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Final Report

Advanced Ultra-High Speed Motor for Drilling

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ABSTRACT

Three (3) designs have been made for two sizes, 6.91 cm (2.72 inch) and 4.29 cm (1.69 inch) outer diameters, of a patented inverted configured Permanent Magnet Synchronous Machines (PMSM) electric motor specifically for drilling at ultra-high rotational speeds (10,000 rpm) and that can utilize advanced drilling methods. Benefits of these motors are stackable power sections, full control (speed and direction) of downhole motors, flow hydraulics independent of motor operation, application of advanced drilling methods (water jetting and abrasive slurry jetting), and the ability of signal/power electric wires through motor(s).

Key features of the final designed motors are: fixed non-rotating shaft with stator coils attached; rotating housing with permanent magnet (PM) rotor attached; bit attached to rotating housing; internal channel(s) in a non-rotating shaft; electric components that are hydrostatically isolated from high internal pressure circulating fluids ("muds") by static metal to metal seals; liquid filled motor with smoothed features for minimized turbulence in the motor during operation; and new inverted coated metal-metal hydrodynamic bearings and seals.

PMSM, Induction and Switched Reluctance Machines (SRM), all pulse modulated, were considered, but PMSM were determined to provide the highest power density for the shortest motors. Both radial and axial electric PMSM driven motors were designed with axial designs deemed more rugged for ultra-high speed, drilling applications.

The 6.91 cm (2.72 inch) OD axial inverted motor can generate 4.18KW (5.61 Hp) power at 10,000 rpm with a 4 Nm (2.95 ft-lbs) of torque for every 30.48 cm (12 inches) of power section. The 6.91 cm (2.72 inch) OD radial inverted motor can generate 5.03 KW (6.74 Hp) with 4.8 Nm (3.54 ft-lb) torque at 10,000 rpm for every 30.48 cm (12 inches) of power section. The 4.29 cm (1.69 inch) OD radial inverted motor can generate 2.56 KW (3.43 Hp) power with 2.44 Nm (1.8 ft-lb) torque at full speed 10,000 rpm for every 30.48 cm (12 inches) of power section.

Operating conditions are 300 voltage AC at the motor leads. Power voltage losses in the cables/wirelines to the motor(s) are expected to be about 10% for 5000 feet carrying 2 amperes. Higher voltages and better insulators can lower these losses and carry more amperes.

Cutting elements for such high tip velocities are currently not available, consequently these motors will not be built at this time. However, 7.62 cm (3 inch) OD, low speed, PMSM radial electric motors based on this project design are being built under a 2006 Oklahoma Center for the Advancement of Science and Technology "proof of concept" grant.

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EXECUTIVE SUMMARY-

Three (3) designs have been made for two sizes, 6.91 cm (2.72 inch) and 4.29 cm (1.69 inch) outer diameters, of a patented inverted configured permanent magnet synchronous machines (PMSM) electric motor specifically for drilling at ultra-high rotational speeds (10,000 rpm) and that can utilize advanced drilling methods. Benefits of these motors are stackable power sections, full control (speed and direction) of downhole motors, flow hydraulics independent of motor operation, application of advanced drilling methods (water jetting, abrasive slurry jetting and more) and the availability of signal/power electric wires through motor(s) for instruments at the bit and additional motors.

Key features of the final designed motors are: fixed non-rotating shaft with stator coils attached; rotating housing with permanent magnet rotor attached; bit attached to rotating housing; internal channel(s) in non-rotating shaft; electric components that are hydrostatically isolated from high internal pressure circulating fluids ("muds") by static metal to metal seals; high power density axial configured, permanent magnet pulsed modulated drive; liquid filled motor with smoothed features for minimizing turbulence in motor during operation; stator and rotor axial spacing fixed through thrust/journal bearing; inner components spring loaded with a sliding seal; new inverted coated metal-metal hydrodynamic bearings and combined seals.

PMSM, Induction and Switched Reluctance Machines (SRM) were considered, but PMSM were determined to provide the highest power density for the shortest motors. Both radial and axial electric PMSM driven motors were designed with axial designs deemed more rugged for such ultra-high speeds and drilling applications. The designed inverted PMSM motors have a generally flat and favorable torque profile versus rotational speed.

The 6.91 cm (2.72 inch) OD axial inverted motor can generate 4.18 KW (5.61 Hp) power at 10,000 rpm with a 4 Nm (2.95 ft-lbs) of torque for every 30.48 cm (12 inches) of power section. The 6.91 cm (2.72 inch) OD radial inverted motor can generate 5.03 KW (6.74 Hp) with 4.8 Nm (3.54 ft-lb) torque at 10,000 rpm for every 30.48 cm (12 inches) of power section. The 4.29 cm (1.69 inch) OD radial inverted motor can generate 2.56 KW (3.43 Hp) power with 2.44 Nm (1.8 ft-lb) torque at full speed 10,000 rpm for every 30.48 cm (12 inches) of power section.

Operating conditions are 300 voltage AC at the motor leads. Power voltage losses in the cables/wirelines to the motor(s) is expected to be about 10% for 5000 feet of 10AWG wire carrying 2 amperes. Higher voltages and better insulators can lower these losses, carry higher amperes for more motors and instruments.

Multiple bearings and seals were investigated, but most were discarded due to such high speeds and the inverted configuration. No type rolling bearing can be used at these speeds. Magnetic type bearings were discarded due to high variability of the drilling loads and downhole power requirements. Hydrodynamic types were preferred due to ruggedness in the drilling operation, but none were available specifically for inverted configurations. Concerns still exist about variable film thickness. Metal to metal bearings were thought needed to maintain the 2 mm (0.0787 inch) airgap between rotating elements, but wear concerns limited airgap maintenance. Thus, a combination metal to metal thrust/journal bearing was designed for inverted configurations that can be coated for longer life. It also contains internal channels that allow for mild hydrodynamic lubrication film generated by the rotating action of the outer bearing/motor, which also aids in extended life.

Power and control board designs were produced for these motors and can be put in the shape required for discs inside the motor. The noted detractions of this electric system are the limited power available (and thus number of motor sections) from the surface through the power wires and ‘cogging’ (variations of speed and power output of the motor) at low speeds.

Based on this design work, 7.64 cm (3 inch) OD, low speed versions of the PMSM electric motor in an inverted radial configuration are being built under a 2006 Oklahoma Center for the Advancement of Science and Technology (OCAST) “proof of concept” grant.

INTRODUCTION-

Very hard and abrasive formations are found in many areas of the world, such as parts of the United States, the Middle East, onshore Germany, the North Sea, west Venezuela and Italy. These formations have compressive strengths exceeding 25,000 psi and pose challenging situations for drilling deep wells or slim holes since the bottom hole assembly cannot be operated at the optimum rate. Extremely hard formations are also problematic to deal with in lost circulation situations for the same reason.

Existing downhole motors that are used for drilling today include turbine, progressing cavity and roller vane types. The dominant dominate motor used in drilling in the industry is a positive displacement, Moineau type progressing cavity style “mud motor”. All of these conventional rotary motors must use a fluid (water, oil, mud, air, nitrogen) to drive or rotate an internal rotor that turns an attached drill bit. These systems are mostly designed to deliver high torque at relatively low rotational velocity.

Currently, very hard and abrasive formations are typically drilled with impregnated bits and high-speed turbine motors. These geared motors are capable of achieving several thousand revolutions per minute (rpm), but have specific performance limitations below and above the optimum rotational speed. Optimum rotational speed for a turbine motor is presently 1000-2000 rpm depending on the application.

Due to hydrodynamics, the power output of a turbine motor is not linear with flowrate (Reich, et. al., 2000) and pressure. This means that a relatively small reduction in mud flow rate can significantly lower the power output of the motor and, hence, the rotation and penetration rate of the bit. In that study, they noted that a 20% decrease in flow rate had a 50% reduction in the turbine motor power output.

Hydrostatic, positive displacement “mud motors” have also been used for regular high speed drilling applications. These motors have different performance characteristics compared to turbine motors. With a PDM, the torque and power output is nearly directly proportional to the differential pressure on/off bottom and the PDM can be directly controlled from the rig floor using standpipe pressure (SPP). Nevertheless, PDMs also suffer power loss and, hence, reduced penetration rate with a reduction in mud flowrate. The earlier stated Reich, et al., study found that the same 20% reduction in mud flow rate decreased PDM motor output by 20%. PDMs are also affected by chemicals, high pressure and temperature since they employ elastomers.

All electric drilling systems have been investigated and all electric coiled tubing systems are under development (Turner, et al., 1999). These systems employ power cables inside conventional or composite coil to transmit power to the bit. A fully electrical connected tool joint for tubing and drill pipe has been patented (Hughes 1999) and is under development. Thus electric drilling systems with coiled or jointed tubing will be available for service. Electrical drilling systems have had the advantage as the drive power is independent of fluid flow and offers a high tolerance to energized (high-pressure) fluids compared to PDMs and turbines. Test data with electrically driven downhole motor systems indicate that if speed is held constant, torque may vary greatly as a function of the demand on the motor.

All of the current conventional and electric motor systems suffer limitations that affect their performance at high rotational speed. Only low rotational speeds (less than 1000 rpm) electrical motors for drilling have been tested to date. Both turbines and PDMs are flow rate limited and turbines may not provide optimum performance at high rotational speeds. Motors in common use today have been designed for typical directional tools, such as those used in 21.59 cm (8.5 inch) down to 16.51 cm (6.5 inch) holes. Most motors for directional drilling have not been designed for micro-hole diameters (< 9.52 cm (3.75 inch)).

In a growing number of applications, slim holes or micro-holes can suffice for inflow requirements and wells can be completed with a smaller well diameter. There is growing interest in micro-holes as a means of drilling wells more quickly, deeper, or with less capital investment. Development of ultra high-speed motors is required to enable drilling in deeper, harsh environments, particularly for smaller diameter wellbores and with new ultra high bits. Full development will allow utilization of smaller hybrid drilling rigs as shown below in Figure 1.

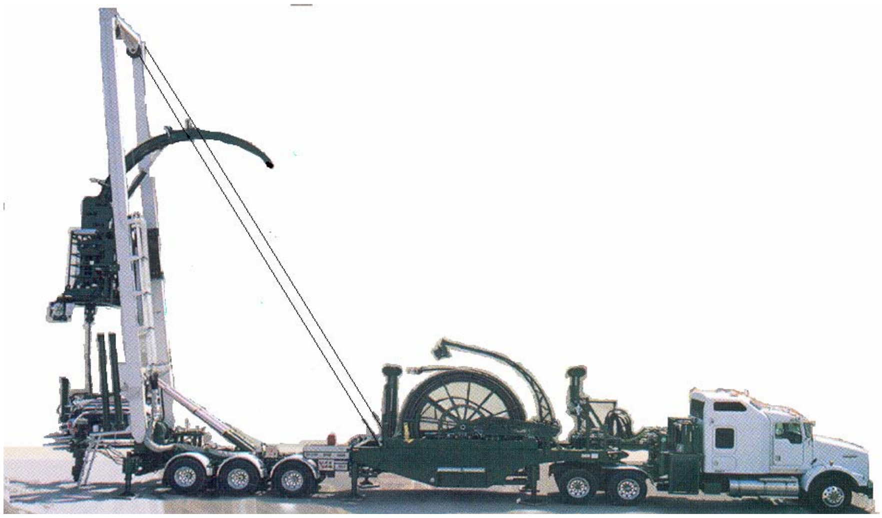

Figure 1. Future Hybrid Coil Tubing Drilling Rig

To fill this need, it is proposed to develop high-speed drilling motors capable of drilling holes of 9.52 cm (3.75 inch) or less, at rotational speeds in excess of 10,000 rpm. The motor is also required to be compatible with drag bits of similar size. This project proposes a feasibility study of an innovative motor configuration, developed by the PIs, combined with the efficiency of electric motors that is aimed at achieving these high rotational speeds while providing sufficient mud flow for bit cooling and improved drilling control.

A survey of existing ultra high-speed bits was conducted to ascertain state of the art in these bits, their current performance characteristics and the future characteristics desired. These design characteristics were used to define the motor loading requirements for the ultra high-speed inverted motor. Two different sizes of inverted configured, DC electric motors were designed based on these bit characteristics, operating depths and conditions. These designs are sufficient to go to motor manufacturers for initial prototype construction.

Current motor designs for ultra-high rotational speed drilling applications, as required in this solicitation, primarily include turbines and Moineau/ Progressing Cavity motors or “mud motors”. Other hydraulic motors include rotary vane motors and gerotors, but these require very clean fluids - not muds - and are not known for even ‘regular’ high speed drilling applications. The specific abilities and limitations of these motors are:

1. Flow and motor power are linked
2. Flow rate and motor rpm are linked
3. Gearing for PDMs to achieve these ultra high rpms
4. Sensitivity of PDMs to chemicals, pressure and temperature
5. Turbine non-linear performance curve in lower flow rate ranges
6. Over speeding of Turbines in no-load conditions
7. MWD and LWD above/behind the motor, delayed information
8. Inability of Turbines or PDMs to handle high pressure due to increased bearing loads
9. Reactive torque from the bit drilling action to the drillstring
10. Long motor sections to obtain the required power performance

Electric motors were not discussed above, but they have a strong history in oilfield production areas with Electrical Submersible Pumps (ESPs) and in drilling. In production applications, a multi-staged centrifugal pump is attached to a downhole AC electric motor via a seal section for pressure and temperature changes. The power to the conventional AC motor is furnished by a continuous cable from the surface and attached to the outside of the production pipe/tubing. This configuration has a long and reliable history for production applications.

Electric motors in drilling also have a long and strong history, but not in the U.S. The U.S.S.R. has performed research, testing and field applications on electric motor drilling for many decades, although little published work has been found by the authors. In the U.S., General Electric worked on downhole electric motors for drilling in a FERC/DOE funded project, cumulating in a final report in 1977. Several problems were noted, most notably the lack of a high capacity, reliable electrical link to the bottomhole assembly via the jointed drill pipe. No significant problems were reported on the conventional style electric motor, although it still has the conventional limitations. Current means to deliver reliable downhole power are available and others are being developed. In particular, FiberSpar's "Smart" Composite Coiled Tubing and the Hughes tooljoint are identified.

Currently, the European Drilling Engineers Association (DEA(E)) has a joint industry project headed by XL Technology that is now in Phase II-field testing of a DC brushless motor of normal range speed. They have identified the benefits of an electric motor as:

- drive power independent of fluid flow
- tolerance for energized fluid
- Safe operation in hazardous conditions
- high temperature applications
- scalable power
- real time information
- low vibration
- reversible direction

Their conventionally-figured DC electric motor, combined with a fully electrified Bottom Hole Assembly (BHA) and used with wired (power and data) coiled tubing has not been fully field tested to the author's knowledge.

Maurer Technology, through a DOE program, has developed a turbine motor and special bearing pack for use with high-pressure. While this motor will allow both high pressure jetting and mechanical action (horsepower to the bit), all fluids must go through the motor section. High wear is expected with regular drilling mud. Wired MWD/LWD at the bit (below the motor) is not possible with this motor design.

Except for the progressive cavity motor, also called "mud" motor, these motors cannot handle abrasive materials in the fluid stream due to wear on critical motor components or plugging. These "mud" motors can handle some solids in the pumped mud and some gas; however, the stator elastomer is sensitive to chemicals, temperature and pressure. Abrasive jetting is not done through these expensive motors due to extremely shortened life concerns. Thus, conventional designed hydraulic/pneumatic powered motors of various types (turbine or positive displacement) cannot handle high pressure or solids in the pumped fluids.

Thus an ideal ultra high speed motor would combine the benefits of an electric motor and have:

1. A natural ability for ultra high speeds without gearing
2. Low vibration
3. A nearly flat performance curve over the desired range of speeds and torques; power and rpm not linked to flow rate
4. Ability to handle a large range of mud and fluid types, even acids, solvents, abrasives, and energized/underbalanced or even 100% gas
5. Ability to handle internal high pressures without rotating seal problems
6. Ability to directly wire MWD and LWD sensors from near the bit to the surface for ultra high speed communication rates in ‘real-time’ not ‘near time’
7. Multiple motors in series or parallel for step or reaming drilling
8. Ability to minimize reactive torque from the bit onto the drillstring by counter rotation of multiple motors in series, especially for smaller drillstrings
9. Ability to have bend subs between multiple motors
10. Short compact design for short radii curves
11. Flexible performance for many drilling challenges

Current motors do not and cannot have all these characteristics and benefits.

