frame 8 Machine

- Envelope
  - 43.8 in (13350mm) tall
  - 41.5 in (12469mm) wide
  - 85.4 in (25969mm) long

- Weight 8,975 lbs (4,071kg)
Frame 8 Stator and Housing

Built by Kato Engineering
- Collaborative design
- Robust stator design and manufacture
- Proven insulation system
Frame 8 Final Assembly

- Rotor insertion at DDS facility
- Special insertion tooling developed by DDS
Frame 8 Demonstration Unit

Insulation system
- Class H designed for class F temperature rise
- Tested up to 10kV and 800Hz

Oil lubricated ceramic ball bearings in squeeze film damper resilient mounts

Machine Rating
- Generator (demo): 4.2kV, 2.8MW, unity PF, 97.5% eff, 15kRPM
- Generator (expected): 3.6kV, 6.1MW, 0.98 PF, 98.2% eff, 15kRPM
- Motoring (expected): 5.5kV, 7.5MW, 0.80 PF, 98.1% eff, 15kRPM

Cooling System
- Forced air cooling over each end turn and through mid-stack vent
- Closed circuit water/glycol cooling through pressed-on aluminum cooling jackets over stator back iron
- Individual valves per each cooling jacket
- Separate fans for mid-stack and end-turn air
Electromagnetic Design

- High-frequency considerations
  - Iron core loss (eddy and hysteresis)
  - Copper eddy loss
  - Rotor eddy loss (magnets and hub/shaft)

- Stator configuration
  - Thinly laminated, low-loss silicon steel
  - Multi-stranded, form-wound coils

- Rotor configuration
  - Pre-magnetized, segmented magnets
  - Large magnetic gap

- Need to balance manufacturing costs and complexity with loss reduction
  - Wroebel conductors or Litz wire
  - Magnetic slot wedges
  - Size of rotor segments
Stator Only Thermal Model

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<th>Iron Loss [kW]</th>
<th>Slot Cu Loss [kW]</th>
<th>End-turn Cu Loss [kW]</th>
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- 60Hz, 1000A
- FE model predicts <10kW of total loss
Back-to-back tests

2MW machine

8MW machine
Open Circuit Voltage
Magnet Material Data

Demagnetization curves at elevated temperature
Modern hard magnetic materials resistant to demagnetization within normal operating temperatures

26 MGOe nominal

32 MGOe nominal
**Open Circuit Voltage**

- FEA pre-build, 20 °C: $4685 \text{ V}_{\text{rms}}$ line-to-line
- FEA post-build, 20 °C: $4392 \text{ V}_{\text{rms}}$ line-to-line
- Measured, average: $4378 \text{ V}_{\text{rms}}$ line-to-line
No-load loss curves
No-load stator eddy currents

- Analytical methods widely varied
- FE ~10kW lower prediction than experimental (correlated w/ CFD)

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Iron loss discrepancies

- University Epstein tests 26% above manufacturer data
- Independent material testing lab, higher still
- Independent material lab data used in FE model predicts ~ 9kW lower loss than justified with CFD
End-reactance & Short Circuit

Analytical methods
- Liwschitz-Garik & Whipple (41.95 µH)
- Puchstein (38.31 µH)
- Fowler (41.84 µH)
- Langsdorf (46.28 µH)
- Still (125.83 µH)
- Lipo (84.0 µH)

PC-BDC: 8 µH
SC test - 2D FE: 150 µH
UT Test Configuration

Frame 8 demonstration unit tested as a generator

- TF-40 turbine as prime mover
  - ISO rating 3MW at 15kRPM
- 3 MW resistive load bank
- Disc pack flexible coupling
Machine Cooling

Heat Balance Figure

Heat Out Through Frame Surface: 0.1 kW
13.5 kW
14 gpm

Back Iron: 28 kW

Copper: 30 kW
Tooth: 22.5 kW
14 gpm

Windage: 24.4 kW

Rotor: 0.9 kW

Heat Out Through Base: 1 kW
13.5 kW
14 gpm

3.5 lbs/s
12.2 kW

Heat Out Through Water/Glycol Cooling Jacket
Water/Glycol Flow
Heat Out Through Air
Air Flow
Losses
Machine Cooling

- Computational fluid dynamics model results
Generating performance

- Active load significantly improves output power
- Simple circuit model diverges from LP model
- Both models track well for low currents
Stator eddy currents

- Includes tooth ripple, skin and proximity effects
- Dwarfs losses due to fundamental, net current
Loss Segregation

- Thermal model (CFD) identifies significantly more loss than other tools (FE, LP) predict
- Both Iron and copper loss miss by ~10kW
- Discrepancy not principally changed from no-load

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Conclusions

- Thermal models can be used for effective allocation of machine losses
- Commercially available tools are not successful in predicting machine losses \textit{a priori}
- Both parameter and physics based models can be modified after prototype testing to predict losses
- Calibrated models can be used to design similar machines