Impact of Extreme Temperature Operation on BLDC Motors

For more than 50 years, Windings has provided engineered electromagnetic solutions for critical applications in Aerospace, Defense, Automotive and Oil & Gas industries. As a full-service provider, Windings is a leader in the design, test, manufacture and support of custom electric motors, generators and related components including rotors, stators, lamination stacks and insulation systems.
**Introduction**

Electric motor design depends on certain basic unchanging laws of electromagnetism and physics that have been well understood for over a hundred years. But as limits continue to be pushed in terms of expected performance and ambient operating conditions, some questions and challenges arise. This paper provides a brief overview of challenges in designing electric motors that will survive and perform in extreme temperature environments.

**Basic Principle of Electric Motor Operation: Electromagnetism**

The laws of physics tell us that current flowing through a coiled conductor (i.e. motor winding) will generate a magnetic field. It is the interaction between the induced electromagnetic field generated in the motor stator windings and the permanent magnetic field inherent in the rotor magnets that produces rotation in a Brushless DC (BLDC) electric motor.

In general, speed is proportional to voltage while torque output is proportional to winding current. It may be tempting, therefore, to select a smaller, less expensive under-sized motor assuming a higher winding current can boost torque output to meet the application requirements. Unfortunately, electrical resistance in the winding generates heat proportional to the increase in winding current. All conductive metals have a positive temperature coefficient of resistance, so motor winding resistance increases as temperature increases, compounding the effect. The current rating, and therefore ultimate performance and life, of any electric motor, is thus limited by the motor’s ability to dissipate operation-induced heat.

The motor’s ability to dissipate heat is strongly dependent on the ambient temperature of the environment in which the motor is operated. Since very few motors are operated at standard room temperature (20°C / 70°F), most motors are rated for continuous operation at an ambient operating temperature of 25°C / 77°F (for “Light Industrial” use) or 40°C / 105°F (for “Heavy Industrial” use). The National Electrical Manufacturers Association (NEMA) publishes temperature standards based on specific thermal insulation temperature tolerance classes:

<table>
<thead>
<tr>
<th>Temperature Tolerance Class</th>
<th>Maximum Operation Temperature Allowed °C</th>
<th>Allowable Temperature Rise at full load 1.0 service factor motor °C</th>
<th>Allowable Temperature Rise at 1.15 service factor motor °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>105</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>B</td>
<td>130</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>F</td>
<td>155</td>
<td>105</td>
<td>115</td>
</tr>
<tr>
<td>H</td>
<td>180</td>
<td>125</td>
<td>-</td>
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</tbody>
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\[ T(°F) = \left(\frac{T(°C)}{9/5}\right) + 32 \]

1) Allowable temperature rises are based upon a reference ambient temperature of 40°C. Operation temperature is reference temperature + allowable temperature rise + allowance for “hot spot” winding.

Example Temperature Tolerance Class F:

\[ 40°C + 105°C + 10°C = 155°C \]

Achieving NEMA certification on a new motor design requires the manufacturer to prove the motor can operate without failure at its nameplate rating for a minimum of 20,000 hours in an atmosphere at the rated ambient temperature.

One method commonly used to boost motor performance is to increase heat dissipation through external motor cooling. Most BLDC motors rely on passive (conductive) cooling to dissipate heat generated in the motor windings. With passive cooling, the motor’s continuous torque rating is typically 25 – 35% of peak torque. For higher duty cycles, an electric fan can be mounted axially to the motor housing, drawing away heat by convection which boosts the continuous torque rating to 60
– 80% of peak. Extreme duty cycles approaching 100% continuous duty cycle may require liquid cooling which uses a pump to circulate a medium, such as ethylene glycol, through the motor and a remotely mounted heat exchanger to dissipate excess heat. This method is uncommon, however, as it significantly increases system complexity and the number of potential failure points.

To guarantee the specified operational life, motor manufacturers provide specific operational ratings, such as power/torque, current/voltage, speed, ambient operating temperature, etc., typically published on a nameplate mounted to the motor’s exterior. In general, every 10°C increase in operating temperature beyond the manufacturer’s nameplate rating reduces the useful life of winding insulation by half. If operated according to the manufacturer’s specifications, BLDC motors should provide years, if not decades, of reliable service.