Inverted Motor Design

The standard configuration of all motors used for drilling today is that the motor housing is attached to the drill string (See Figure 2). The power section within the housing turns an internal shaft which extends out the motor section and housing and is attached to a tool or bit. A few motors in this conventional configuration have a hollow shaft that allows some fluid flow to bypass the power section. These motors cannot handle high pressures (1,000psi+) across the motor or in the motor (i.e., a high delta-P across a bit nozzle) due to rotating seals and bearing limitations due to generated forces on the end of the shaft. Thus, drilling at high pressure is not possible with these motors. Neither can they allow flow or wires to pass through these motors to lower instrumentation packages.

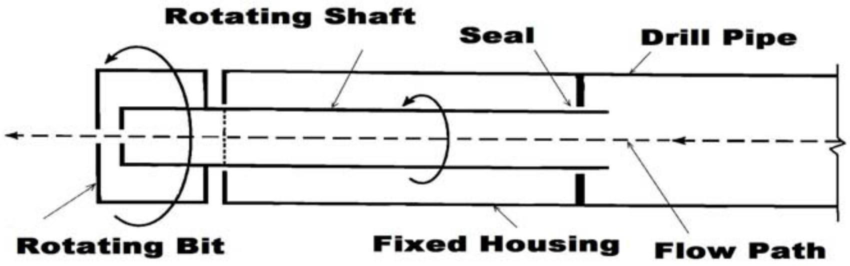

Fig. **2**

Conventional Electric Motor

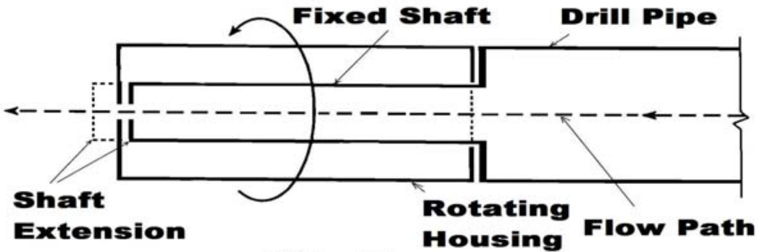

Fig. **3**

Inverted Electric Motor

To solve many of the problems and limitations listed earlier and not addressed by available motors, a new motor design is proposed that is based on two U.S. patents by the Principal Investigators and titled "An Inverted Motor for Drilling Rocks, Soils and Man-Made Materials and for Re-Entry and Cleanout of Existing Wellbores and Pipes."

Figure 3 (above) shows that the Inverted Motor (IM) basic design difference is that the hollow motor shaft is now fixed and non-rotating relative to the drill pipe. The motor housing now rotates and turns a bit or drilling tool attached to or as part of the housing. The hollow shaft transverses the full motor section and can fully extend to or out of the lead drill tool (bit) end. The exiting shaft can also be attached to another motor shaft or to the drill pipe. The prime mover (i.e., motor power section) is between the shaft and housing can be any motor style or type-electric, hydraulic or pneumatic, turbine or Positive Displacement. The key design change is that a solid, non-rotating tube now contains the internal fluids and wires with no seals-providing a continuous flow/wire channels. Internal pressurized fluids, solids and wires can fully bypass the motor section through channels in the motor shaft without entering the motor's power section.

The IM motor concept can be driven by a positive displacement motor (PDM), turbine or an electric version. A PDM in the inverted configuration is described as a gerotor design in the Patent. In this application, a modification of the power transfer method between the rotating ring and the outer motor housing would be made. Multiple stages of rotating rings which would transfer power to the housing. However, PDMs of this style require clean fluids (10micron particulate or less) and cannot tolerate dirty drilling muds. Another hydraulic motor in the IM configuration is a turbine. It has the advantage of not requiring as clean a fluid and imparts ultra high speeds easily. The IM inventor/PI has built turbine motors in an inverted configuration already. This design was built, bench and field tested at up to 103 mp (15,000 psi) pressure loss across the motor/bit. It was based on an earlier linear flow design and had bearing problems with the imparted unidirectional force. This problem can be solved by better bearings (identified) or by utilizing a newer balanced flow design described in the patent. However, neither PDMs nor turbines in the Inverted configuration have the full capabilities of electric IM versions and thus, in this project, a brushless AC/ DC electric motor is proposed.

Inverted Motor Design Merit

From the above discussion it should be clear that the benefits of an electric AC/ DC IM motor include:

- Low vibration
- High torque and ultra high speeds performance capabilities that are mostly flat over the range required and highly adjustable
- Reversible directions in the same string and changed 'on the fly'
- Multiple motors that can turn in opposite directions to minimize the overall reactive torque to the small drill string
- Multiple Liquids/Gases/Solids- pumped fluids can completely bypass the motor section allowing use of solids, strong acids, bases and 100% gas fluids; energized fluids; abrasive jetting now possible since solids can bypass the motor section through the non-rotating, hollow shaft
- Flow rate for optimum hydraulics and motor power/ speed are now fully decoupled

- High Pressure applications utilizing the fluid bypass (full or partial/ nozzled) of the motor (power, seals, bearings) allowing high pressure hydraulic jetting
- Wired MWD / LWD at the bit, with wires through the motor(s)' non-rotating, hollow shaft
- High energy applications (such as ASJ, laser or other advanced methods under discussion) at the bit, through the non-rotating hollow shaft
- Multiple modular motors that can be coupled (stacked) or independent, wired in series or parallel and providing power in series or parallel
- Multiple bent subs between IM design motors for directional work
- the majority of the mass is at the most outward radius, allowing higher momentum and maintaining higher speeds under alternating loads

Integrations with MWD, LWD and other Instrumentation

Not included in this proposal, but important to the overall future design of such drilling systems, is the ability of a motor to allow the obtaining of useful drilling and lithology data. With the proposed electric IM motors, measurement-while-drillling (MWD)/ logging-while-drilling (LWD) at the bit and wired through all motors to the surface is now possible for instant transmission and analysis of this critical drilling data allowing immediate adjustment of drilling heading and actions. The basic drilling data (MWD) needed to optimize drill rate and prevent problems are- weight-on-bit (WOB), rpm, downhole pressure and torque. These basic measurements are typically measured at the surface during the drilling operation with inference to the bottom hole.

The basic data needed for directional drilling (also MWD) are: inclination from vertical, azimuth and (tool face) direction. Various methods are now utilized to obtain this basic directional data including: stopping drilling and running survey tools on wireline/ slickline to a grooved or slotted joint section of non-magnetic pipe where alignment and a survey (inclination and azimuth) can occur. If the bit is rotated from the surface with no downhole motor, the survey point can be very close to the bit. However, with a downhole motor or other restriction, this survey point is above the motor and now 30' to 50' above the bit - 'where we were but not where we are'. This is also basically true for most MWD systems.

Real time petrophysical formation data, Logging-While-Drilling (LWD), is also helpful during drilling to stay in zone and target 'sweet spots'. This data includes formation gamma ray, density, and fluid/formation resistivity. Conventionally, this data is measured above the motor and far behind the bit - the same limitation as MWD.

Recent and more expensive technology now allows LWD (and MWD) behind the bit sub with a motor using various non-wired means to send a signal around the motor section to the surface. The data transfer rate with this new methodology is very slow. Thus, unless very expensive technology is utilized, the heading of the bit in the drilled hole is only known where it has been- 30+ feet and many minutes/hours before. This forces very inefficient and costly directional control operations, mistakes and corrections.

With the proposed inverted electric motor, small diameter instrumentation packages can be installed downstream of the motor(s) near the bit tip. This allows MWD and LWD at the bit capabilities - answers to ‘where are we now?’. This is possible because both the pipe and the motor allow both flow and wiring/fiber through it. The problems then are thickness, length and selection of the sensors/instruments and the transmission of the data to the surface.

Advanced Physics Systems (APS), in Mountain View, California, can modify their existing miniature angular orientation sensor, the Model 544, to provide a steering tool of less than 2.54 cm (1inch) OD. Inclination and azimuth determinations are provided via reliable and proven magnetometer, accelerometer and instruments packages. Some loss of accuracy may occur, but within acceptable tolerances. APS is a long time provider of directional steering tools for the oil and gas drilling industry. APS’s current steering tool has been seen used by the PI in drilling two horizontal laterals in a well of the PI. Design parameters are 70^{o}C (158^{o}F) temperature and 207+ bar (3000+psi) pressure.

Packages for WOB (strain gauge) internal and external pressures and temperature were not researched, but are not difficult instruments to find ‘off the shelf’. Powering them downhole may be a problem if voltage varies. The biggest problem will be to send data to and record data at the surface, but APS does have a package for this need.

A small gamma ray detection package has been found at Saint-Gobain Crystal in Houston which can provide a (estimated) 2.41 cm (0.95 inch) OD package with modifications of existing crystal and instrument packages. A Sodium crystal provides reliable detection of natural and man-made nuclear gamma rays. Other minimum requirements are 66^{o}C (150^{o}F) and 207 bar (3000 psi) conditions for the pressure tube and electronic components.

Electrical Motor Properties and Considerations

Mechanical characteristics of the load and electrical characteristics of the source (AC/DC voltage, impedance, etc.) are important and must be determined first. Operational speed, demanded torque, moment of inertia, friction and stiffness of the load are among the most significant mechanical parameters that are to be precisely (to the best extent possible) identified. As far as the electrical characteristics are concerned, operating voltage (type and magnitude) and the input/output characteristics of the source must be closely defined. Furthermore, equivalent impedance of the connecting cables and the internal impedance of the electric source must be defined since connecting cables tend to introduce a significant reactive power to the system. They also intensify the problem of signal reflection at high switching frequencies. And, for long cables, the problem of the signal attenuation can cause significant problems. This problem is critical in the case of sensed signals such as position, current, etc. and deserves due attention. In most design practices, it is preferable to have the power electronics controller integrated with the motor. This will be investigated to determine feasibility. Once all these factors are defined, then the selection of the motor and its magnetic configuration can be made.

Electric motors are differentiated based on the way their electromagnetic torque is generated and controlled. In order to develop a feasible solution for a particular application, selection of the type, electric excitation and material should take into account the special circumstances imposed by the application. In our case, operation at ultra-high speeds and under harsh ambient conditions creates a unique situation. To accommodate the high-speed characteristics of the machine, a candidate with a wide speed range over which a constant mechanical power is maintained is preferable. This is primarily due to the fact that such machines offer a more compact geometry, which in turns simplifies the geometrical constraints that are caused by this application (very small diameter and length). In addition, operation at very high-speeds (10,000 rpm) and above increases the speed of alteration in the magnetic field of the machine. This, in turn, results in an elevated eddy current and hysteresis losses (a.k.a. core losses). Excessive heat generated by these losses deteriorates the performance of the magnetic materials such as permanent magnets and can increase the value of the resistances in the coils both of which will have an adverse impact on the productivity of the electric motor. Therefore, selection of the material, thickness of the lamination and cooling considerations are of paramount importance in this case. Mechanical integrity of the moving parts (in an interior or exterior rotor) is another problem that needs to be considered.

Centrifugal forces at very ultra high speeds can cause ‘fly out’ of the coils, permanent magnets, etc. Therefore selection of a rugged structure is highly recommended for these types of applications.

Finally, due to the hazardous conditions, the type of the excitation should be chosen very carefully. Use of brushes and slip rings are highly discouraged. The electric arcs that are commonly seen in brushed DC machines and wound rotor induction drives can cause major safety issues and, thus, are not recommended. Brushless configurations are among the best candidates for these applications. The brushless drives necessitate an AC form of excitation. The magnitude of the voltage will be selected such that the targeted speed is reached. One should remember that ultra high speeds of rotation induces large voltages that work against the terminal voltage. In fact, the maximum speed of the drive at a given power rating is normally limited by the available terminal voltage. The necessary voltage may be transmitted at high levels to the motor or can be boosted at motor terminals using power electronics-based converters.

Once the geometry and type of excitation are finalized, a numerical model of the machine should be developed. Finite Element Analysis (FEA) is an effective approach in predicting the motor performance in which an accuracy of up to 5% (compared to measured data) can be achieved. Since development of prototypes is a relatively expensive part of the project, it is preferred to conduct an optimization on the geometry of the machine via FEA. The Emerson energy conversion laboratory at the University of Missouri-Rolla is equipped with 2-dimensional and 3-dimensional state-of-the-art FEA software packages. This software allows for precise modeling of the material, geometry and power electronics interface. Once a problem is defined in FEA software detailed magnetic, electric and mechanical quantities of interest can be retrieved and processed. Therefore, virtual prototypes of a motor can be built and examined. The objective for optimization is usually cost, size and efficiency.

The determination of the control methods and instrumentation (surface and downhole) required to optimize motor performance must then be identified and set. It is important to note that the size of an electric motor depends upon the level of the torque generated by the machine. In this project, the compactness of the motor (an outer diameter of 8.89 cm (3.5 inch) or less) is essential. In order to improve compactness in the inverted motor, operation at constant power is targeted (see Figure 4).

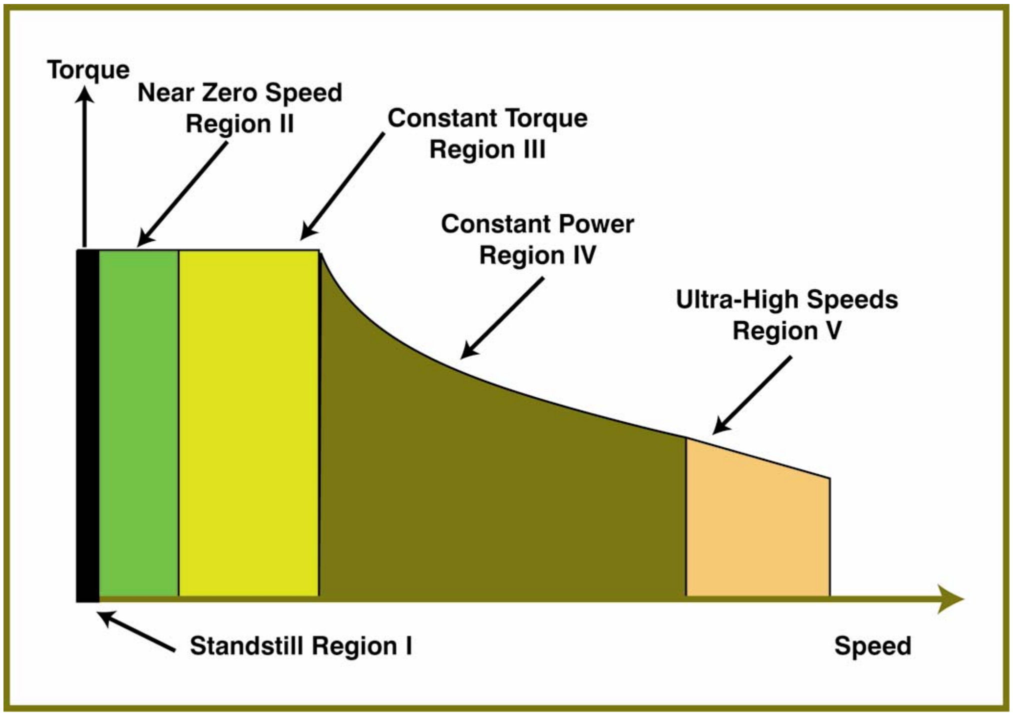

Figure 4: Various regions of operation in electric motors

This can be done by proper control of the excitation using power electronics inverters. Dr. Fahimi was leading a similar project for ultra high speed aerospace generators and will design and simulate control routines for the inverted motor such that a constant power operation can be accommodated. Furthermore, design of the controller should take into account the possibility of the signal attenuation and ambient conditions. Two scenarios for control at the surface and down hole to investigate and solve the potential problems in the control of the proposed motor are needed. The main controlled variable will be the speed of the rotation. In order to achieve this goal, first a closed loop torque control system will be designed. Once satisfactory operation in 4-quadrant torque control is achieved a cascaded speed control will be added to the system (see Figure 5).

