Key Performance Parameter Driven Technology Goals for Electric Machines and Power Systems

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Panel Focus Questions

- Feasibility for Large Aircraft
- Near Term Technology Readiness Levels Required
- Suggested Research Priorities
Electric Drive System Feasibility

It is feasible for drive systems to scale up to large aircraft with reasonable TRL advancements through several plausible paths.

Reviewing feasibility of components/subsystems:

- Electric Machines: Generator & Motor
- Power Conditioning: Converters & Controllers
- Power Distribution: Architecture & Devices

Electric drive system components are common to the possible hybrid electric, turboelectric, and electric propulsion aircraft. Electric drive systems are being used now for small aircraft.
Electric Drive Systems tied to Aircraft

System and component feasibility must be discussed in context of vehicle configuration

1 MW electric machines are identified as a reasonable feasibility study point
Electric Drive Key Performance Parameters

System studies inform the requirements for aircraft electric drive system

Range of target performance objectives. Each component must meet or exceed system target.

Minimum acceptable system performance based on analysis using by-pass ratio, boundary layer ingestion, and lift/drag benefit potential for small to large transport class aircraft

Jansen et al., Turboelectric Aircraft Drive Key Performance Parameters and Functional Requirements (AIAA 2015-3890)
Electric Machine State of the Art

Typical TRL 9 motors have performance outside target zone

Industrial Motors, 0.5-1MW, ~0.17 kW/kg (0.1 hp/lb), 96% efficiency

2008 Lexus, 110kW, 2.5kW/kg (1.5 hp/lb), 91% efficiency

UAV (Launchpoint) 100 kW 10.7 kW/kg (6.5hp/lb), 93% efficiency -- Can this performance be extended to higher power?

Note: Lines represent minimum breakeven performance for different benefit assumptions. Components must exceed minimum drive system performance

References in backup material
Electric Machine Development Potential

TRL 2-3 Motor design analysis for 1 MW size predicts performance feasibility

Synchronous reluctance motor optimized for SOA materials (open circle), with advanced materials (solid circle)

Interior Permanent Magnet motor optimized for SOA materials (open square), with advanced materials (solid square)

NRA Contract: TRL 4 Demo by 2018 for 1 MW machine with 13 kW/kg (8hp/lb), 96% efficiency (triangle)

1 MW analysis by Duffy, Electric Motors for Non-Cryogenic Hybrid Electric Propulsion (AIAA 2015-3891)
Motor Development Options  
**Power Level**—within class specific power scales with power  
**Topology**—electromagnetic design greatly affects component specific power  

Materials of Construction  
**Near Term Material Improvements** that can improve electric machine performance:  
- TRL 6-7: Soft Magnetic Alloys—nanocrystalline structure decreases core losses  
- TRL 3-4: Improved Insulation—increases coil packing factor and decreases temperature driven conduction losses  

**Farther Term Materials Improvement**  
- TRL 2-3: Improved Permanent Magnets  
- TRL 1-2: Higher electrical conductivity wire  

Motor analysis was used to study the performance sensitivity to new materials.
Why Superconducting Electric Machines

Superconducting (infinitely small direct conduction loss) leads to much higher specific power and greatly enhances feasibility for larger aircraft dist. propulsion

TRL 2-3: Projections for fully superconducting electric machines greatly exceed those for other motor types.

TRL 3-4: Wind turbine industry is considering superconducting power generation for volume reduction and improved component lives.

TRL 7: Limited data on specific power, reported values as high as 7 kW/kg*, with flat (not twisted) stator wire

TRL 9: Extensive use of superconducting magnets in medical imaging

*HTS fully superconducting, GE, 2007
Superconducting Electric Machine Potential
Motor/Generator Designs based on superconducting electric windings have much higher specific power potential

TRL 2-3: Detailed Concept Design of 12 MW Fully Superconducting Machine achieving 41 kW/kg (25 hp/lb) assuming practical subcomponent improvement in fine, twisted MgB$_2$ (Trudell, 2014)

Generator speed 8,000 rpm
Power 12 MW (16,086 hp)
Weight* 288 kg (635 lb)
(*SolidWorks design)

Efficiency 99.8 %
Specific Power 41 kW/kg
Overall length 0.83 m (32.5”)
Outer diameter 0.52 m (20.6”)

KPP Driven Technology Goals for Electric Machines and Power Systems
Superconducting Electric Machine Potential
Key Issues in continued superconducting machine development

Power Loss—minimal resistivity losses, but still have losses driven by alternating currents. Strands with filaments as low 10 μm and twist pitch as low as 10 mm per twist have been demonstrated.

