



Design Considerations for BLDC Motors in High Pressure/High Temperature Applications

From Housings and Stators to Magnet Wire

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

Offering comparable reliability but significantly higher efficiency and power density, permanent magnet brushless DC (BLDC) synchronous motors are increasingly replacing conventional asynchronous (induction) machines in general industrial applications. Studies show that BLDC motor efficiency ranges from 91 - 93% for highspeed applications and 85 - 89% for high torque applications, consuming an average of 23% less energy than an induction motor of equivalent power. Furthermore, BLDC motors have the capability of delivering full torque over the entire operating range including startup.

With the development of advanced construction materials such as high temperature magnets, magnet wire and insulation systems, designers are now applying BLDC motors in increasingly hostile environments.

Design Factors

The following is a list of common design factors that must be taken into consideration when designing BLDC motors for high temperature, high pressure environments:

- Ambient Environment
 - Temperature min/max
 - Pressure min/max
 - Surrounding fluid
 - Heat transfer (motor sizing)
 - pH (corrosion)
- Required Power Output
 - Torque at speed
 - No-Load
 - Stall
- Available Input Power
 - Voltage
 - Current
- Winding Construction
 - Slot fill
 - Current load on windings

- Magnet Material Selection
 - Temperature survival
 - Magnetic strength
- Magnet Wire and Insulation System Selection
 - Temperature
 - Pressure
- Bearing Selection
 - Mechanical load
 - Max speed
 - Duty cycle
 - Lubrication

Downhole Tooling Applications

For example, typical application requirements for downhole tooling in the oil and gas industry can be summarized as follows:

- Ambient Temperature: 150 to 220°C
- Ambient Pressure: 10k-32k PSI
- Open or Pressurized Construction
 - Open: submerged in oil, holes in housing to equalize pressure
 - Pressurized: sealed housing to keep motor interior dry
- Voltage: 24 - 600 VDC
 - Lithium ion battery power source
- Vibration: 25 G
- Shock:
 - 100 G axial
 - 50 G radial
- Diameter Constraint: 2" - 4"
- External Housing Material: stainless steel
- Feedback: Hall sensor, resolver or sensorless
- Magnet Material: SmCo
- Life: 2,000 hours of operation between service intervals

High Pressure High Temperature (HPHT) Motors require specific design to survive the harsh environments seen downhole. Such motors demand

the ability to operate at ambient conditions of at least 220° C, 32Kpsi, with 4% water content, to perform exploration directional drilling, such as:

- Drilling
 - Rotary Steerable Systems (RSS)
 - Logging While Drilling (LWD)
 - Measurement While Drilling (MWD)
- Wireline
 - Formation Evaluation
 - Wireline Tractor Propulsion
 - Mechanical Pipe Cutter

Reliability and durability requirements for high temperature and pressure applications are becoming more critical. In the Oil & Gas example used above, the cost of down time in downhole drilling applications can vary from \$250K to \$1M per day depending of type of drilling and environment (soil conditions, depth of drilling on-shore/off-shore, etc.). Because of the potentially high cost of failure, careful attention must be paid to material selection when designing BLDC motors intended for operation in high ambient temperature and pressure.

Typical Design Construction

The cutaway shown in the figure 1 below represents the typical construction of a BLDC motor for high temperature / high pressure downhole tooling applications:

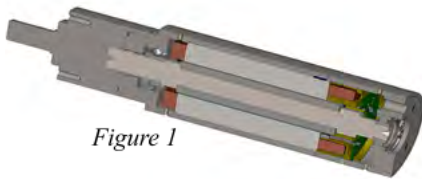


Figure 1

Common Motor Failure Modes

According to data gathered from major Oil Field Service companies, a common motor failure in downhole tooling applications is the stator windings. Operating conditions that can cause motor failure:

- A breach of the hull introducing harmful external elements

– Also known as flood event

- Being run at a higher voltage for too long causing a short
- An excessive amount of external pressure
- Corrosive effects of chemicals in the drilling mud

Below are the most common failure modes seen in high temperature and pressure applications:

- Magnet Wire Insulation breakdown due to excessive temperature
- Magnet Wire failure due to the effects of hydrolysis
- Hall sensor failure due to the excessive temperature and pressure
- Bearing failure due to shock and vibration
- Bearing failure due to insufficient lubrication
- Bearing failure due to contamination (open bearing construction)

Housing / End Cap

Housings should be cylindrical in shape, typically made of stainless steel machined from bar stock. Bar stock size should be selected from the nearest size slightly larger than the OD (outside diameter) of the housing to minimize machining. Standard motor dimensioning and tolerancing should suffice. After machining is complete, and prior to assembly, the housing normally requires passivation to inhibit any corrosion that may occur over time as a result of the manufacturing processes.