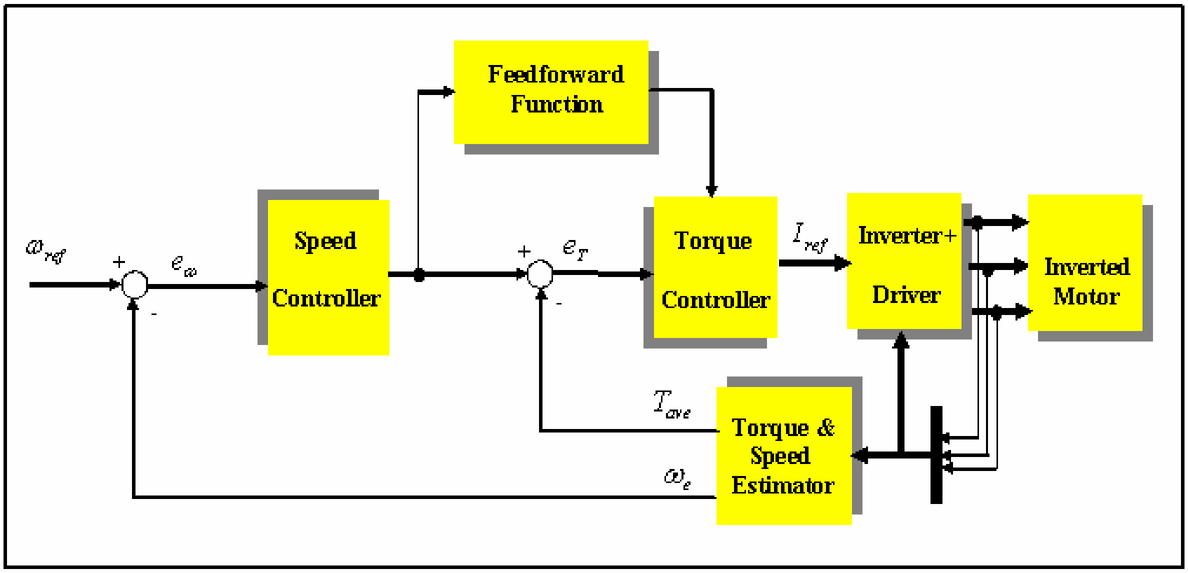

Figure 5: Cascaded Speed control system for an inverted motor

This will ensure a robust operation in maintaining the speed of rotation as the mechanical load changes. Finally, the control routines will be modified such that they can be used for a modular set of inverted motors. The stationary shaft and compact geometry provides an optimal condition for modular utilization of the proposed motors and this should be incorporated in the development of the control routines.

Once the geometry and details of the design for an optimal motor solution are obtained, a system level study of the source-motor-mechanical load is important. The model used for the motor will contain large scale properties that are calculated using the FEA, but will be comprised using lumped parameters to allow for an abstract model that is adequate for system level studies. The interaction between the load, electric machine, control and the source must be investigated. Issues with the design need to be rectified at this stage by going back to the FEA and modifying the magnetic design of the motor. This includes any harmonics generated in motor as impacting the drillstring and BHA and prediction of any destructive frequencies.

What was originally proposed for this Project:

Phase I - Characterize Ultra High Speed Bits and Motor Requirements

Task 1 - Obtain full characteristics of the ultra high speed (10,000 rpm) bits.
Task 2 - Obtain the targeted operating conditions, bit sizes, depths, temperatures, pressures for the motor.

Task 3 - Identify the output and input characteristics of the electric motor.

Phase II - Prepare CAD Drawings and Perform Motor Hydraulics

Task 1 - Run hydraulic calculations.
Task 2 - Prepare basic CAD drawings.

Phase III - Magnetic Model of Motor Performance

Task 1 - Selection of the magnetic configuration, material and type of excitation.

Phase IV- Develop a Numerical Model for the Electric Motor

Task 1 - Perform static finite element analysis.
Task 2 - Determine control methods and instrumentation (surface and downhole) required to optimize motor performance.

Phase V - Develop Simulation Model for the Source-Motor-Load Combination, Finalize Design and Report Results

Task 1 - Development of a simulation model for the source-motor-load combination.
Task 2 - Identify seals for the motor.
Task 3 - Identify bearings for the motor.
Task 4 - Final motor design and report to project sponsor.

Stated DELIVERABLES:

1. A survey of current ultra high-speed bit performance, requirements and desired design capabilities. Sample of available ultra-high speed drilling case studies will be included.
2. Summary of bit loading characteristics for ultra-high speed applications.
3. A set of screening criteria for designing ultra-high speed motors for deep, harsh environment, and ultra slim hole or micro hole drilling conditions.
4. A finite element model of two sizes for an inverted configured, electric motor designed for ultra high-speed service.
5. Simulations of the motor performance under various expected loading situations.
6. Final motor design based on findings of the study, including prototyping ready CAD drawings, simulations, material specifications and recommended operational loading.
7. Names of potential motor manufacturers who may consider prototyping.

EXPERIMENTAL METHODS-

FEA studies of the various motor configurations were accomplished and these are discussed in the RESULTS AND DISCUSSION section below. The methods on how that was done is also covered in the section below.

RESULTS AND DISCUSSION-

All objectives of the project were accomplished and are discussed below. This discussion will be organized by the Phase and Tasks originally set out. Repeat discussion of the same effort or overlapping effort will be covered in the first section and subsequent sections will refer back to the original section where it was first discussed.

Phase I- Characterize Ultra High Speed Bits and Motor Requirements

Task 1 – <u>Obtain full characteristics of the ultra high speed (10,000 rpm) bits</u>.

Speed, weight on bit, torque, bit type and cutting element material are key considerations in determining overall drilling characteristics and requirements of the motor. Bits types, capabilities and operating ranges were studied by reviewing industry bit catalogs and by visiting with industry manufacturer representatives. Arnis Judzis, Alan Black and Homer Robertson with TerraTek in Salt Lake City, Utah, were also consulted in this regard. Studies using diamond studded core type bits at TerraTek have indicated that very high penetration rates can be obtained at ultra high (10,000 to 50,000 rpms) revolutions, but no current bit can long sustain such generated heat and shock loads.

Several bit manufacturer representatives were consulted, in particular Bob Radke with Technology International in Houston, Texas, and Marcel Boucher with ReedHycalog. Only fixed cutter bits can be considered for these ultra high rotational speeds in drilling. Basically no bits are available for rotation speeds above about 1500 rpm. The cutting elements and holding methodology are the limiting elements. Currently only diamond impregnated and new thermal stable cutting elements can come close to actual field utilization at ultra-high rpms. Technology International has a new thermally stable cutter material on the market, but these are not published to be capable of 10,000+ rpm.

Torque and force on bit, commonly known as “weight on bit” or WOB, are directly connected for most drilling. From standard bit published industry recommended practices it is indicated that WOB decreases as rotational speed increases for all fixed cutter bits. The optimum rotational speed and WOB specification of a given bit is very dependent on formation type. But, by extending this general trend, the ultra high rpms will necessitate minimal weight on bit and low torque.

TerraTek, Salt Lake City, is currently performing a study “Smaller Footprint Drilling System for Deep and Hard Rock Environments; Feasibility of Ultra-High-Speed Diamond Drilling”, DE-FC26-03NT15401 for the U.S. Department of Energy on ultrahigh speed drilling. TerraTek’s earlier work in this study utilized rotational speeds of 10,000 rpm up to 50,000 rpm and weight on bit forces of 1500 grams (3.3 lbs) to 3500 grams (7.7 lbs) for nominal 1.91 cm (0.75 inch) diameter core type bits. This is the only study known by the authors in utilizing these ultra-high rotational speed for drilling.

A comparison of current industry rotational speeds to TerraTek’s study for common bit sizes is important because cutting element and, in particular, tip velocity is the key concern since that controls the heat generated and cutter premature failure. Table 1 (next page) shows the relative sizes for differing rpms with constant tip velocities. Descriptions of the sub-sections of that table, for increasing speeds, are:

A. Current industry speed of 250 rpm for a 12.1 cm (4.75 inch) bit
B. High industry speed of 1000 rpm for a 12.1 cm (4.75 inch) bit
C. TerraTek’s low speed of 10,000 rpm for a 1.905cm (0.75inch) bit
D. TerraTek’s ultra-high speed of 50,000rpm for their 1.905cm (0.75 inch) bit

Thus, for a fixed rpm for all sizes of bits, the lowest tip velocity of the cutters would be in small bits and the highest tip velocities would be in the larger bits. That condition would point to smaller microhole wells exclusively. However, if the more important tip velocity were held constant for all bit sizes the opposite decision would be made. The concern of heat generation and excessive cutter wear at ultra-high rpms necessitates the need to keep tip speeds within useable speeds (rate of heat generation) for available and near-future cutters. As seen in the following subsets of Table 1, larger bits keep tip velocity high with lower rpms. For example in extending the table for larger bits, a 15.9 cm (6.25 inch) bit for a 10 m/sec (32.7 ft/sec) tip velocity would only turn at 1200 rpm and a 21.6 cm (8.5 inch) bit would only be at 885 rpm. These lower ranges of tip velocity are close to the range of what is available in cutter technology currently.

Table 1

Diameter inches	Speed rpm	Velocity ft/sec
0.75	1,585	5.18
1.68	708	5.18
2	594	5.18
3	396	5.18
3.5	340	5.18
4.75	***250***	***5.18***

Diameter inches	Speed rpm	Velocity ft/sec
0.75	6,335	20.72
1.68	2,828	20.72
2	2,376	20.72
3	1,584	20.72
3.5	1,358	20.72
4.75	***1,000***	***20.72***

C. TerraTek -Lower Range Speed

Diameter inches	Speed rpm	Velocity ft/sec
0.75	***10,000***	***32.7***
1.68	4,464	32.7
2	3,750	32.7
3	2,500	32.7
3.5	2,143	32.7
4.75	1,579	32.7

D. TerraTek Ultra-High Speed

Diameter inches	Speed rpm	Velocity ft/sec
0.75	***50,000***	***163.5***
1.68	22,321	163.5
2	18,750	163.5
3	12,500	163.5
3.5	10,714	163.5
4.75	7,895	163.5

The next thing to consider the required weight-on-bit (WOB) for ultra-high speed drilling. While TerraTek's bits study cannot be directly translated to specific weights on bit (wt/area) due to the unknown and variable cutting surface area of the bits. An estimated range of specific force (as weight) on bits can be made by using those same WOBs given and assuming a cutting area around a nominal 1.905cm (0.75inch) diameter of:

A. 0.95 cm^2 (0.15 in^2) area for 22 and 52#/in^2, respectively
B. 3.48 cm^2 (0.54 in^2) area for 6.1 and 14.3#/in^2, respectively

From this work specific WOBs in the range of 0.32 to 1.59 Kg/cm^2 (10 to 50 lbsf/in$^{2)}$ are to be expected, and probably on the lower end of that range.

The next consideration is in estimating the required torque for the speed and specific weight on bit desired. Looking back on TerraTek's study that ulilized the available maximum torque of a Koford Motor with specifications of:

- 1.6" Hall Effect synchronous brushless DC Motor
- 51,000 rpm maximum
- 120 VAC at 10 amps maximum
- Stall torque - 5.56 Nm (788 oz-in, 4.10 ft-lbs)
- Continuous torque - 0.565Nm (80 oz-in, 0.41 ft-lbs)

- Max. Continuous power - 2700 watts
- Peak output - 7383 watts (measured at 9 amps maximum)

It should be noted that TerraTek had problems in keeping constant high rotational speeds for the specific weight-on-bits that were used. Thus these available horsepower and torque levels are inadequate for their specific WOBs utilized.

An old torque calculation (unknown source- 1970s Chevron drilling information) estimates torque (T) based on bit size and weight on bit as

$$\mathbf{T=0.5D*WOB*FC/12}$$

where FC=friction coefficient and is 0.2 for hard formations and 0.25 for soft formations using roller bits. FC is 0.2 to 0.4 for other bit types. Also WOB is weight on bit in pounds-force and D is diameter of bit in inches. The safety factor, if any, used in this calculation is unknown. The data in Table 2 on the next page shows the range of calculated torques based on this equation using a FC=0.4 (i.e., worst case).

Due to heat buildup on the cutter elements and the basic cutting characteristics of PDC type bits, a very low specific weight on bit is expected, in the range of 0.45 N/cm2 (20 lbs/in2). This calculation shows that a torque of only 20Nm (15 ft-lbs) would be required for microhole sized ultra-high rotational speed drilling.

In an effort to confirm these values, shop tests were performed in January 2005 to estimate startup torque required to overcome drag of the drillstring on the wellbore face. Start up torque (from a stall) were estimated at 4 ft-lbs based on horizontal pipe on a roughened steel bed. These value ranges fit the above calculation.

Thus for ultra-high rotational speed drilling microholes sized bits (less than 9.53 cm (3.75 inch)) are desired. Specific weights on bit would be about 0.45 N/cm^2 (20 lbs/in^2) and require a torque of 20Nm (15 ft-lbs). Unfortunately no bits are capable of these rotational speeds at this time.

No matter what the bit size or rotating speed, it is interesting to note that for a given cutter as the radius decreases to the center the cutter velocity decreases to zero. Thus, it should be recognized that different cutting mechanism must exist as a function of radii and rpm. For ultra-high velocities, the outer ultra-high speed cutting edge can be a shearing cutting mechanism. The middle can be a gouging method. But, this begs the question: What is the bit cutting mechanism at and near the center where the cutter speed is near zero and zero? The center must be more of a crushing column method than a grinding mechanism. The cutting method's efficiency at the center is suspect. If the center column were cut by water jetting or abrasive jetting then improvements in drilling rate may be realized. This changing cutting mechanism should be studied further and tied to advanced cutting methods. It should be noted that the TerraTek study utilized a thin cutting surface of relative constant diameter, i.e. no changing cutting method to consider, similar to a core bit.

Table 2
Estimated Torque and Specific WOB

Required Torque Calculation in foot-lbs

Bit Diameter inches	Weight On Bit in lbs			
	50	100	200	500
2.00	1.7	8.3	16.7	41.7
2.50	5.2	10.4	20.8	52.1
3.00	6.3	12.5	25.0	62.5
3.50	7.3	14.6	29.2	72.9
4.75	9.9	19.8	39.6	99.0

Required Torque Calculation in Newton-meters

Bit Diameter CM	Weight on Bit in Kilograms			
	22.7	45.4	90.8	227.0
5.08	2.3	11.3	22.6	56.5
6.35	7.1	14.1	28.3	70.6
7.62	8.5	17.0	33.9	84.8
8.89	9.9	19.8	39.6	98.9
12.07	13.4	26.8	53.7	134.2

Specific Weight on Bit in lbs/square inch

Bit Diameter inches	Weight On Bit in lbs			
	50	100	200	500
2.00	15.9	31.8	63.7	159.2
2.50	10.2	20.4	40.8	101.9
3.00	7.1	14.2	28.3	70.8
3.50	5.2	10.4	20.8	52.0
4.75	2.8	5.6	11.3	28.2

Specific Weight on Bit in Newtons/cm2

Bit Diameter CM	Weight on Bit in Kilograms			
	22.7	45.4	90.8	227.0
5.08	0.11	0.56	1.12	2.79
6.35	0.22	0.45	0.89	2.23
7.62	0.19	0.37	0.74	1.86
8.89	0.16	0.32	0.64	1.59
12.07	0.12	0.23	0.47	1.17

Task 2 – Obtain the targeted operating conditions, bit sizes, depths, temperatures, pressures for the motor.

Standard bit sizes are now 6-1/4" to 6-3/4' bits for setting 4-1/2" and 5-1/2 inch nominal casing sizes. Larger holes require larger bits and bigger motors to turn. Ultra-high cutting speeds are not currently possible for the larger holes due to extreme cutting tip velocities discussed earlier. These ultra-high rotational speeds are within reach of microholes and slimholes sizes. Bit sizes relate to the final casing size to be run and the industry trend is toward smaller slimhole and microhole sizes (per DOE Microhole Technology Initiative) due to drilling speed and costs savings. The validity and benefits of higher cutting speeds for even normal sized bits is still real and valid; however, slimhole and microhole sizes are more targets for this technology, at least initially. Thus, bit sizes less than 12.1 cm (4.75 inch) will be considered, and the smaller the better. Specifically, bit sizes of 9.5 cm (3.75 inch) and smaller to pass through nominal sized 4-1/2 inch casing and 6.29 cm (2.375 inch) and smaller bits to pass through nominal sized 2-7/8” tubing are targeted.

Standard drilling operations are 207 bar (3000 psi) at the standpipe but this pressure is increasing to 517 bar (7,500 psi) in newer rigs. For water jetting and abrasive slurry jetting the higher pressures are required. Depths average close to 1524 meters (5000 feet) and 66°C (150°F) but newer fields and exploration wells are going deeper to 6096 meters (20,000 feet) and upwards to 110°C (230+°F).