Cryogenic thermal management is crucial. Vehicle design can play a roll via fuel selection. Component solution is cyro-cooler development targeting 8 kW/kg based on input power.

Need to continue development of reliable, cryogenic power components.
Power Conditioning Developments
Industry is advancing development at all component levels

Power Conditioning Electronic Components of interest include:
- Rectifier – convert AC to DC
- Inverter – convert DC to AC
- Motor Controller – control motor speed, for system efficiency integrate with

Power Components are improved by:
- Advance topology
- Sophisticated software control
- Sophisticated thermal management
- Advanced devices
Power Device Developments

Power Devices are the building blocks of Power Components

- Different classes of power devices are needed based on the power level needed.
- Advanced component topologies can allow lower power devices to be used in high power applications.
- Underlying material advancements are greatly reducing the weight and volume of power conversion devices.

Advanced materials are driving device capabilities:

- New wide band gap (SiC, GaN) semiconductors have higher current densities, frequency response, and temperature range.
- New soft magnetic and capacitor materials extend voltage and frequency capabilities → increases device efficiency and decreases weight and volume.
Power Distribution

Mass, packaging, and atmospheric pressure induced insulation breakdown represent unique challenges to aircraft distribution grid.

Small electric aircraft are establishing the SOA in aircraft distribution.

Detailed system analysis/layout to confirm feasibility of 2 MW grid ground test for 16 Ducted Electric Fans and 2 Turbo-generators.

Diagram:
- Rectifier 480VAC to 600VDC
- Facility 600Vdc Bus
- Turbine Inverters
- Generator Inverters
- Fan Load motor inverters
- 100kW Battery simulator
- Motor inverters

$\frac{1}{4}$ System Scale

Engine | 33% Span | 56% Span | 80% Span |
------- |---------:|---------:|---------:|
High   | 4        | 8        | 16       |
Ultra  | 2        | 8        | 16       |

Figure 3: Depiction of OWN Fan Propulsive Areas Distributed Along Various Wing Spans Highlighting the Wide Range of DP Coverage Evaluated Under this Effort.
Power Distribution

Highly distributed power can provide system redundancy but also challenges

- **TRL 8-9**: Marine and Wind Power Generation are providing some relevant grid, component and standards development
- **TRL 5-6**: 1MW level aircraft distribution has been demonstrated for non–propulsive loads on aircraft.
- **TRL 2-3**: High Voltage, advanced AC/DC distribution approaches attractive but requires new technology
- **TRL 1-2**: Highly conductive transmission lines (superconducting, carbon nanotube, etc.)
Challenges of High Voltage

• Paschen Discharge Curve
  Breakdown voltage across a gap is a function of pressure and gap distance
  Pressure at 40,000 ft greatly reduces breakdown voltage

• Electromagnetic Interference
  The aircraft will have multi MW power systems, instrumentation, and people within a very confined space. EMI considerations will be significant.

• Standards
  Many elements of a power system need to be coordinated in order to operate successfully as a system
  Definition of voltage, frequency, and interfaces helps facilitate the move to a new voltage.

Partial Discharge Voltage for a representative aircraft cable.
Near-Term Technology Readiness Needs
Going from FEASIBLE to DEMONSTRATED

TRL 4-5 component demonstration of specific power & efficiency as determined by KPPs

- Demonstrate electric machines, power electronics & power grid at 1 MW level

TRL 6 for subscale power/propulsion ground system verification leading to

- Higher fidelity vehicle configuration analysis and refined component requirements for high power and high voltage
- Representative aircraft demonstrations

TRL 2-3 for 300 PAX cryogenic turbo electric drive system

- Fully Superconducting machines & distribution represents a feasible solution for revolutionary, large aircraft
- Maintain steady, long-term investment
Research and Development Priorities

Electric Drives Systems must be informed by vehicle and system integration; large aircraft initially must focus on concentrated and less-distributed propulsion.

**Non-Superconducting Drive Technology**

- High Efficiency, Specific Density Electric Machines & Power Electronics - emphasis on advanced topologies and materials of construction
- Power protection devices and methodology for high voltage distribution
- Some investment in break-through technology such as revolutionary conductors, self-healing insulation

**Cryogenic Superconducting Drive Technology**

- Fully Superconducting Electric Machine Technology - Fine filament/twisted conductor wire and machine design
- Light, efficient cyro-cooler technology
- Cryogenic power protection devices and methodology for kV distribution
- Some investment in break-through technology such as fine filament/twisted superconductor for higher temperatures (other material systems)
Panel Focus Questions

Q: For various electric drive system technologies currently under development for aviation and other applications, what is the feasibility that they can be scaled up to meet the requirements of a large commercial transport in terms of key parameters such as power, energy, reliability, and safety?

