GE Electrical Machines Portfolio

GE Businesses

Joint Technology Development

Global Research
Technology incubation & prototyping
GE Electrical Machines Portfolio

develop ➞ design ➞ manufacture ➞ monitor ➞ service

Broad capability across infrastructure domain
# Electrical Machines Performance Entitlement Reached with Multi-Discipline Integration

<table>
<thead>
<tr>
<th>Advanced Motor Controls</th>
<th>Advanced Motor Topologies</th>
<th>Advanced Insulation Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>High speed/bandwidth, Optimal efficiency, sensorless, fault tolerant</td>
<td>Permanent magnet, reduced rare-earth topologies, self-sensing</td>
<td>High frequency/voltage, high temperature, high thermal conductivity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Advanced Power Converters</th>
<th>Advanced Magnetic Materials</th>
<th>Monitoring and Diagnostics</th>
<th>Thermal Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide-band gap devices (SiC) Integrated Motor &amp; Drive</td>
<td>Lower cost PM, high strength &amp; dual phase soft magnetic materials</td>
<td>On-line turn fault diag. Fault tolerant operation</td>
<td>Air cooling, liquid cooling, phase-change cooling</td>
</tr>
</tbody>
</table>

- Smaller system footprint
- Lower system cost
- Higher efficiency
- Reliability / harsh environment
Magnetic Materials for Electrical Machines

Soft magnetic materials:
1. Mechanical Properties
   • Yield strength,
   • Ductility,
   • Creep and fatigue strength
2. Magnetic and Electrical Properties
   • Saturation magnetization
   • Coercivity
   • Electrical resistivity
3. Thermal conductivity

Permanent magnet materials:
1. Magnetic and Electrical Properties
   • Energy product
   • Temperature Stability
   • Electrical resistivity
2. Thermal conductivity
3. Sustainability
   • Rare earth content
   • Recyclability

Machine Power = Speed × Thermal Utilization × Magnetic Utilization × Volume

High strength rotor
Low core loss, high thermal conductivity material
High magnetic saturation/energy product material
Dual Phase Magnetic Material

- A new alloy and process for producing motor laminations with locally patterned non-magnetic regions
- This enables improved control of magnetic flux distribution in motor laminations
- Enables Synchronous Reluctance machines to have performance on par with IPM’s using NdFeB permanent magnets

Cross section of interface between magnetic and non-magnetic regions

Non-magnetic bridges and posts patterned into magnetic laminate

Masked laminate with un-masked bridges and posts ready for nitriding

Nitrided and cleaned laminate. Stripe domain pattern shows through non-magnetic bridges and posts
# Cross-Cutting Impact of Dual-Phase Material Machine Topology

|------------------|-----|-----------|-------------|--------------|
| Performance Benefits | • Higher power density Improved power factor  
                           • Pole shaping-> torque ripple reduction  
                           • Sensorless control | • Improved power density (ability to go to higher tip speeds)  
                           • Improved power factor->  
                               (a) Reduction in converter VA rating  
                               (b) Reduction in cable sizing/cost  
                           • Sensorless control | • Higher power density  
                           • Improved power factor  
                           • Wider constant power speed range (CPSR)  
                           • Pole shaping-> torque ripple reduction  
                           • Sensorless control | • Lower windage losses at high speeds  
                           • Torque ripple reduction |

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Composite Structures and Additive Manufacturing
GE is considered a leader in industrializing additive manufacturing

Integration of additive design, materials, and manufacturing for novel capabilities

Over 350k sq ft of development & manufacturing at 6 locations in the US (NY, PA, OH, SC, WI, AL)

Novel weight-saving components for aircraft engines

Original

Re-designed (conceptual)

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Thermal Management

\[ P_{th} = (1 - \eta) \times P_{el} \]

- \( P_{el} \): Electrical Power Density (KW/m\(^3\))
- \( P_{th} \): Thermal Load (KW/m\(^3\))
- \( \eta \): Efficiency
CNT-Cu Wire