Hydraulics limit the hole size, pipe size and depths attainable. These were studied in a companion study for the DOE entitled “Advanced Mud System for Microhole Coiled Tubing Drilling,” contract number DE-FC26-04NT15502. Tables 3a and 3b and Figure 6 (on next page) are from that study and show the range of capabilities for various well and pipe configurations.

From that study, minimum pipe sizes to reach 1524 meters (5000 feet) depths in microhole nominal pipe sizes of 1.25”, 1.5” and 1.75” through 2.375” and 2.875”. For these small pipe sizes the possible minimum bit sizes (ie., resultant hole size) are 5.4 cm (2.125 inch) through 12.1 cm (4.75 inch). Some applications require the bit and motor to pass through existing casing of standard nominal sizes of 2”, 2.5”, 3.5” and 4.5”. To fit these general conditions the selected motors sizes were 4.29 cm (1.69 inch) and less than 7.62 cm (3.0 in) outer diameters. These motor sizes will allow passage through 2” nominal pipe (6.03cm (2.375 inch) OD and 4.95 cm (1.95 inch) ID) with a bit and through nominal 4-1/2” (9.4 cm (3.7 inch) ID) sized casing with a bit.

A 1524 meter (5000 feet) targeted depth also sets a 172 bar (2500 psi) external pressure and 66° C (150°F) temperature for the motor to deal with. These conditions are within the capabilities of the electronics of the motor.

The next requirement of the Inverted Motor is in utilizing high pressures (i.e., 1034 bar (15,000 psi) for water jetting) or extremely abrasive fluids (i.e., slurries) at moderate pressures (i.e., 517 bars (7500 psi)). Note that 517 bar (7500psi) operating pressures fit the pressure capabilities of newer rigs. Since the Inverted Motor has internal metal to metal static seals, these conditions are of little concern if proper thickness and hardness are considered. Ballooning of the shaft to high pressure will occur and must be taken into account in the design.

Table 3a

DOE Mud System

Pressures for various flow rates and systems

Case Descriptions:

S1 500' surface casing point, 3.5" jointed DP, 9.875" hole, lite mud system
S2 500' surface casing point, 3.5" jointed DP, 9.875" hole, premium mud system
S3 500' surface casing point, 3.5"jointed DP, 6.75" hole, premium mud system
S4- 500' surface casing point, 3.5 jointed DP, 6.75" hole, water
S5- 500' surface casing point, 3.5" jointed DP, 9.875" hole, water

P1- 5000' casing point with 6.75" hole, 2.875"CT, premium mud, 3.5" BHA
P2- 5000' slimhole with 4.75" hole, 2.875"CT, premium mud, 3.5" BHA
P3- 5000' microbore with 3.5" hole, 2.375"CT, premium mud, 2.875" BHA
P4- 5000' microbore with 2.5" hole, 1.75"CT, premium mud, 2.0" BHA

L1- 1000' horizontal lateral microbore of 3.5"hole, 1.75"CT at 5000"TVD in 5.5" casing
L2- 1000' horizontal lateral, microbore 2.5" hole, 1.75" CT at 5000' TVD in 5.5" casing
L3- 1000' lateral of 3.5" microbore, 2.375"CT at 5000'TVD in 5.5" casing

Table 3b

DOE Mud System

Pressures for various flow rates and systems

Summary of Runs

Standpipe Pressures (psi) for various Flow Rates and Wellbore Configurations

	Flow Rate in Gallons per M (GPM)inute										
Case	**0**	**10**	**15**	**25**	**50**	**75**	**100**	**200**	**300**	**400**	**500**
S1							98	425	850	1420	2308
S2							90	350	830	1400	2119
S3					31	70	100	390	780	1300	2135
S4							85	350	780	1350	2162
S5								355	788	1425	2151
P1				150	210	325	533	1493	2838	4543	
P2				225	300	400	600				
P3				380	800	1250	1701	5036			
P4		3000	5000								
L1				300	700	1300	2000	5000			
L2				475	1125	2005	3300				
L3				300	500	800	1400				

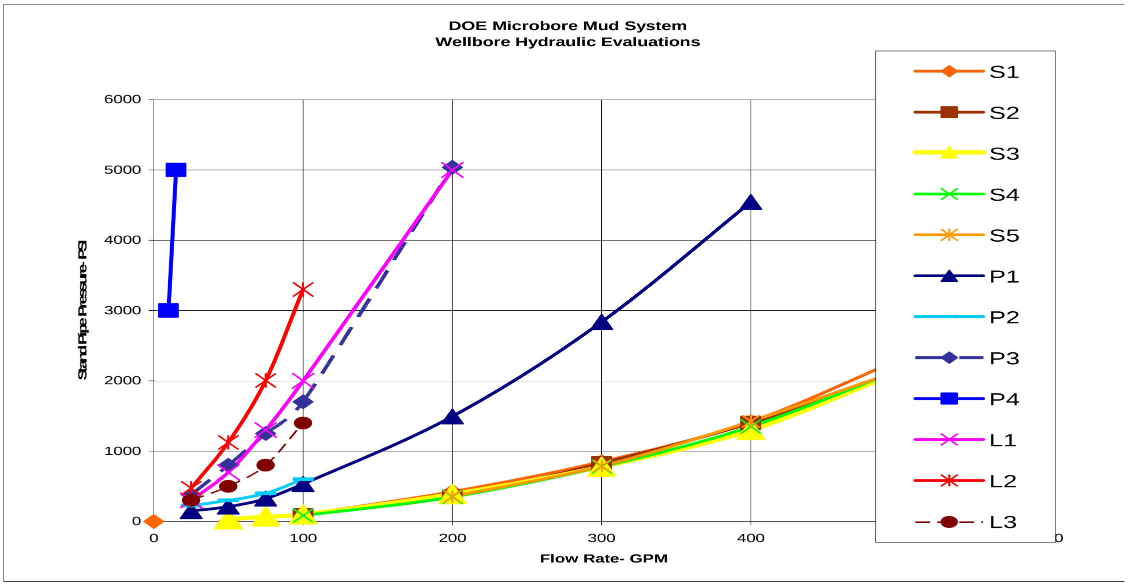

Figure 6 - Plot of Standpipe Pressure (psi) versus Flow Rate (gpm) for various well Configurations

Task 3 –Identify the output and input characteristics of the electric motor.

Operational speed was set at 10,000 rpm as a condition of the Request for Proposals. This does not take into account tip velocity for various bit sizes, as discussed earlier. With this rpm requirement microhole sized bits are required. With an inverted motor the generated momentum is very high as the outer mass is rotating at 10,000 rpm.

Cooling of the motor will occur by flow of high pressure fluids thorough the internal shaft and by return flow on the outside of the housing. These flows must cool the heat generated by friction of bearings and seals, heat generated by the magnetic flux of the motor. Minimum flow rate for cooling cannot be set until a prototype is built and tested.

Standard voltages in the field are 110VAC single phase, 220VAC 3 phase, 460 VAC 3 phase, 762 VAC 3 phase and 1000 VAC 3 phase. Primary voltages can also be utilized, but higher voltages limit available insulators for shielding. Transformers can be utilized to provide any surface voltage desired for downhole use. Higher voltages require lower amperes and, thus fewer losses, especially if better and more costly insulators can be utilized. In weighting voltage losses versus higher voltage problems a 300VAC 3 phase system at the motor was chosen. This requires a higher voltage at surface due to losses in the line between the surface and motor. As more motors and more instruments are added to the system, higher 3 phase voltages may be required to handle the current.

Nothing was done to quantify the "stiffness of the load". This means the ability of the drilling assembly to maintain a straight line of drilling so that any weight on bit will not unduly buckle the assembly. Since the motor is such a short segment of the assembly, this could not be characterized at this time.

In this study we did not determine the internal impedance of the electric source was not determined since the exact source of power couled not be identified. This will be dependent on the specific well and application. Signal reflection could not be determined at this time as well.

Reactive power to the system was calculated for specific speeds based on simulations. Those computer simulations indicate that at nominal operating point the power factor should be better than 90% at the motor terminals. This is very good indicator of effective power utilization.

The adequate cables for carrying the required current at 300V-DC was identified; however, selected cable/wire sizes cannot be selected only on one motor since multiple motors and instruments can be included in the system. Voltage losses of 10% were estimated for a 2 ampere current in a 300 volt 3 phase AC line system with 24 AWG wire at 1524 meter (5000 feet). The equivalent impedance of these cables can be obtained from data sheets once the specific cables are selected.

Useful power (rate (time function) of doing work) equations for this effort are:

$$\text{Hp} = \text{Torque (lb-ft)} * \text{rpm} / 5252$$

$$\text{Kilowatt} = \text{Torque (Nm)} * \text{rpm} / 5192$$

Using these equations to calculate the required power indicate that 30 horsepower or 21 kilowatts of power are required to drive the bit at 10,000 rpm. For multiple motors this can be divided by the number of utilized, but the total power provided by the wireline or cable from the surface is at this level. This full power requirement translates to cable or wireline current requirements and capabilities shown below in Table 4.

Table 4
Maximum Current Flow for Estimated Power Requirement

220V requires 95 amperes DC….55 amperes 3 phase AC
440V requires 48 amperes DC….26 amperes 3 phase AC
760V requires 27 amperes DC .. .16 amperes 3 phase AC

These are very large current flow requirements to transmit downhole, but can be reduced further by going to higher voltages and better insulators. This mechanical/electrical power requirement can also be greatly reduced by utilization of advanced drilling methods to precut the hole, such as abrasive slurry drilling or high pressure waterjetting, that are possible with these Inverted Motors.

Next concern is the size of the internal flow channel in the fixed shaft. Maximum flow rates of abrasive slurries were determined by using guidelines proposed by Dr. David Summers. He stated that 10 meters per second (33 ft/sec) up to 12.2 meters/ second (40 ft/ sec) were the upper ranges were severe erosion begins. Thus, for abrasive slurry jetting, the internal channel in the shaft must handle the required flow rate of 19 - 284 lpm (5-75 gpm) at less than 10 m/sec (33ft/sec) velocity to prevent excessive abrasion of the interior shaft channel. This translates to a required or minimum diameter of the internal flow channel as shown below in Table 5.

Thus for microbore flow rates of 57 lpm (15 gpm), as shown in Table 3 and Figure 6 on page 27, a diameter of the internal channel for flow should be 1 cm (0.38 inch).

Table 5
Minimum Flow Channel Diameter to Prevent Erosion

19 lpm (5 gpm)	0.56 cm (0.22 in)
57 lpm (15 gpm)	0.97 cm (0.38 in)
189 lpm (50 gpm)	1.77 cm (0.70 in)
284 lpm (75 gpm)	2.16 cm (0.85 in)

Phase II- Prepare CAD Drawings and Perform Motor Hydraulics

Task 1- Run hydraulic calculations.

Two concerns exist in utilizing hydraulic fluids and abrasive slurries for drilling: hydraulic ability to circulate the viscous fluids down the drillpipe and up the annulus, cleaning the cut rock and added abrasives to the surface with the available pressures of the pump and pipe; and prevention of the abrasive slurries from erosional cutting the pipe, rock and equipment.

Hydraulic calculations based on various well configurations (bit size, casing size, pipe size, depths, and deviation) were performed for a companion U.S. Department of Energy project entitled “Advanced Mud System for Microhole Coiled Tubing Drilling Systems,” contract number DE-FC26-04NT154765. That study was fully discussed earlier with Table 3 and Figure 6 of the data shown earlier. Maximum flow rates were 189- 284 lpm (50-75 gpm), but in many cases can be as low at 57 lpm (15 gpm) and must be closely controlled due to maximum surface pressures. Normal mud pressure loss is related to the flow channel OD and nozzle size.

For jetting and ASJ applications, as desired in this work, the pressure loss is mostly at the nozzle at the bit and must be at least 345 bar (5000 psi) pressure differential across the nozzle for effective abrasive cutting. In addition, for hydraulic jetting, the pressure must be greater than the strength of the rock to cut or must be pulsed. The annular pressure thus must be as low as possible or the internal pressure must exceed the bottom hole dynamic pressure during drilling by that critical pressure. Sometimes this requires underbalanced methods of lighter fluids or injected gases. Gases ahead of the bit also aid jet and abrasive drilling by providing a low density and viscosity phase that the jet must penetrate to get to the rock.

For internal pipe and external annular considerations (through motor channel considered earlier) the maximum flow rates of abrasive slurries were determined by using guidelines proposed by Dr. David Summers. Those limits were 10 meters per second (33 feet per second up to 40 feet per second) were the upper velocity ranges (convertible to flow rates) were severe erosion can take place. Table 5 previously showed specific internal diameters required for set abrasive flows to prevent erosive velocities. Table 6 below shows the corresponding maximum rates based well configuration (pipe size and hole size). As seen from Table 6, only for the internal motor flow channels is there any concern for utilizing abrasive slurries.

Table 6

Maximum Slurry Flow Rates to Prevent Erosion

Internal Diameter		Max Flow Rate			Minimum Hole Size	
cm	**inches**	**lpm**	**gpm**	**bpm**	**cm**	**inches**
1.905	0.75	170.93	45.4	1.1	3.4	1.35
2.54	1	303.87	80.8	1.9	4.3	1.70
3.175	1.25	474.80	126.2	3.0	5.2	2.05
3.81	1.5	683.71	181.7	4.3	6.1	2.40
4.445	1.75	930.60	247.3	5.9	7.0	2.75
5.08	2	1215.48	323.0	7.7	7.9	3.10
6.35	2.5	1899.19	504.8	12.0	9.7	3.81
6.985	2.75	2298.02	610.8	14.5	10.6	4.16
7.62	3	2734.83	726.9	17.3	11.5	4.52

Based on the discussed mechanical, hydraulics and erosion concerns, targeted bit and motor geometries were initially set as shown in Table 7.

Table 7

Initial Bit, Hole and Motor Geometries

	Hole Size	Motor Housing		Shaft	Internal Channel
	diameter	OD	ID	OD	OD……..
	8.9+cm	6.90 cm	5.69cm	3.18cm	1.91cm
	(3.5+in	2.72 in	2.24 in	1.25 in	0.75 in)
and					
	6.35+cm	4.29 cm	3.38 cm	1.91 cm	0.95 cm
	(2.5+ in	1.69 in	1.33 in	0.75 in	0.375 in)

While these motors do not meet all the requirements of all conditions, they do meet the requirements for the expected hole size and drilling conditions. These motor requirements were delivered to Dr. Fahimi for subsequent motor electro-magnetic-mechanical design and analysis. Modifications in these specifications were made based on his work and are reflected in the final design.

Task 2 - Prepare basic CAD drawings.
Preliminary designs were prepared with SolidWorks based on the above specifications aand delivered to Dr. Fahimi for FEA simulation studies. Several iterations were made varying the motor geometries to fit Dr. Fahimi's electro-mechanical requirements. These changes are reflected in the final design. See Phase V, Task 4 and Appendices D,E and F for the final SolidWorks drawings.

Phase III- Magnetic Model of Motor Performance

Task 1 - Selection of the magnetic configuration, material, and type of excitation.

Appendix A provides the details of the evaluation of the various electro-magnetic-mechanical configurations, materials and control types of motors considered. Because of the desire to utilize advanced drilling methods of aggressive fluids (erosion, pressure, etc.) and wires through the motors, only Inverted Motors were considered. Various electro-magnetic drives were considered and studied for these motors, including Permanent Magnet Synchronous Machine (PMSM), Inductance and Switched Synchronous Reluctance Machines (SRM). In the end, PMSM motors were considered to have higher power density and ruggedness than SRM and Induction drive types for this ultra-high speed drilling application. Furthermore, both axial and radial configured PMSM motors were studied. Axial versions of the PMSMs are believed to be more rugged for drilling operations than radial PMSMs. This study compared both axial and radial PMSMs for this drilling application, with the attributes of each listed in Table 8 on the next page.

Materials for Motor Lamination: The machine that is being designed has a very small outer diameter and stack length. For this purpose, materials had to be chosen that would tolerate higher values of magnetic field densities. M-19 is a very commonly used material for motor laminations; however, this alloy was found unsuitable for the field density anticipated. Therefore Hiperco 50A alloy was chosen which has a maximum saturation induction of

Table 8
Comparison between Radial and Axial Machine Geometries

Radial PMSM	Axial PMSM
■ More productive when the motor has a longer shaft. ■ Manufacturability is easier.	■ Generally chosen for applications with limited space and for rapid acceleration and deceleration. ■ Expensive to manufacture. ■ Possibility of heating at the stator pole- back iron contact points.