A: The data presented here shows feasibility with reasonable TRL advancements. The electric drives can be utilized at power appropriate to several plausible transport class vehicles. (Such as concentrated propulsion w/ non-cryogenic motors vs. distributed vehicle configurations with cryogenic, superconducting machines). Energy savings must be addressed at system level. Architecture for distributed can distribute engine-out failures. Component reliability must be determined.

Q: What are the technology readiness levels of technologies needed to realize the next generation or two of electric drive system performance?

A: TRL 4 component and component material demo of power density & efficiency
TRL 6 for subscale power/propulsion ground system verification leading to
• Higher fidelity vehicle configuration analysis and refined component requirements
• Small aircraft flight demonstrations

TRL 2 for 450 PAX cryogenic turbo electric and 150 passenger battery power systems
Panel Focus Questions

Q: What would be the highest priority electric drive research and technology development projects?

• Electric Machines (8-20 kW/kg): Concurrent development and maturation of both non-superconducting and cryogenic superconducting machines will give maximum potential for credible transport class aircraft architectures.

  There are no current-industry drivers for performance level aircraft requires.

• Power Conditioning & Distribution: Extending 2-4 times SOA in Power Density at MW levels for the higher voltages and higher frequencies of interest.

• Electric Machines and Power Electronics: enabled by both clever architectures, advanced topologies and improvements in building block materials.

Also:

• Deep dive system studies and subsystem validation testing are needed concomitant with drive component development to ensure the correct technical focus.

• Performing electric drive system testing will inform higher fidelity vehicle configuration studies.

• Electric drive system characteristics require for flight control development.
Backup: Electric Drive Definitions

Electric Drive Technology Development Impacts Power Suite. “Hybrid Electric” occasionally used generically for Electrically Augmented Propulsion

**Electric** – A single power source from stored energy

**Turbo Electric** – A single power source from fuel burning turbine engine and transmitted electrically

**Hybrid Electric** – Power is generated from more than one source, such as through turbine shaft power and battery energy storage

**Parallel Hybrid Electric** – Power sources mix at the point of application

**Series Hybrid Electric** – Power from all sources are distributed electrically

**Series/Parallel Hybrid Electric** – Power sources mix at the point of application and can operate independently.
## Backup: SOA Drive System & Elec. Machines

<table>
<thead>
<tr>
<th></th>
<th>Size Range</th>
<th>Overall System</th>
<th>Motors / Generators</th>
<th>Power Electronics</th>
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</thead>
<tbody>
<tr>
<td><strong>Ships</strong></td>
<td>10-120MW</td>
<td></td>
<td>0.48 kW/kg</td>
<td>2.6kW/kg³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>99%</td>
<td></td>
</tr>
<tr>
<td><strong>Trains</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cars (1)</strong> Lexus 600h</td>
<td>50-300kW</td>
<td>1.15kW/kg</td>
<td>91%</td>
<td>11.5kW/kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.3kW/kg 2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>91%</td>
<td></td>
</tr>
<tr>
<td><strong>Wind Turbine (8)</strong></td>
<td>Up to 8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>96-99</td>
<td></td>
</tr>
<tr>
<td><strong>Industrial (5)</strong></td>
<td>1-500HP</td>
<td></td>
<td>- 0.17 kW/kg</td>
<td>~96%²</td>
</tr>
<tr>
<td></td>
<td>500-575kW</td>
<td></td>
<td>96%</td>
<td>~ 96%</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>UAV (6, 7)</strong></td>
<td>6 kW</td>
<td>1 kW/kg</td>
<td>93%</td>
<td>93%</td>
</tr>
<tr>
<td></td>
<td>100 kW</td>
<td></td>
<td>8.2 10.7 kW/kg</td>
<td></td>
</tr>
</tbody>
</table>

1) DOE, “Advanced Power Electronics and Electric Motors R&D”, May 2013 APE00A, page 5
2) DOE” PREMIUM EFFICIENCY MOTOR SELECTION AND APPLICATION GUIDE”, February 2014, page2-4
3) GE Power Conversion Brochure, “MV7000 Reliable, high performance medium voltage drive” 2013
5) Marathon Electric Motor catalog
7) [http://www.launchpnt.com/portfolio/transportation/electric-vehicle-propulsion/](http://www.launchpnt.com/portfolio/transportation/electric-vehicle-propulsion/)
Backup: Electric Propulsion Drive State of the Art