Typical Example:

- Motor Housing Material: Stainless steel, 416 Condition T
- Surface Treatment: Passivate per ASM 2700 method 1 Type 2

Bearings

Stainless steel bearings conforming to ABEC Class 3 or 5 (pending on the size of the bearing) should be selected. The ABEC class ensures proper fitment of the bearing in the motor. For open bearings (no shields) initial lubrication is recommended to prevent bearing damage during manufacturing testing.

Shielded bearings must be lubricated with high temperature oil. Proper lubrication of the bearings is required in order to achieve proper function over the life of the motor. Material and lubrication selection are critical for bearings applied in high pressure and temperature applications.

Typical Example:

- Bearing Housing Material: 440C
- Bearing Type:
 - Submerged: Open
 - Dry: Double shielded
- ABEC Class: 3 or 5 (depending on size)
- Radial Clearance: .0002-.0005"
- Lubrication:
 - Submerged in oil: Windsor
 - Dry: Braycote 601, 25% fill

Stator Core and Assembly

A stator core is comprised of stamped steel laminations that are bonded together using high temperature epoxy. The stator assembly must be insulated to prevent dielectric breakdown using an insulation system that is carefully selected to withstand the anticipated ambient temperature. The insulation system includes slot liners used to line the slots in the stator core, lacing cords used to hold the end turns of the wound stator together, impregnation varnish used to permanently bond the windings in place, lead wires that need to be able to carry the current. Secondary components such as flux, solder and shrink tubing must also be selected to survive anticipated operating temperatures.

Typical Example:

- Insulation: Nomex, Kapton insulation materials
- Lead wire: SAE-AS22759/11, Silver coated, Multistrand, Teflon insulation
- Solder: Sn5/Pb95
- Flux: RMA 285
- Lacing Cord: Aramid (Nomex) with Loctite
- Varnish: Dolph's CC-1105
- Kapton Tape
- Teflon Shrink Tubing

Stator Laminations

Laminations are used to hold the windings in place and carry the flux in a complete magnetic circuit. Slot numbers, shape and size are determined by the application, desired motor characteristics and flux density. Lamination geometry, thickness of the material, annealing requirements and thickness of the material have to be taken in consideration. Lamination material is normally selected based on required flux density.

Typical Example:

- M19 for standard applications
- Hipercor Carpenter 50 for high performance applications

Magnet Wire

Survival in such environments with potentially 4% water content requires a magnet wire's ability to resist hydrolysis to maintain integrity. Magnet wire that is resistant to failure due to the effects of hydrolysis at HPHT should be selected. W. L. Gore & Associates new GORE Magnet Wire is coated in Gore's ePTFE which makes it highly durable in extreme environments, and resistant to harmful and corrosive chemicals seen in those environments. Tests, see figures 2 & 3, illustrate that GORE Magnet Wire, provided superlative electrical performance in temperatures ranging from -55° to +260° C.

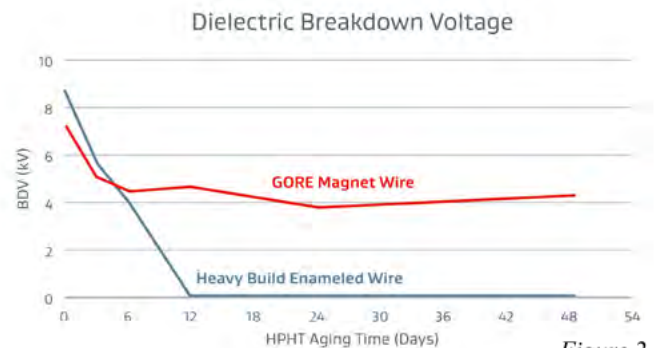


Figure 2

Property	Value
Operating Voltage Range (V) AC	300-600
Spark Test Voltage (V)	1500
Dielectric Breakdown Voltage (kV) tested per ANSI/NEMA 1000a	4.4
Wire Insulation	Engineered Fluoropolymer
Conductor	Bare Copper
Operating Temperature Rang (C°)	-55 to +260
RoHS	Compliant