1.7 Tesla as shown in Table 9 and Figure 7 below. This alloy finds typical applications in aircraft motors and generators. A summary of reasons for this choice are:

- High knee point in BH characteristics (allows high flux densities)
- High D.C. maximum permeability
- Low D.C. coercive force
- Low A.C. core loss
- Higher strength

Table 9
Composition of Hiperco 50A steel

Carbon	0.00 %	Manganese	0.05 %
Silicon	0.05 %	Cobalt	48.75 %
Vanadium	2.00 %	Iron	Balance

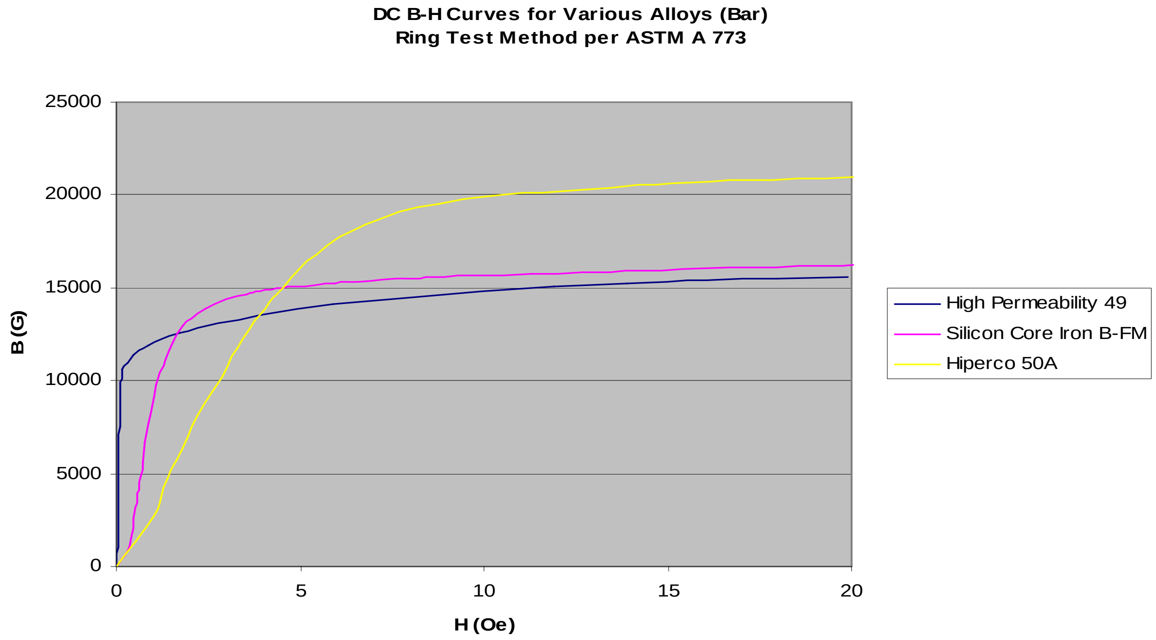

Figure 7: DC B-H curves for various alloys, including Hiperco 50A

Materials for Permanent Magnet: A permanent magnet in this machine is used to magnetize the core of the machine. Electrical excitation is then applied to generate torque of a desired magnitude. Choice of magnets is based on the dimension of the machine, available airgap length and other magnetic parameters. For our application, N40SH (Sintered Neodymium Ferrite Boron) was chosen. Sintered Neodymium Ferrite Boron (NdFeB) is formed by powder metallurgical process. They can be die-pressed or isostatically pressed. Magnetic domains are aligned during pressing by application of a magnetic field to optimize magnetic performance to suit requirement. Characteristic features of conventional NdFeB are:

- High Maximum Energy product ((BH)max)
- Temperature stability unaffected up to 180 °C, ideal for temperature < 80 °C
- Lower corrosion and oxidation than Samarium Cobalt (SmCo)

Table 10: Magnetic Properties of Sintered NdFeB

Br (kiloGauss)	12.4 -12.8	BH_{max} (MGOe)	38 – 41
Hc (kiloOersted)	>11.8	Curie Temp. (°C)	340
Hc_i (kiloOersted)	>20	Max Op. Temp (°C)	150

Material for the Shaft, Housing and surrounding construction components: The housing holds the drilling tools desired. The shaft provides the continuous axial strength for adding additional drill string and tools, bending and compression forces. Thus it should have a high tensile yield strength in excess of 100,000 psi. It also must withstand the erosive nature of the pumped fluids with appropriate harness or have a hardened liner, thus a high Brinnel (200+) or Rockwell (100+) hardness is required. The material used for the shaft and housing should be non-ferromagnetic due to the fact that a ferromagnetic material will allow for additional magnetic losses such as eddy current and hysteresis losses. These losses generate heat within the motor and will deter the overall efficiency of the motor drive.

High alloy, high strength stainless steels were good candidates for accommodating these requirements. A list of all considered construction materials is given in Appendix B. Specifically, heat treated SISI Type S45500 series stainless steels fit these requirements and appear to be well suited for this application.

Phase IV- Develop a Numerical Model for the Electric Motor

Task 1 - Perform static finite element analysis.

This work was done using the Power Electronics and Controlled Motion Laboratory facilities at the University Of Texas - Arlington which is equipped with the necessary facilities to conduct this research program. We used the three dimensional FEA package, Magnet 6.2 from Infolytica Corporation to perform the necessary numerical analysis.

Simulation studies that emulated a 4-quadrant torque control were conducted at various speeds in Finite Element Analysis (FEA) environment. The studies indicated that the four quadrant operation in torque versus speed plane (motoring and generating in clockwise and counterclockwise directions) offers an adequate bandwidth necessary for implementation of a closed loop system for high speed drilling applications.

See the results of the Numerical Model in Phase V below and in Appendix A.

Phase V- Develop Simulation Model for the Source-Motor-Load Combination, Finalize Design and Report Results

Task 1 - Development of a simulation model for the source-motor-load combination.

Dynamic studies were made from the static models prepared to identify maximum magnetic saturations and potential heat buildup. This FEA work was setup in the previous Phase IV and it fully reported in Appendix A. A dynamic model movie of the magnetic field flux was also prepared for evaluating maximum flux and magnetic field saturation levels. All components and regions of the motor were within acceptable levels of all requirements.

The designed inverted PMSM motors have a generally flat and favorable torque profile versus rotational speed. Based on these models, prior to deduction for bearings and seals, the 6.91 cm (2.72 inch) OD axial inverted motor is estimated to generate 4.18 KW (5.61 Hp) power at 10,000 rpm with a 4 Nm (2.95 ft-lbs) torque for every 30.48 cm (12 inch) of power section. The 6.91 cm (2.72 inch) OD radial inverted motor should generate 5.03 KW (6.74 Hp) with 4.8 Nm (3.54 ft-lb) torque at 10,000 rpm for every 30.48 cm (12 inch) of power section. The 4.29 cm (1.69 inch) OD radial inverted motor should generate 2.56 KW (3.43Hp) power with 2.44 Nm (1.8 ft-lb) torque at full speed 10,000 rpm for every 30.48 cm (12 inch) of power section.

Task 2 – Identify Seals for the Motor.

Based on the motor design, operating temperature, external motor pressure, motor specifications and size constraints, seal mechanisms were studied to meet these specifications. This was perhaps the most problematic of the non-electromagnetic elements since we were dealing with rotating seals AND the initial desire for a gas phase in the interior power section AND the requirement of NO possible (salt) water encroachment into or metal shavings in the motor power section AND dealing with pressure increases/changes in the motor section due to:

- going into the hole (increasing external hydrostatic pressure)
- temperature increase due to going into the hole (thermal gradient)
- temperature increase due to bearing friction during operation,
- temperature increase due to motor losses during operation

Then, subsequent cooling for just the opposite conditions from ‘pulling out of the hole’ or stopped motor operation. No estimates of the pressure changes due to these effects were made, since too many input elements are unknown and must come from prototype testing.

Several engineering design companies have been contacted and visited about availability of such seals. These companies included APS, Kalsi Engineering and several industrial seal catalogs. Basically, no company makes seals for outer rotating elements for the conditions set above. Seals are not effective for very large pressure differentials across them. Internal gas phases prevent balanced pressures across seals, except in very large seals elements. These facts forced a re-evaluation of the motor conditions.

First, the gas phase requirement was dropped to allow a very clean light oil in the motor power section. Second, this necessitated redesigning the motor interior sections to be very smooth to prevent turbulence and erosion at these very high speeds. Alternatively, a coating could be applied to provide this smooth surface.

Third, a seal design was considered that is combined with the journal bearings and spring load all internal motor sections for slight compression. These bearing/seals are then lightly press fitted onto the shaft and housing. The bearing/seal is allowed to slide with internal motor pressure variations. With this movement, the required seal materials can be made of DEVLON, a material used for Impact's High Pressure Slurry Pump valves.

Task 3 - <u>Identify Bearings for the Motor.</u>

Thrust bearings are needed to allow axial forces to be placed on the motor for "weight on bit" forces and shock loads while going in the hole. Reverse light bearings loads are also needed for rotating while pulling out of hole. Thrust bearings at the back and front ends of the shaft base are desired to spread out the required load and for one bearing to serve as backup for the other bearing as they wear. Specific dynamic thrust loads of 0.45 N/cm2 (20 lbs/in2) in normal operation and specific static shock loads of 4.5 N/cm2 (200 lbs/in2) are expected from previous Table 2. Static reverse loads of up to the strength of the pipe can be expected when pulling out of a stuck condition (where the drillstring is held at or below the motor in question.

Journal bearings are also needed to keep the centered for rotation during side loads of 445 N (100 lbs) causing bending and twisting during drilling operations. These bearings keep the internal static/non-rotating portions from colliding with the external rotating portions of the motor. The internal sections of the bearings should allow for pressure equalization during running in and pulling out of the well and operation cycles.

Thrust bearings for axial configured motors also keep the required air gap between the stator and rotor in the power section. Journal bearings for radial configured motors keep the required air gas between the stator and rotor in the power section during operation. This 'air-gap' was set at 2 mm (0.0787 inch) with absolute tolerance to keep rotating parts from touching set at 1 mm (0.39 inch). In these cases the bearing surface must be kept as close to the power section as possible.

It was quickly determined that roller or needle bearings were not sufficient for these ultra-high speeds. Magnetic bearings were considered since power is available downhole, but the estimated power demand and lack of ruggedness ruled out this possibility. Metal to metal bearings are highly regarded because of the absolute need for keeping close tolerances with the air-gap. Coating these bearings (e.g., General Magnaplate Coatings) would give extra wear life but loss of the coating could allow shift in air-gap tolerances. Hydrodynamic bearings allow a film of lubricant to coat the metal faces of the bearings for less wear and longer life. Variable lubricant film thickness due to viscosity and heat can cause loss of tolerance control. This was considered possible with a metal to metal backup for the absolute tolerance control. However, no hydrodynamic bearings for inverted configurations (outer surface rotating) were found.

Required structural materials (potential) listings are given in Appendix B. Since these bearings will be near the power elements, non-magnetic stainless steel is the favored bearing material for construction.

To keep the 2 mm (0.0787 inch) gap between rotor-stator, a hard metal-metal stop at 1 mm (0.039 inch) with a 1mm (0.039 inch) coating and/or hydrodynamic film was decided the most likely viable bearing candidate. Furthermore, a combined thrust and journal bearing would work best for these motors to same on space and cost. A search of patented and industry available bearings/seals was made and none were found. Since none are available in an inverted configuration, a new combination inverted hydrodynamic bearing and seal was designed, but not prototyped and tested. Combination bearings save space and the lubrication feature can be shared. These designs are considered proprietary and will be patented in the near future, if warranted. Illustration drawings of the new bearing are shown in Appendix C.

The specific difference is that these new bearings are combination journal and thrust bearings and utilize the outer rotating ring’s centrifugal forces for pumping lubricant through the bearing’s static channels. Sealing elements are installed on the inside and outside of the bearing surfaces and lightly pressed onto the shaft and housing so that they do not rotate, only slide a minor amount. Devlon was found to be a good abrasive resistant material for this application.

Task 4 - Final motor design and Reporting

The finalized geometries of the bit, hole and motor are given in Table 11 below. Finalized estimates of motor power and torque outputs are given in Table 12 below. Final motor drawings are shown in Appendices D, E and F for each motor to coincide with the geometries listed in Table 11 below. Specific details are not given due to the proprietary nature of the motors.

Table 11- Finalized Bit/Hole and Motor Geometries

	Hole Size	Motor Housing		Shaft	Internal Channel
	diameter	OD	ID	OD	OD……
RADIAL	8.9+cm	7.62cm	5.69cm	3.18cm	1.91cm
	(3.5+in	3.0 in	2.24in	1.25 in	0.75 in)
RADIAL	6.35+cm	4.29 cm	3.38 cm	1.91 cm	0.95 cm
	(2.5+ in	1.69 in	1.33 in	0.75 in	0.375 in)
AXIAL	8.9+cm	7.62cm	6.35cm	3.18cm	1.91cm
	(3.5+in	3.0 in	2.5 in	1.25 in	0.75 in)

For 300 VAC at the motor leads, the motor output per 30.48 cm (12 inch) of power section are:

Table 12- Motor Power and Torque Output Estimates

Type	Motor OD	Power @ 10,000rpm	Torque……….
RADIAL	6.91 cm (2.72 inch)	5.03 KW (6.74 Hp)	4.8 Nm (3.54 ft-lb)
RADIAL	4.29 cm (1.69 inch)	2.56 KW (3.43 Hp)	2.44Nm (1.8 ft-lb)
AXIAL	6.91 cm (2.72 inch)	4.18 KW (5.61 Hp)	4.0 Nm (2.95 ft-lb)

Material selections are given in Appendix B. Basically only SISI Type S45500 series stainless steels have the very low resistivities, high hardness (Rockwell in excess of 100) and yield strengths in excess of 689 megapascal (100,000 psi) for the metallic parts around the energized motor to minimize magnetic, power losses and heating and provide continuity of the drilling string. These materials will fit for all components.

DELIVERABLES-

1. **Survey of current ultra high-speed bit performance, requirements and desired design capabilities. Sample of available ultra high speed drilling case studies will be included.** There are no bits nor cutters that can be utilized for drilling at these ultra-high rotational speeds even for microhole sizes. The key limitation is the velocity of the outer tip cutting elements - and not rpm, per se. Diamond impregnated bits currently have the closest capabilities, followed by Technology International's TSP bits and other thermal stable designs. TerraTek is currently performing a study "Smaller Footprint Drilling System for Deep and Hard Rock Environments; Feasibility of Ultra-High-Speed Diamond Drilling", DE-FC26-03NT15401 for the U.S. Department of Energy on ultra-high speed drilling evaluation which should be ready in 2008.

2. **Summary of bit loading characteristics for ultra-high speed applications.** Microhole bits of less than 9.53 cm (3.75 inch) with specific weight-on-bit loading of about 0.45 N/cm2 (20 lb/in2) and requiring a maximum of 20 Nm (15 ft-lbs) torque were identified characteristics required for ultra-high speed applications. Less equivalent weight on bit (force on bit cutters) require less torque for drilling.

3. **A set of screening criteria for designing ultra high-speed motors for deep, harsh environment, and ultra-slim hole or microhole drilling conditions.** For a 1524 meter (5000 foot) depth requirement, hydraulic studies showed that a nominal sized 1.25" or 1.5" tubing was required at minimum. This meant that a minimum sized motor of 4.29 cm (1.69 inch) would fit that requirement and allow for transmission with a bit/ mill through 2" nominal tubing. Standard current motors to drive 4-3/4" bits are normally 3" OD up to 3-1/2". Travel with a bit through 4-1/2" casing (11.43 cm with an ID of 9.4cm (3.7 inch)) would require closer to the 7.62 cm (3 inch) or smaller OD motor size. Thus 4.29 cm (1.69 inch) and 6.92 cm (2.72 inch) OD motors would provide the full range of microhole and slim-hole drilling options required. Bit sizes and flow rates required to clean the hole can be found in the hydraulic study provided in Phase I above. Relatively any fluids can be used, but it recommended that ASJ, with specific internal

flow channel sizes indicated, be utilized for any hard rock and high temperature conditions.

4. **A finite element model of two sizes for an inverted configured, DC electric motor designed for ultra high-speed service.** Three (3) models were studied with Finite Element Analyses that were performed by Dr. Fahimi and summarized above in the discussion of Phases IV and V and shown more fully in Appendix A.