Range 7000 nautical miles
40MW - 4160V AC, turbines & diesel generator sources

117MW - turbines/diesel generator sources

3.2 MW diesel electric generator source

265 mile range
310kW electric motor
85kW-hr battery
>75,000 units
>1 billion fleet miles

1-2 people
2x30kW motors
Battery powered
1 hour flight time
Electrical Drive Definitions

**State of the Art** Electric Drive System **Sized** for Large Aircraft

Relative weight and efficiency associated with a crude analysis of turboelectric system for large aircraft—does not close with net benefit. Electric Machines are a primary system development driver.
### Backup: Electric Machine Development Potential

General motor design analysis for multiple topologies optimized for 1 MW size with start-of-art and advanced materials of construction

<table>
<thead>
<tr>
<th>Drive</th>
<th>Motor Type</th>
<th>Baseline Materials</th>
<th>Improved Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Power Density kW/kg (HP/lb)</td>
<td>Efficiency</td>
</tr>
<tr>
<td>Stand.</td>
<td>SPM</td>
<td>10.6 (6.4)</td>
<td>95.1%</td>
</tr>
<tr>
<td></td>
<td>IPM</td>
<td>10.4 (6.3)</td>
<td>96.6%</td>
</tr>
<tr>
<td></td>
<td>SRM</td>
<td>4.6 (2.8)</td>
<td>93.5%</td>
</tr>
<tr>
<td></td>
<td>IM</td>
<td>3.5 (2.1)</td>
<td>94.8%</td>
</tr>
<tr>
<td>Tip Drive</td>
<td>SPM</td>
<td>9.6 (5.8)</td>
<td>90.9%</td>
</tr>
<tr>
<td></td>
<td>IPM</td>
<td>9.8 (6.0)</td>
<td>96.5%</td>
</tr>
<tr>
<td></td>
<td>SRM</td>
<td>8.7 (5.3)</td>
<td>96.4%</td>
</tr>
</tbody>
</table>

Motors must meet or exceed system goals. Highlighted designs meet preliminary target of 5.8 kW/kg for electromagnetic subsystem weight.

Duffy, Electric Motors for Non-Cryogenic Hybrid Electric Propulsion (AIAA 2015-3891)
Electric Machine Development Potential

Motor analysis was used to study the performance sensitivity to new materials.

Developmental magnetic materials have been shown to increase efficiency in electric machines and power electronics.

- Machine (or electronic) efficiency goes up with switching frequency but magnetic losses go up with switching frequency.
- Amorphous and nano-crystalline magnetic materials have demonstrated lower power loss losses.

![Graph showing the performance sensitivity of different materials to frequency](image.png)

Ohodnicki, 2015
Motor analysis was used to study the performance sensitivity to new materials.

- Increasing wire insulation thermal conductivity allows faster heat removal for lower conduction losses.
- Increasing dielectric breakdown voltage allows thinner insulation for tighter coil coupling with volume & electromagnetic benefits.

**Can Increase Conductivity by**
- Polymer chemistry
- nano-composites

BN has the potential to impact both thermal conduction and electrical resistance.

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**Effect of Insulation Thermal Conductivity on Coil Temperature**

- $I^2R = 1.8 \text{ kW}$, $h_{\text{cool}} = 5000 \text{ W/m}^2\text{K}$

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**Decreasing coil temperature leads to small conduction losses**

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**KPP Driven Technology Goals for Electric Machines and Power Systems**
Coils With High Electrical Conductivity

Challenge:
- CNT fiber with electrical conductivity greater than Cu
- Fabrication of coils with CNT fiber

2013- carbon nanotube fiber with high specific electrical ampacity by Rice Univ.
Low AC loss MgB$_2$ conductor development

Successful strand design recipe:
- small $d_{\text{eff}}$
- small twist pitch
- resistive matrix
- non-magnetic sheaths
- higher $T_{\text{op}}$ (e.g. 20K); lower $B_{\text{op}}$ (e.g. 0.6T)

$J_c$ measured with 10 µm filaments at 0.29 mm. Work progressing to get obtain 10 µm filaments with larger wire diameters.

$J_c$ maintained with twist pitches as low as 10 mm.