CNT + Cu → CNT-Cu composite wire

~ 65% of CNT
~ 35% Cu
50% Cu weight
100x Cu current density

Enabler for high power density electric machine

C. Subramamian, et. al., Nature Comm., DOI:10.1038/ncomms3202
Advanced Insulation Technology

High temperature insulation

- Aviation > 220°C
- Locomotive > 180°C
- Industrial > 130°C
- Down hole drill > 250°C
- Geothermal > 350°C

High thermal conductivity (TC) insulation

- Nano dielectric fluid
- High TC ground wall insulation
- High TC varnish

Converter-duty HVHF insulation

- Nanocomposite
- DC Bus
- Variable Speed Peripheral Drives
- Supershield
- Barrier properties
- Confined ionic conduction

- High thermal stability
- High voltage, thin film insulation
- High dV/dt pulse resistant
- High thermal conductivity
- Chemical resistant

Enable

Reliable, high power density power generation & conversion

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# Higher Strength Silicon Steel Alternatives

<table>
<thead>
<tr>
<th></th>
<th>Composition (mass%)</th>
<th>$W_{10/400}$ (W/kg)</th>
<th>RT YS (ksi)</th>
<th>RT UTS (ksi)</th>
<th>Strengthening Mechanism</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu precipitate hardened</td>
<td>0.93<del>8.53 Cu &lt;2.5Al (1</del>8 Cr)</td>
<td>8~24</td>
<td></td>
<td>53~114</td>
<td>High density of ultrafine Cu precipitates (&lt;15nm)</td>
<td>US patent 2007/0062611 A1, Max-Planck 2010 MRS talk, JP 2004 339603</td>
</tr>
<tr>
<td>steel (Nippon Steel)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dislocation strengthened</td>
<td>35HXT590T 35HXT680T 35HXT780T (2Si, &lt;0.15Nb)</td>
<td>41 45 46</td>
<td>≥85</td>
<td>≥98 ≥113</td>
<td>Nb moderately suppress dislocation annihilation and recrystallization</td>
<td>Nippon Steel Property sheets, I. Tanaka, H. Yashiki, IEEE Trans. On Magnetics, 2010; 46; p290</td>
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</tr>
<tr>
<td>Conventional Fe-3Si M19</td>
<td>3Si</td>
<td>20</td>
<td>60</td>
<td>68</td>
<td>Si solid solution</td>
<td>Protolam data 0.35mm sheet</td>
</tr>
<tr>
<td>steel</td>
<td></td>
<td></td>
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</tbody>
</table>

- Nippon Steel technologies not commercially available in U.S.
- Other strengthening mechanisms (i.e. nanoferritically strengthened steels) at early level of technology readiness
Soft Magnetic Composites

Soft magnetic composites are pressed Fe powder parts suitable for some motor designs. Enables 3-D flux paths:
- Size and weight reduction
- Suitable for claw-pole and linear brushless DC motors
- High speed motors

Products include Somaloy from Höganäs:

<table>
<thead>
<tr>
<th>Somaloy Material</th>
<th>$\rho$ (µΩ-cm)</th>
<th>$B/10,000$ A/m (T)</th>
<th>$\mu_{\text{max}}$</th>
<th>$W_{1.0/100}$ (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130i</td>
<td>8000</td>
<td>1.4</td>
<td>290</td>
<td>12</td>
</tr>
<tr>
<td>700</td>
<td>400</td>
<td>1.56</td>
<td>540</td>
<td>10</td>
</tr>
<tr>
<td>700 HR</td>
<td>1000</td>
<td>1.53</td>
<td>440</td>
<td>10</td>
</tr>
</tbody>
</table>

IMFINE sintered lamellar SMC:
- $W_{1.0/60} < 2$ W/kg, $\mu > 2,000$, $B_{\text{max}}$ 1.7 T

P. Lemieux, JOM, Vol. 64, 2012, pp. 374-387
GE SC Machine Experience

Topologies
- Conductors: LTS, HTS, MgB$_2$
- Machine Type: Wound field synchronous, Homopolar Inductor Alternator
- Magnetics: Iron core, Airgap winding, Air core
- Mechanical Configuration: rotating field winding, stationary field winding

GE has the broadest experience in Superconducting machines