5. **Simulations of the motor performance under various expected loading situations.** Dynamic FEA models were performed by Dr. Fahimi and summarized above in the discussion of Phase IV and V and more fully in Appendix A. Short movies of the simulations were also prepared.

6. **Final motor design based on findings of the study, including prototyping ready CAD drawings, simulations, material specifications and recommended operational loading.** Final SolidWorks computer 3D models were developed based on the FEA work performed. In addition, a listing of possible material selection was given in Appendix B with AISI S45500 stainless steel identified as the best material based on hardness, tensile strength and low resistively. The final motor design, including model, materials and recommended operating loads were given in Phase V, Task 4 and shown in Appendices D, E and F. Although this particular ultra-high (rotational) speed motor version will not be built immediately, a 6.91 cm (2.72 inch) OD radial, 1000 rpm speed version of this electric motor is being built by Impact under an Oklahoma Center for the Advancement of Science and Technology (OCAST) grant for “Proof of Concept” leading up to commercialization. Thus specific CAD drawings for manufacturing are considered proprietary and not disclosed in this report.

7. **Names of potential motor manufacturers who may consider prototyping.** Potential manufacturers for an electric drilling motor are: Emerson, Reda/Schlumberger, General Electric (earlier FERDA drilling motor study), Woods and Weatherford. None will be contacted until a prototype has been built and tested.

CONCLUSIONS-

Three (3) inverted configured electric PMSM motors were designed for microhole drilling at ultra-high speeds of 10,000 rpm. These inverted configured motors have specific benefits for drilling, including allowing advanced drilling methods (waterjetting, abrasive slurry jetting, other) to be used. The designed PMSM motors have sufficient power and torque when stacked for drilling. New seal methods and bearing designs were required for this application and were designed, but not built or tested. Since no bits can support sustained operation these ultra-high operational speeds, there is no current need to prototype these motors. However, based on this DOE sponsored work, low speed (1000 rpm) inverted PMSM radial motors are now being prototyped for testing and commercialization.

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LIST OF ACRONYMS AND ABBREVIATIONS-

AC - alternating current
BHA - bottom hole assembly
BPD - barrels per day
cm - centimeter
DC - direct current
DOE - United States Department of Energy
FEA - finite element analysis
ft- feet
ft-lb- foot- pounds of force
GPM - gallons per minute
Hp - horsepower
ID - inner diameter
IM - inverted motor configuration
Kg - kilograms
KW - kilo watt
LWD - logging while drilling
Mp - mega pascals of pressure
MWD – Measurement while drilling
N - Newtons of force
NETL - National Energy Technology Laboratory in Tulsa
Psi - pressure in pounds force per square inch area
OCAST - Oklahoma Center for the Advancement of Science & Technology
OD - outer diameter
PDM - positive displacement motor
PMSM - permanent magnet synchronous motor
rpm - revolutions per minute
SRM - switched reluctance machine

APPENDICES-

A. Final Electro-Mechanical Analysis Report, by Dr. B. Fahimi
   Including separate report on the Estimation of Iron Losses

B. Final MatLab Material Selection Listing

C. Inverted Thrust/Journal Bearing Drawings

D. Drawings for a 6.91 cm (2.72 in) Radial Motor

E. Drawings for a 6.91 cm **(**2.72 in) Axial Motor

F. Drawings for a 4.29 cm **(**1.69 in) Radial Motor

G. Technical Status Reports to the US Department of Energy / NETL
   1. May 5, 2005
   2. August 2005
   3. March 31 2006
   4. June 6, 2006
   5. January 2007

H. Presentations to the US Department of Energy / NETL
   1. July 27, 2005
   2. September 12, 2005
   3. September 16, 2005 to University of Tulsa Graduate Seminar
   4. November 16, 2005 to PTTC Houston Workshop
   5. April 12, 2006

I. Technical Paper Presented to 2006 IEEE Meeting in Athens, Greece
   "Comparative Evaluation of Axial Flux and Radial Flux Permanent Magnet Synchronous Machines", by Mahesh Krishnamurthy, Babak Fahimi and Kenneth Oglesby

APPENDIX A

Final Electro-Mechanical Analysis Design Report

of an

Ultra-High Speed Inverted Electric Motor for Drilling

by

Dr. B. Fahimi

OBJECTIVE: Design of a high speed permanent magnet synchronous machine for drilling applications.

REQUIREMENTS:

- Inverted rotor (Exterior rotor) configuration
- Torque = 2.1 Nm at standstill
- Power = 3 hp @ 10,000 rpm
- Nominal speed: 10,000 rpm
- Maximum stack length allowed = 12”
- Number of phases: 3
- Design geometries investigated:
    - Radial
    - Axial

OPTIMIZING PARAMETERS:

II. Outer diameter
III. Stack length
IV. Air-gap
V. Generated Torque

I. ASSESSMENT OF AVAILABLE MACHINE TOPOLOGIES

In this study, both these designs have been investigated. Similar constraints are applied to both machines in terms of outer diameter and speed. Table I presents some pros and cons of the machine geometries being investigated. A comparison based on our overall findings has been presented in the concluding section of this report.

Table I: Comparison between radial and axial machine geometries

Radial PMSM	Axial PMSM
■ More productive when the motor has a longer shaft. ■ Manufacturability is easier.	■ Generally chosen for applications with limited space and for rapid acceleration and deceleration. ■ Expensive to manufacture. ■ Possibility of heating at the stator pole- back iron contact points.

II. CONSTRUCTION DETAILS OF THE HIGH SPEED DRILLING MACHINE:

Motor lamination: The machine that is being designed has a very small outer diameter and stack length. For this purpose, materials had to be chosen that would tolerate higher values of magnetic field densities. M-19 is a very commonly used material for motor laminations. However this alloy was found unsuitable for the field density anticipated. Therefore Hiperco 50A alloy was chosen which has a maximum saturation induction of 1.7 Tesla. This alloy finds typical applications in aircraft motors and generators.

A summary of reasons for this choice are:

- High knee point in BH characteristics (allows high flux densities)
- High D.C. maximum permeability

- Low D.C. coercive force
- Low A.C. core loss
- Higher strength

Table II: Composition of Hiperco 50A steel.

Carbon	0.00 %	Manganese	0.05 %
Silicon	0.05 %	Cobalt	48.75 %
Vanadium	2.00 %	Iron	Balance

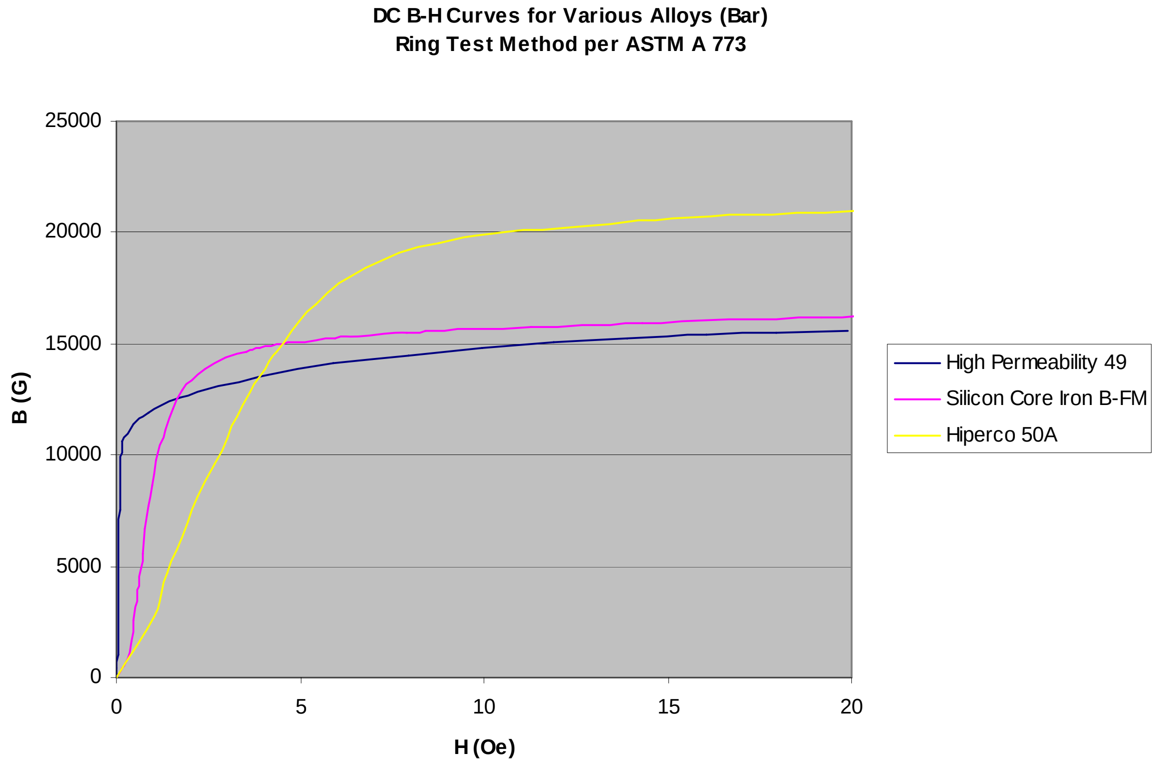


Figure 1: DC B-H curves for various alloys versus Hiperco 50A

Permanent Magnet: A permanent magnet in this machine is used to magnetize the core of the machine. Electrical excitation is then applied to generate torque of a desired magnitude. Choice of magnets is based on the dimension of the machine, available airgap length and other magnetic parameters. For our application, N40SH (Sintered Neodymium Ferrite Boron) was chosen.

Sintered Neodymium Ferrite Boron (NdFeB) is formed by powder metallurgical process. They can be die-pressed or isostatically pressed. Magnetic domains are aligned during pressing by application of a magnetic field to optimize magnetic performance to suit requirement.

Characteristic features of conventional NdFeB:

- High Maximum Energy product ($(BH)_{max}$).
- Temperature stability unaffected up to 180 °C, ideal for temperature < 80 °C.
- Lower corrosion and oxidation than Samarium Cobalt (SmCo).

Table III: Magnetic properties of Sintered NdFeB

Br (kiloGauss)	12.4 -12.8	BH_{max} (MGOe)	38 - 41
Hc (kiloOersted)	>11.8	Curie Temp. (°C)	340
Hc_i (kiloOersted)	>20	Max Op. Temp (°C)	150

III. FINITE ELEMENT SIMULATION OF VARIOUS MACHINE CONFIGURATIONS

Type 1: Radial configuration

In this configuration, the rotor is mounted with a diameter than that of the stator. It is called a “radial” machine owing to the flow of magnetic flux in the radial direction. It is also an “inverted” configuration since conventionally stator is placed around the rotor. This model has a 3-phase, 4-pole configuration.

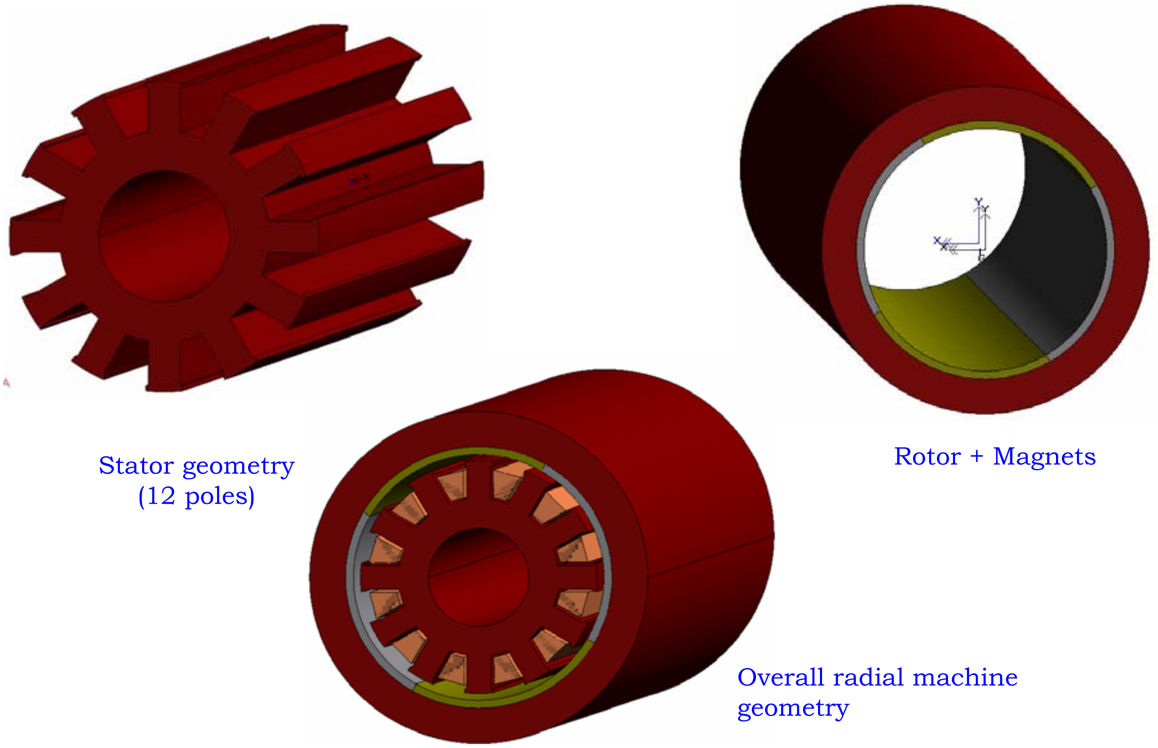


Figure 3: FEA model of radial geometry

Design Geometry 1: 1.69 inch diameter

- Rotor OD = 1 11/16”
- Stator OD = 1.1802”
- Shaft OD = 0.5”
- Air gap length = 2 mm
- Phases = 3
- **Stack length required = 12”**
- No. of turns = 65
- Current = 2A

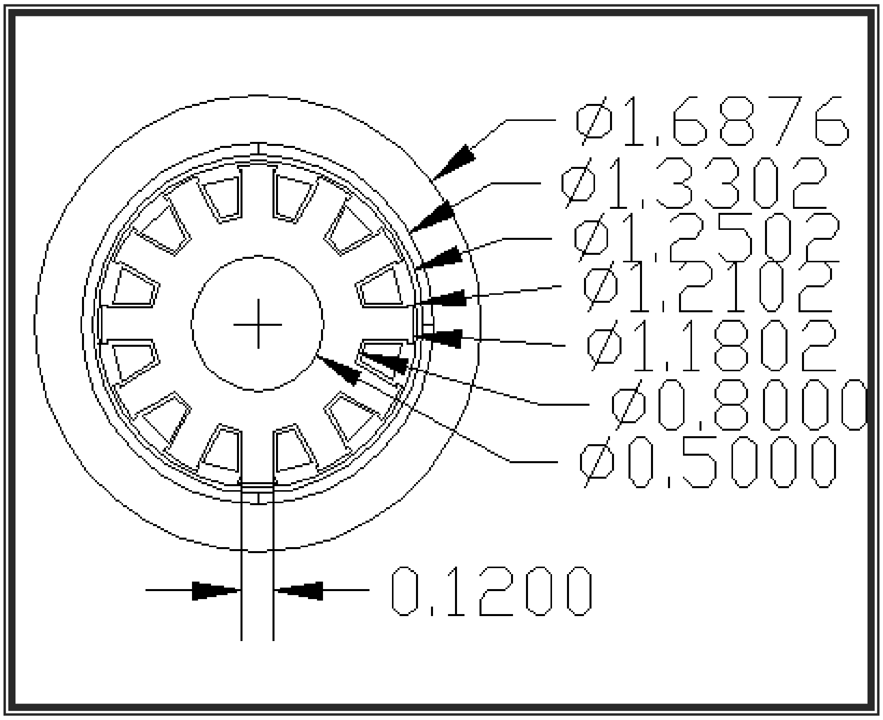


Figure 2: Dimensions of the radial 1.69” geometry

Note: In the 1.69” geometry, the size of the bore cannot be made more than half the overall OD of the machine. Therefore in this machine, only 0.5” has been chosen for the shaft. Further modifications were not made.