Common Temperature-Related Electric Motor Failure Modes

By far the biggest source of temperature-induced motor failure is winding insulation breakdown due to operational overload (driving a motor beyond its rated capability). While individual components may still perform within specifications, heat generated by excessive winding current will eventually degrade the winding insulation, resulting in a short circuit and permanent damage. While roughly one-third of electric motor failures are the result of overloading, most can be avoided by careful selection before the motor is put in service—that is, matching the motor’s nameplate ratings to its intended use.

A significant source of motor overload is operating conditions that change over time. A motor that runs cool when a machine is new might start to run hotter and hotter as operating conditions change. For instance, dirt and debris can settle in machine mechanisms creating additional system friction which must be overcome, and insufficient lubrication of moving components will produce the same result. In extremely dusty environments, such as sawmills and corrugated box manufacturing, dust can blanket a motor and act as an insulator, thus lowering the motor’s ability to dissipate heat. Under these conditions the operating conditions significantly increase performance required of the motor relative to the machine’s original design parameters.

Poor power quality can also have a negative effect on winding insulation. Changes to adjacent loads or fluctuations in the power grid caused by weather can lead to significant voltage transients. Because transients are intermittent, they are most often understood in hindsight after a motor fails. One way to reduce vulnerability to transients is to isolate and condition the power supplied to mission-critical motors. In a three-phase distribution system that serves a single-phase load, all three phases should have the same magnitude. An imbalance in impedance or load distribution can disrupt all three phases. This can result in excessive current flow in one or more of the phases, which increases operating temperature and can lead to breakdown of winding insulation—another path to a short circuit.

Elevated Ambient Temperature Considerations

As mentioned previously, a designer should specify a motor whose nameplate rating meets or exceeds the requirements of the application. Unfortunately, the available motor options diminish quickly when the ambient temperature exceeds 40°C / 105°F. All is not lost, however. In addition to exploring external cooling options mentioned previously, the designer can manipulate the NEMA temperature tolerance formula mentioned previously to a certain extent during the selection process to increase the available options. The temperature tolerance formula assumes the motor will be required to operate at full capacity at the rated ambient temperature. If the ambient temperature is increased to, say, 50°C / 122°F and the designer can select a motor that will provide the desired output with a correspondingly lower temperature rise, the overall allowable maximum temperature rating will not be exceeded and the motor should perform as intended:
Reference (Ambient) Temperature + Allowable Temperature Rise + Allowance for “Hot Spot” Winding = Operation Temperature

40°C Ambient Example:  
40°C + 105°C + 10°C = 155°C

50°C Ambient Example:  
50°C + 95°C + 10°C = 155°C

For the motor to provide the required output at a lower temperature rise, an over-sized motor must be selected such that less than full motor output (and therefore less than full motor current draw) will satisfy the application requirements, a process known as motor derating. To de-rate a motor, the designer must select a motor whose rated output exceeds the application requirements by the ratio of the desired temperature rise to rated temperature rise:

\[
\text{Desired Temperature Rise} / \text{Rated Temperature Rise} = \text{Motor Over-size Ratio}
\]

\[
95°C / 105°C = 1.105 = 10.5%
\]

Theoretically this process of motor derating will apply up to the point where Reference (Ambient) Temperature = Allowable Temperature Rise, the point at which heat from the motor can no longer be absorbed by the environment and the motor will is no longer capable of producing useful power.

Extreme ambient temperatures can negatively impact more than the motor winding insulation, however. Bearing lubrication becomes less viscus and can leak out of the bearing or boil off entirely, leaving the bearing unprotected against wear and friction. Plastics and polymers used in seals and gaskets can break down and fail. And delicate electronic components used in some feedback devices may succumb to failure at elevated temperatures. Therefore, it is highly recommended that designers consult with their motor manufacturer to confirm their calculations and that the manufacturer’s warranty will still apply.

One example of operation at extremely elevated ambient temperature is downhole tooling used to drill and maintain oil and gas wells. At depth, ambient temperatures can easily exceed 200°C. In this extreme case standard motor construction and the previously mentioned derating formulas no longer apply. The only means of cooling is water-based, oil-based, or gaseous drilling fluid. The importance of drilling mud as a cooling agent is critical to heat dissipation. Even so, all materials used in motor construction must be carefully considered for their ability to withstand the extreme temperature. Magnet wire with exotic thermal insulation, high temperature grease for bearing lubrication and resolvers or hall sensors for feedback are all examples of motor design considerations that are unique to high temperature operation environments.