Figure 3

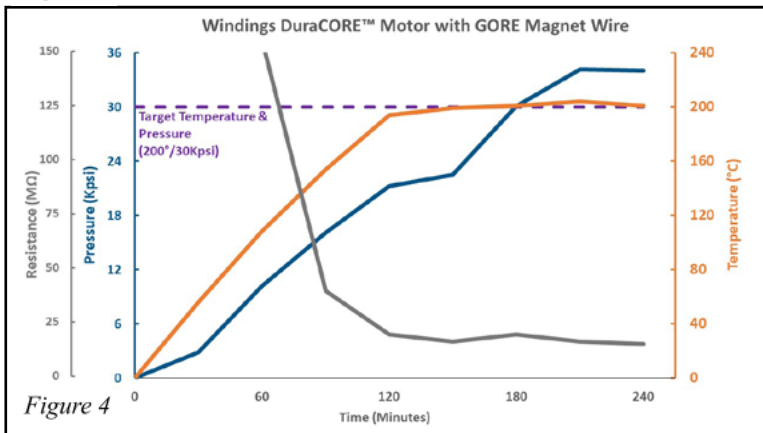


Figure 4

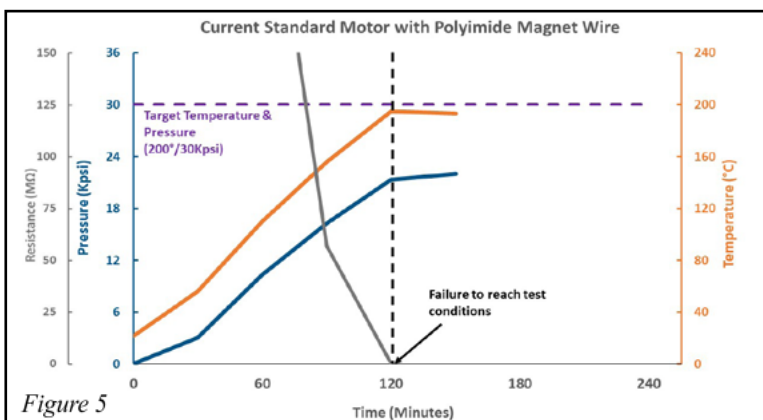


Figure 5

Additional tests, see figures 4&5, illustrate how GORE Magnet Wire performs with up to 4% water content when compared to MW16C polyimide magnet wire.

GORE Magnet Wire was specifically designed to improve reliable operations in the harsh environments such as those seen in the oil & gas industry. The

utilization of this wire in a motor increases durability, reliability, and decreases the risk of a failure from overheating, overpressure, flood events, and more. GORE Magnet Wire uses a unique, engineered fluoropolymer insulation, representing a new innovation in these environments

Typical Example:

- GORE Magnet Wire
- HML
- Hitachi

Shaft

Motor shafts are typically made of a stainless steel to minimize eddy current losses. This material is easy to machine and provides good mechanical and magnetic properties at a large range of temperatures. As with the stainless steel used in the motor housing, the shaft should be passivated prior to assembling the rotor to prevent corrosion.

Shaft dimensions and tolerances must be selected based on thermal expansion and contraction, and mechanical loads.

Typical Example:

- Material: Stainless steel, 416 condition T
- Surface Treatment: Passivate per ASM 2700 method 1 Type 2
- Bearing Shoulder Tolerance: +/- .002"
- Bearing Fit: .0001" - .0005" slip fit

Magnets

There are many types of magnets, but in high temperature applications SmCo type of magnets are used due to their tolerance for high temperatures and resistance to corrosion.

Typical Example:

- Sm2Co17, type available from Shin-Iitsu, EEC.

Rotor/Stator Sleeves

Thin sleeves are often added to the motor rotor to provide a holding force for magnet retention. In some



dry applications sleeves are added to the stator to isolate it and the windings from cooling media, as well as to remove pressure from the winding components. Stainless steel is typically used for sleeving, because of its high strength and non-magnetic properties.

Typical Example:

- Material: 300 series Stainless Steel (316 preferred)
- ID Clearance to Machined Magnets: .001-.003”
- Wall Thickness: 1/16” (before grinding)
- OD tolerance: +/- .010”
- Rotor Balancing (if needed):

Rotor OD (In.)	<10 kRPM	10<kRPM<20	20<kRPM<50	>50 kRPM
<1	G-16	G-2.5	G-2.5	G-1
1<OD<2.5	G-6.3	G-2.5	--	--

Feedback Devices

Hall sensors and resolvers are the most commonly used feedback devices in high temperature and pressure applications. Readily available industrial hall sensors are typically rated for use in +155C ambient. Higher ambient temperatures require

additional temperature testing to ensure long-term survival of the sensors. Although not as common, high temperature ceramic hall sensors are available for use in extremely high ambient temperature conditions.

Summary

The environmental factors in high temperature and high pressure applications require a motor that has the ability to operate beyond typical motor conditions. When faced with these elements, operators are forced to push industry standard products to the absolute limit of their capabilities risking the possibility of a failure.

Each component of a BLDC motor used in the HPHT conditions stated above, must be precisely engineered to safeguard the chances of a failure from overheating, overpressure, flood events, and more. Such motors are designed for the durability, and reliability necessary to properly function in HPHT environments such as downhole tooling by minimizing the risks of a catastrophic failure, a failure that could cost the operators exorbitant amounts of money in unproductive rig time.

For further information, please contact us!

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