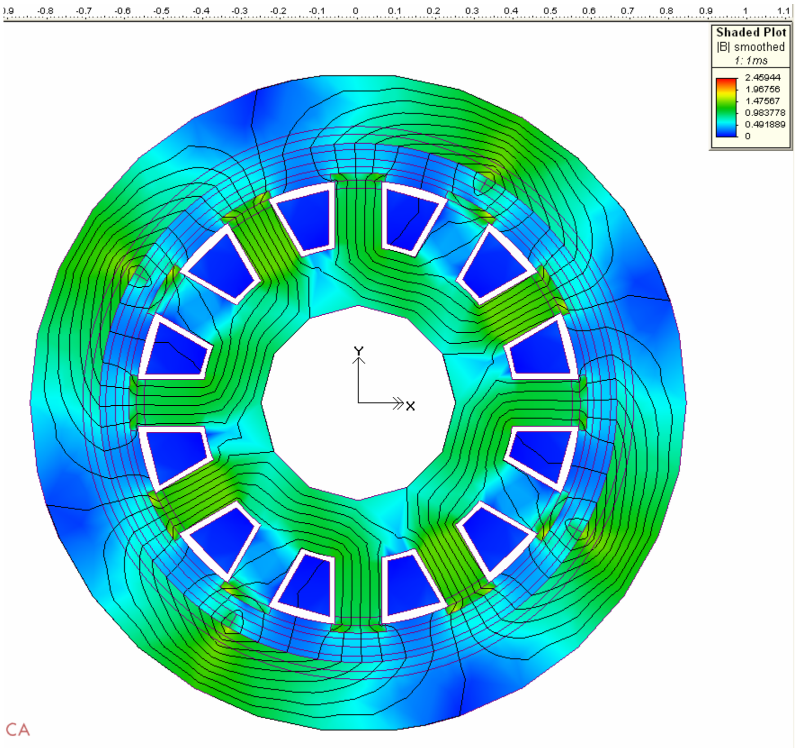


Figure 3: Flux density distribution for 3A, 65 turns for 1 ft long stack.

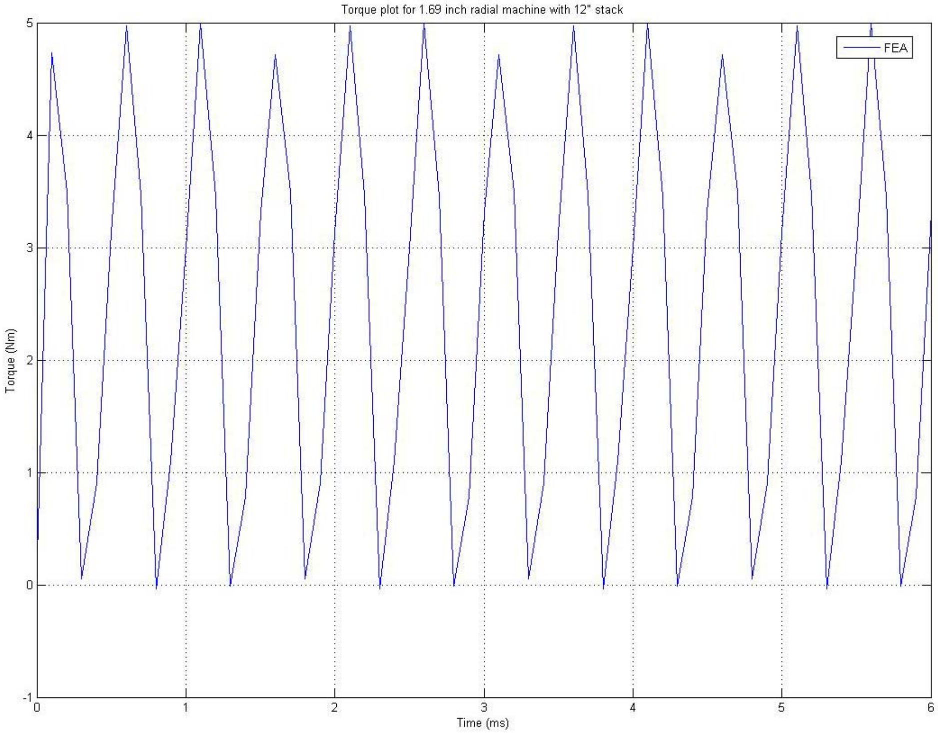


Figure 4: Torque plot for 2A, 65 turns for 1 ft long stack. Average torque = 2.44 Nm.

Design Geometry 2: 3 inch diameter

- Rotor OD = 2.72”
- Stator OD = 2”
- Shaft OD = 1”
- Air gap length = 2 mm
- Phases = 3
- **Stack length = 6”**
- No. of turns = 65
- Current = 3A

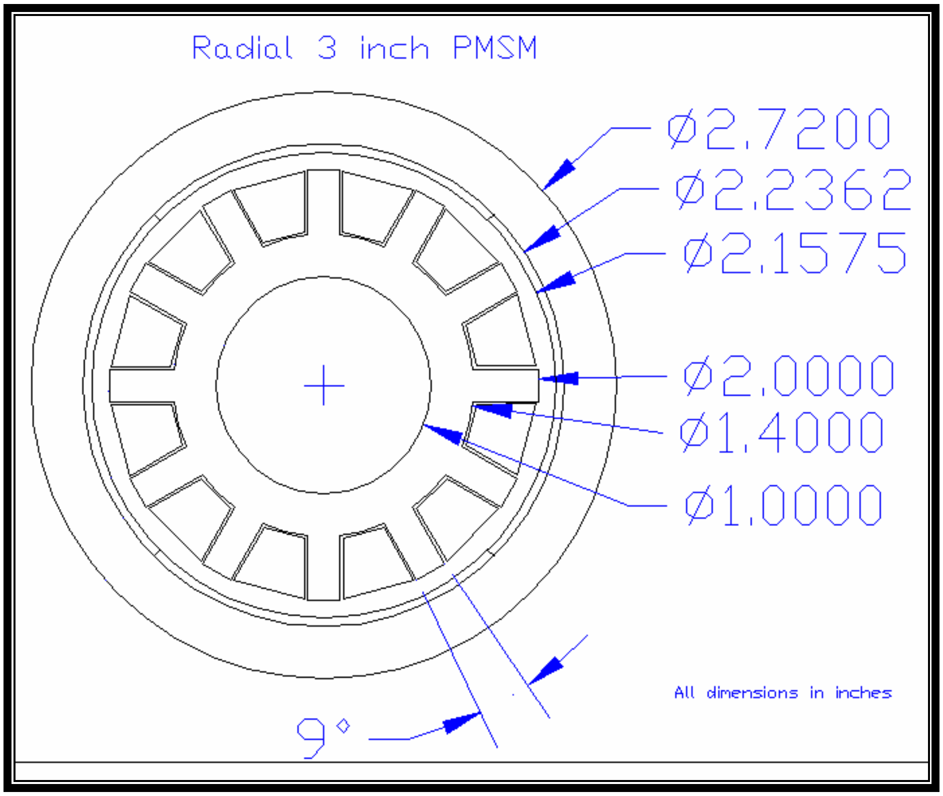


Figure 5: Dimensions of the radial 3” geometry.

Note: *Initially a bore size of 1.25” was targeted. However, increasing the shaft OD to major proportions reduces the area available for the coils to be wound. Additionally there might be saturation in the stator which would result a drastic loss in efficiency. No further modifications were made.*

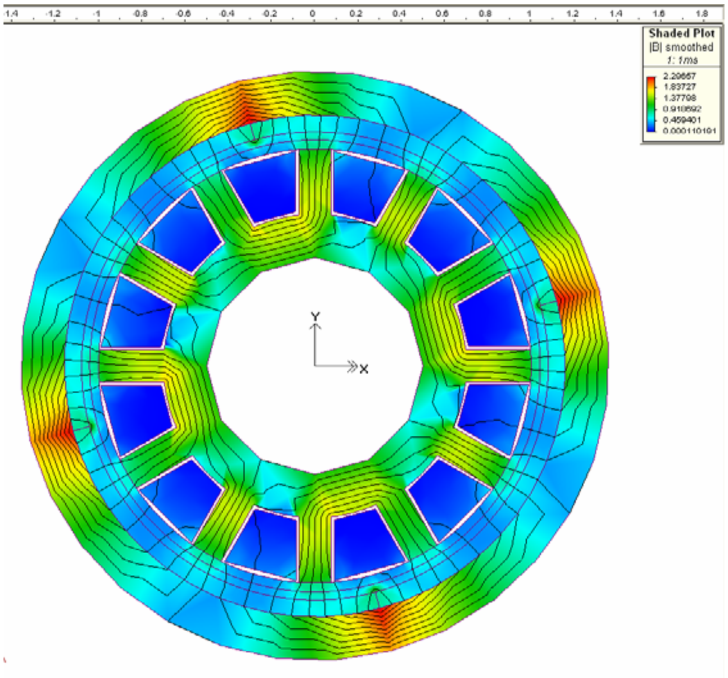


Figure 6: Flux density plot for 3A, 65 turns for 6 inch long stack.

Note: The flux density of 2.2T in the rotor of the machine will not result in an increase in the loss of the machine since the relative change in the level of flux density in the rotor is negligible. In other words, the machine has poles that are shift with the same frequency as the mechanical system.

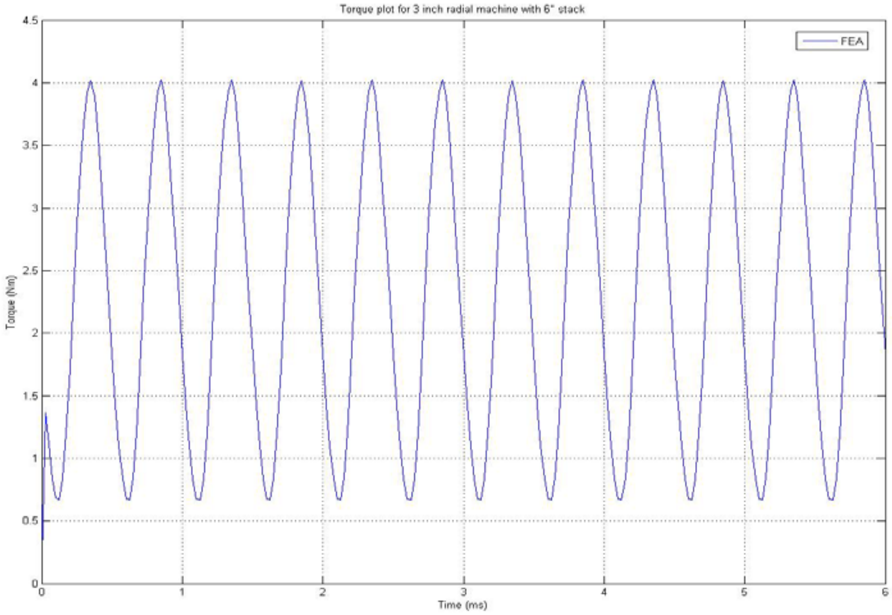


Figure 7: Torque plot for 3A, 65 turns for 6 inch long stack. Average torque = 2.4 Nm.

Type 2: Axial configuration

As the name suggests, this configuration has magnetic flux flowing along the z-axis (stack) of the machine. The rotor and stator of the machine are mounted along the axis.

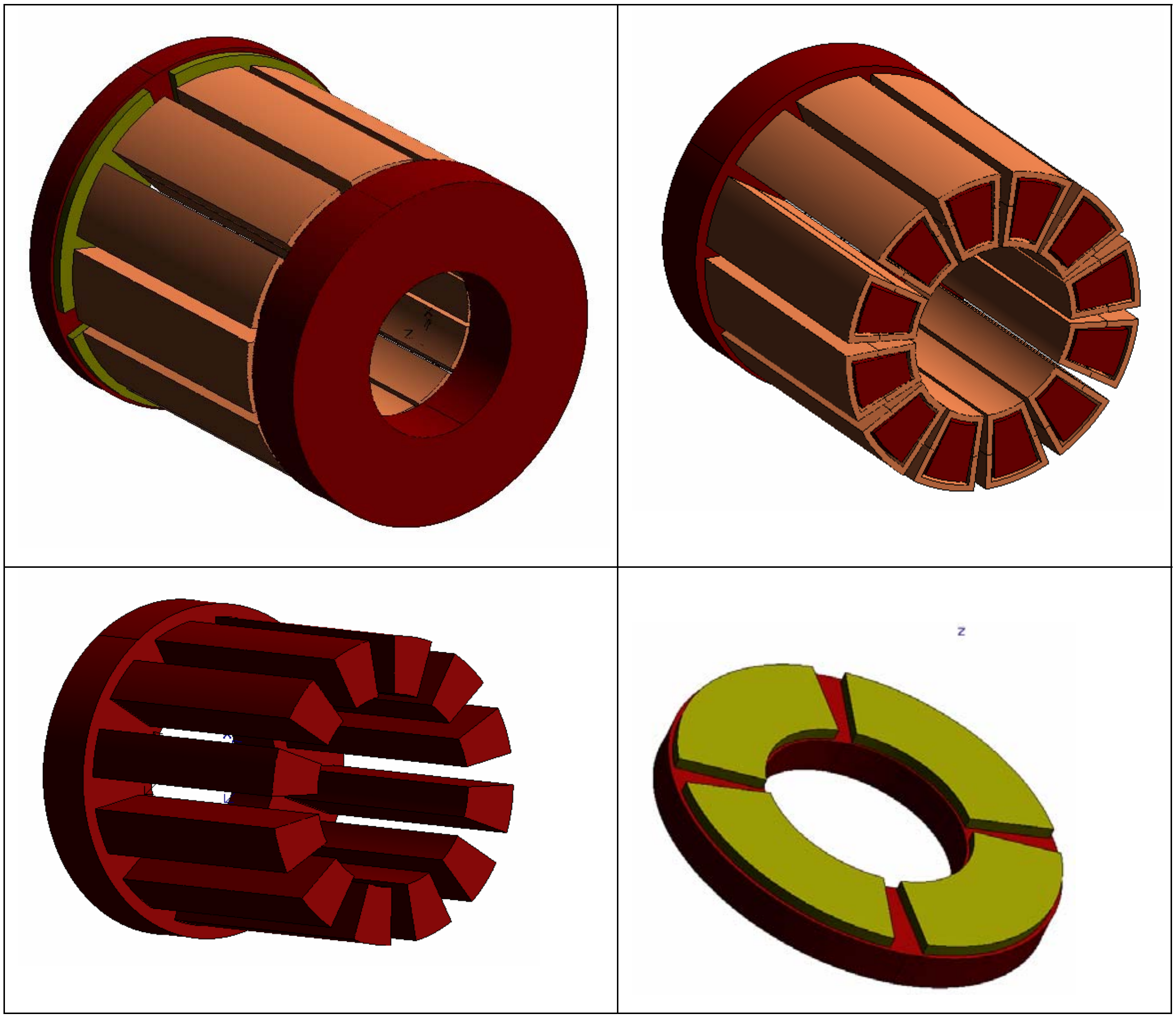


Figure 8: Finite Element model of axial PMSM

This configuration is significantly different in operation from its radial counterpart since flux flows along the y-z plane while motion of the rotor is along the x-y plane. Our investigation suggests that majority of the motional forces are generated at the surface of the permanent magnet.

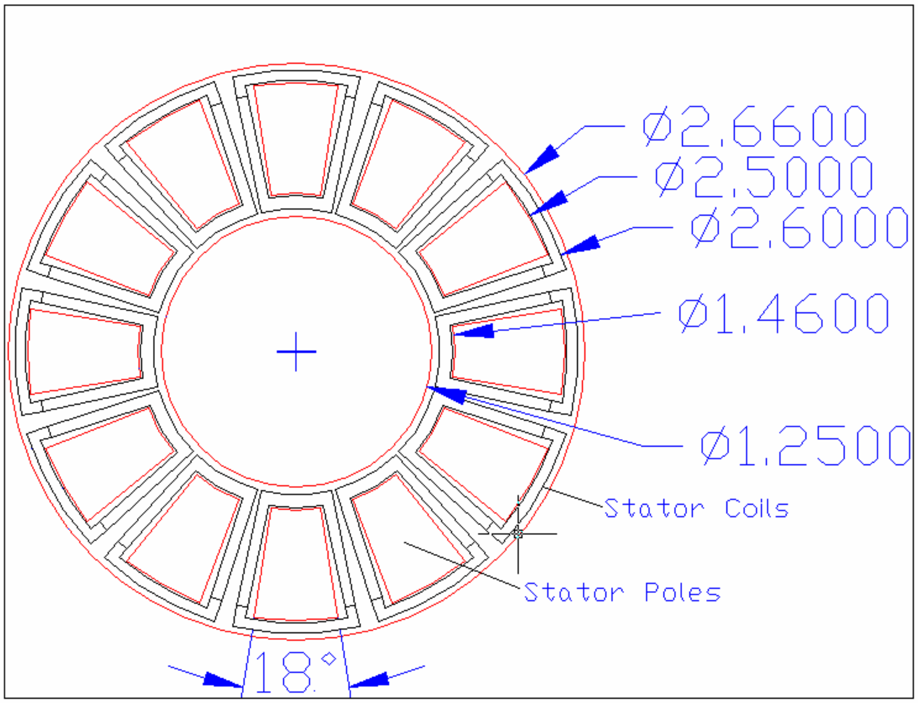


Figure 9: Stator of the axial 3" axial geometry.