Reduced Ambient Temperature Considerations

Whereas an elevated ambient temperature works against the motor’s ability to dissipate heat, a reduced ambient temperature works in its favor, allowing the motor to dissipate more than rated heat. The same formulas used to de-rate a motor in the previous example can be used to “up-rate” a motor (i.e. select a motor whose rated output is slightly less than what is required by the application).

As with elevated ambient temperatures, however, reduced ambient temperatures can have a negative impact on components other than the motor winding. Bearing lubrication becomes more viscus which increasing friction, and in extreme cases external heating elements may be required to allow cold starting the motor, and plastics and polymers become increasingly brittle and can crack. In the development of electric motors for use in cryogenic pumps, manufacturers tested drive shafts made of 17-4 stainless at temperatures down to −167°C, as an example. Therefore, as mentioned previously it
is highly recommended that designers consult with their motor manufacturer to review the application prior to finalizing their motor selection.

**Combined High/Low Ambient Temperature Considerations**

When the operational environment can swing from high to low ambient temperatures and back again, such as with aviation and aerospace applications, the designer is faced with a combination of the extreme temperature challenges discussed previously. Selecting materials appropriate for one extreme or the other can be difficult but finding materials that are able to withstand both can be nearly impossible. In addition, with cyclical temperature swings the designer must now take rate of thermal expansion and contraction of different materials into consideration.

As if a wide temperature swing isn’t enough of a design challenge, air becomes less dense with altitude which reduces the motor’s ability to dissipate heat. Although at least partially offset by colder ambient temperatures, the thinner air requires careful derating of motor output. Developing the proper motor ratings for such an environment can therefore be a real challenge for the designer.

**High/Low Ambient Temperature + Vacuum Considerations**

In outer space, temperatures can rapidly swing from +200°C in direct sun exposure to −200°C in shade, sometimes within a second or two. This presents two threats to magnet wire insulation: degradation from excessive heat and breakage from sudden brittleness. In addition, rapid thermal expansion and contraction can loosen fasteners, cause chaffing at mating surfaces and induce metal fatigue in high stress parts and materials of all kinds become brittle at extremely low temperatures. Any air or moisture trapped during manufacturing can become a potential explosion hazard and thermal shock can cause brittle parts to crack or even shatter completely. The stresses of launch vibration, pressure changes, and thermal cycling can deform stamped metal parts, so every component must be machined. All the while, limits on size and weight mean most components will be operating at their practical limits.

As if that weren’t challenging enough, Space is a vacuum. In the absence of a surrounding liquid or gas, an electric motor cannot dissipate excess heat through convection. Radiation can heat systems when they face the sun, so temperatures can increase, but the only means of cooling in a vacuum is conduction, which is limited to the differential between the motor and its housing. Also, a phenomenon unique to vacuum environments, called outgassing, causes some materials to vaporize suddenly. It affects petroleum-based lubricants more quickly and silicone lubricants more slowly; either way it negates their usefulness and turns them into particulates. Adhesives and varnishes are also vulnerable to this effect. The resulting gas or vapor may be absorbed or dissolved or frozen, but not controlled. The only way to keep this contamination from condensing on critical components is to prevent its formation in the first place. The entire manufacturing process, from the laminations of the rotor and stator to the insulating material used on the windings, must account for outgassing. That means selecting materials with proven resistance to outgassing. The NASA Outgassing Database (<http://outgassing.nasa.gov/cgi/uncgi/search/search_html.sh>) classifies materials by their potential for outgassing in vacuum environments. The current testing standard, titled Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment, is ASTM Test Method E595-93 (<https://www.astm.org/Standards/E595.htm>).

Considering the cost and risk involved in getting an electric motor to space, some design engineers recommend building redundant systems. To keep weight at a minimum, space agencies have not embraced mechanically redundant motors, but have accepted some designs that feature two electrical circuits in a single motor housing. Redundant electrical circuits require multiple windings within the same stator slots. Parallel (bifilar) windings have the
same risks of overheating and insulation failure but help protect against broken wires or solder joints. Of course, this means each stator slot will contain only half as many coil windings that can be used at once. To achieve torque comparable to that of a stator with one set of windings, this design will require up to four times as much input current. That changes the relationship of input to resistance and multiplies the likelihood of overheating.

**Conclusion**

These two environments—extreme high temperature and extreme low temperature—are frontiers of exploration that inspire and require innovation. The challenges of material selection, component design, and quality construction test our knowledge, imagination, and engineering capabilities. At Windings, we help our clients develop solutions to seemingly impossible design challenges for critical applications.

For further information, please contact us!

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