Superconducting Lit

- Two CRs from 2nd RTAPS near publication
Aircraft Power/Voltage Through Time

• 1900 to 2015
  Power Increased from a few watts to 1.5MW

• 2015 to 2050 (AATT)
  • Power Increased from 1.5MW to 50MW
  • What will the voltage be?
APEEM Technical Targets

Traction Drive Systems (TDS)

<table>
<thead>
<tr>
<th>Year</th>
<th>Cost ($/kW)</th>
<th>Specific Power (kW/kg)</th>
<th>Power Density (kW/l)</th>
<th>Efficiency (%)</th>
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<tbody>
<tr>
<td>2010</td>
<td>19</td>
<td>1.06</td>
<td>2.6</td>
<td>&gt;90</td>
</tr>
<tr>
<td>2013</td>
<td>16</td>
<td>1.15</td>
<td>3.1</td>
<td>&gt;91</td>
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<tr>
<td>2015</td>
<td>12</td>
<td>1.2</td>
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<td>&gt;93</td>
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<tr>
<td>2020</td>
<td>8</td>
<td>1.4</td>
<td>4.0</td>
<td>&gt;94</td>
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Power Electronics (PE)

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<tr>
<th>($)</th>
<th>kW</th>
<th>kW/kg</th>
<th>kW/l</th>
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<tr>
<td>7.9</td>
<td>10.8</td>
<td>8.7</td>
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<td>6.5</td>
<td>11.5</td>
<td>10.2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>14.1</td>
<td>13.4</td>
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</table>

Electric Motors (EM)

<table>
<thead>
<tr>
<th>($)</th>
<th>kW</th>
<th>kW/kg</th>
<th>kW/l</th>
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<tbody>
<tr>
<td>11.1</td>
<td>1.2</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>9.5</td>
<td>1.3</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>4.7</td>
<td>1.6</td>
<td>5.7</td>
<td></td>
</tr>
</tbody>
</table>

Traction Drive System Requirements: 55 kW peak power for 18 sec; 30 kW continuous power; 15-year life

* 2010 traction drive system cost target met with GM integrated traction drive system; 2015 weight and size targets were also met
## Backup: Marathon Electric Industrial Motors

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Output 50Hz kW</th>
<th>Output 60Hz kW</th>
<th>Frame Size</th>
<th>Starting Torque Nm</th>
<th>Starting Current</th>
<th>Motor Efficiency %</th>
<th>Rotor Torque Nm</th>
<th>Power Factor</th>
<th>Efficiency Class</th>
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<tbody>
<tr>
<td>DM1 71K-2</td>
<td>0.37</td>
<td>0.43</td>
<td>71</td>
<td>2750</td>
<td>3300</td>
<td>0.96</td>
<td>91</td>
<td>0.91</td>
<td>1</td>
<td>IE1</td>
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<tr>
<td>DM1 71S-2</td>
<td>0.55</td>
<td>0.64</td>
<td>71</td>
<td>2775</td>
<td>3330</td>
<td>1.35</td>
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<td>1.22</td>
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<tr>
<td>DM1 80K-2</td>
<td>0.75</td>
<td>0.87</td>
<td>80</td>
<td>2870</td>
<td>3440</td>
<td>1.86</td>
<td>1.77</td>
<td>1.69</td>
<td>1.85</td>
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<tr>
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<td>1.27</td>
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<td>2875</td>
<td>3450</td>
<td>2.52</td>
<td>2.39</td>
<td>2.28</td>
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<td>IE1</td>
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<tr>
<td>DM1 90S-2</td>
<td>1.5</td>
<td>1.73</td>
<td>90S</td>
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<td>3410</td>
<td>3.53</td>
<td>3.35</td>
<td>3.19</td>
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<td>DM1 90L-2</td>
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<td>3430</td>
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<td>100L</td>
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<td>6.25</td>
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<td>DM1 112M-2</td>
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<td>4.6</td>
<td>112M</td>
<td>2860</td>
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<td>6.99</td>
<td>7.66</td>
<td>IE1</td>
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<td>6.33</td>
<td>132S</td>
<td>2890</td>
<td>3470</td>
<td>10.9</td>
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<td>9.9</td>
<td>10.8</td>
<td>IE1</td>
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<td>7.5</td>
<td>8.63</td>
<td>132S</td>
<td>2880</td>
<td>3430</td>
<td>14.4</td>
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<td>IE1</td>
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<tr>
<td>DM1 160Mx-2</td>
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<td>17.3</td>
<td>160M</td>
<td>2930</td>
<td>3520</td>
<td>27.8</td>
<td>26.4</td>
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<td>IE1</td>
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<td>3530</td>
<td>34.5</td>
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<td>IE1</td>
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<tr>
<td>DM1 180M-2</td>
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**Specifications:**
- **Frame Size:** 2-pole, 50/60Hz, IP55, Insulation F/B