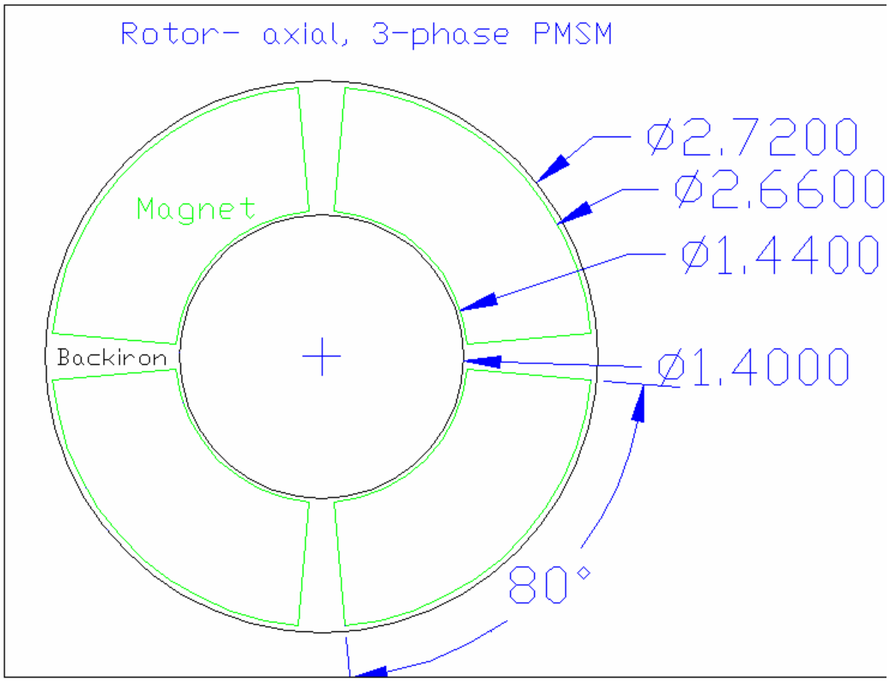


Figure 10: Rotor of the axial 3" axial geometry.

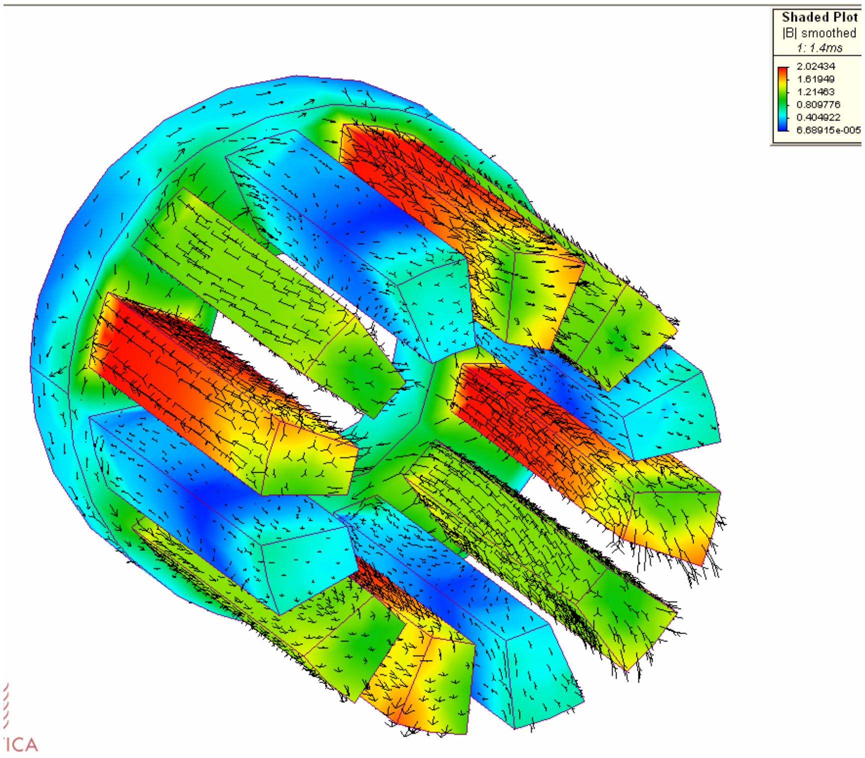


Figure 11: Flux density distribution for axial 3” geometry.

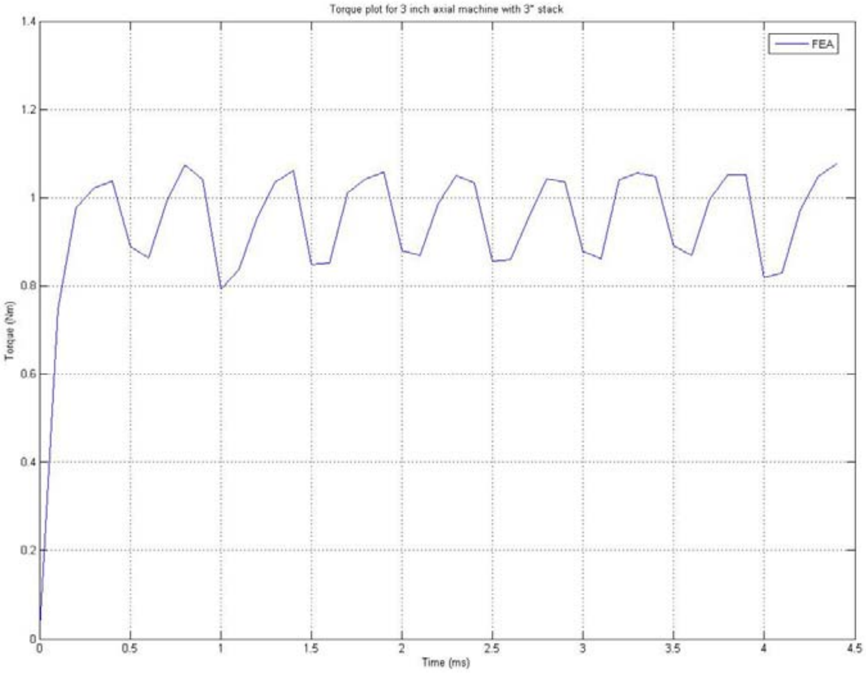


Figure 12: Torque plot for 3A, 200 turns, 3 inch long stack. Average torque = 0.98 Nm.

For a torque of 2 Nm, there would be two machines cascaded. Therefore the overall stack length would be 6 inches. It needs to be mentioned that for a machine-train as mentioned here, appropriate spacing would be required between the two.

IV. POWER ELECTRONICS SPECIFICATIONS FOR ULTRA HIGH-SPEED DRILLING

Methods of transmission of power for the PMSM:

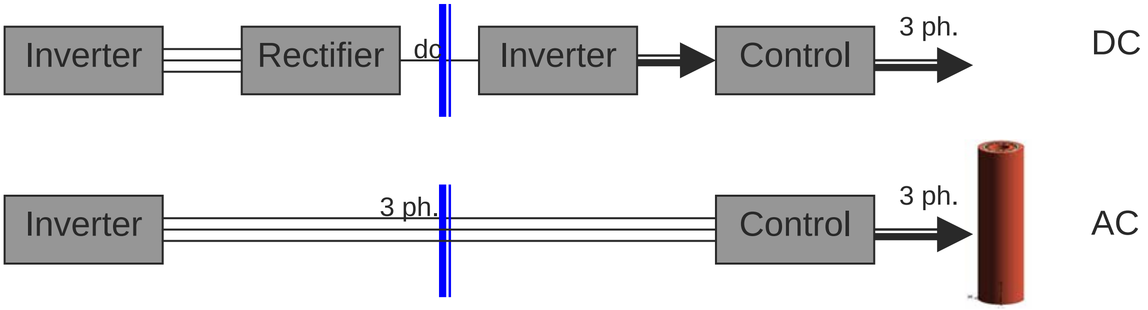


Figure 12: Power transmission arrangements.

Voltage drop across the cable in dc transmission is lower. However ac transmission is suggested. Reasons for this choice are:

- DC transmission would require converter to be placed underground with the machine. This reduces accessibility and impedes corrective measures.
- Signal wires need to be sent in with the dc transmission which would be subject to attenuation. Such an arrangement is not advisable since these wires need to be kept short to avoid introduction of noise and faulty trigger.

Drawbacks of this system are:

- Three ac cables would mean extra cumulative losses in the cables due to inductive reactance.
- Shielding of cables needs to be much better than that required for dc.

- *Copper cable for transmission:*

  Required current = 3A

  Voltage at surface = 208 V

  Including safety factor, Suggested conductor for transmission = AWG 10

  Diameter = 0.1019”

  Resistance per 1000 ft = 0.9989 Ω

  Current capacity = 15A

- *Copper coil winding calculation for machine geometry:*

The sizing of coils has been done very conservatively. Gauge sizes selected have been assumed to be wound with a filling factor of 80%, which is a very conservative number. From the calculations, it can be seen that the area available for the windings is sufficient. The calculation of the number of turns possible and the required number of turns has been shown below. Magnet wires have been used for calculation purposes. Further details and specifications are available at www.mcmaster.com. Here single conductor of AWG 24 has been suggested. These conductors have an outer diameter of 0.022".

- *Voltage drop over 5000 feet long 3Φ copper conductor with 2A current at 208V:*

Supply = 208V, 3-phase
Current = 2A
Depth = 5000 ft
Wire gauge = AWG 10
Voltage drop = 20.9 V
Voltage at receiving end = 187.1 V

V. WINDING SIZE ESTIMATION FOR RADIAL AND AXIAL PMSM

1. High speed radial design (4-pole, rotor OD = 1.69”)

AWG 24 has a current capacity of 5A.

Required current = 3 x 65 = 195 A-T

Available length of slot = 0.35 inch = 8.89 mm

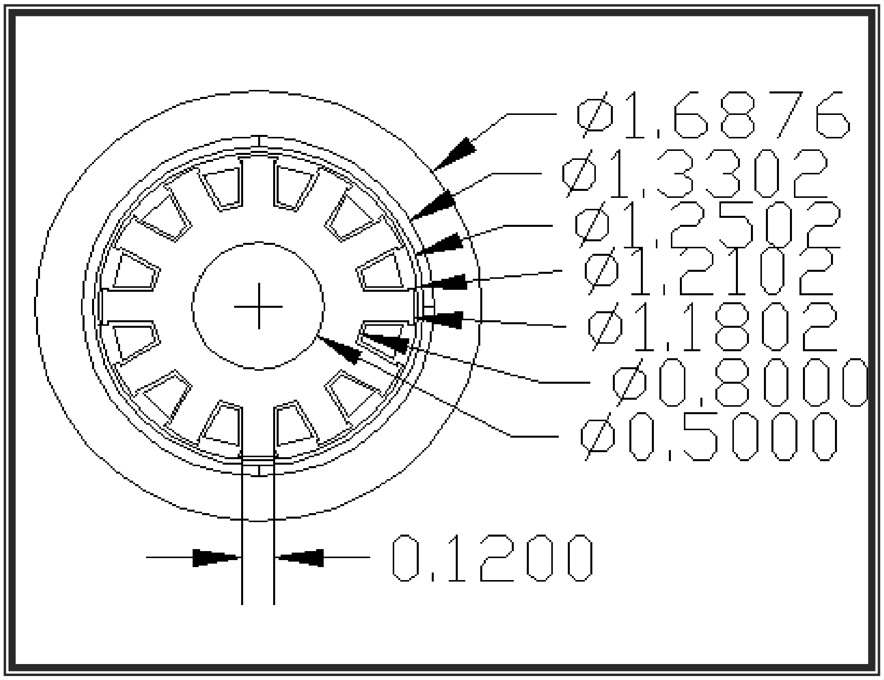
Width available (bottom) = 2.128 mm (= (12[deg] / 360) x pi x d)

where d = 0.8 inch (slot diameter)

Width available (top) = 3.139 mm (= (12[deg] / 360) x pi x d)

where d = 1.18 inch (slot diameter)

Available coil area = 46.8 mm^2



Required conductor AWG for winding = **AWG 24**

Resistance per 1000 ft = 6.385 Ω

Current capacity = 5 A

Diameter of conductor = 0.022” = 0.5588 mm

Area of each conductor = 0.245 sq. mm

Number of conductors possible = ff x (46.8 / 0.245)

= ff x 191

Where ff = filling factor = 0.8 (can be modified)

= 152 turns

Therefore 65 turns with 3A current can be used.

2. ***High speed radial design (4-pole, rotor OD = 3")***

AWG 24 has a current capacity of 5A.

Required current = 3 x 80 = 240 A-T

Available length of slot = 0.3 inch = 15.24 mm

Width available (bottom) = 3.8 mm (= (12[deg] / 360) x pi x d)

where d = 1.4 inch (slot diameter)

Width available (top) =5 mm (= (12[deg] / 360) x pi x D)

where D = 2 inch (slot diameter)

Available coil area = 67 mm^2

Required conductor AWG for winding = **AWG 24**

Resistance per 1000 ft = 6.385 Ω

Current capacity = 5 A

Diameter of conductor = 0.022" = 0.5588 mm

Area of each conductor = 0.245 sq. mm

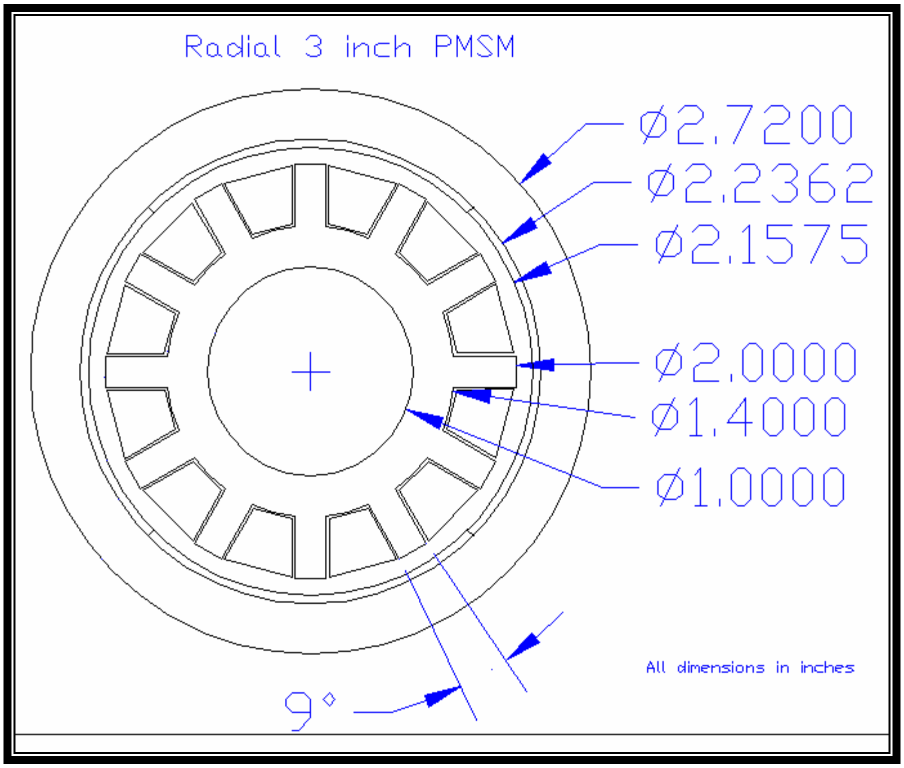
Number of conductors possible = ff x (67 / 0.245)

= ff x 270

Where ff = filling factor = 0.8 (can be modified)

= 200 turns

Therefore 80 turns with 3A current can be used.



3. ***High speed axial design (4-pole, rotor OD = 3”)***

This machine is designed to have concentrated windings. Therefore number of wires in each slot is double the number of turns around each stator pole.

AWG 24 has a current capacity of 5A.

Required current = 3 x 200 = 600 A-T
Available length of slot = 2 inch = 50.8 mm
Width available = 0.05” = 1.27 mm

Available coil area = 65 mm^2

Required conductor AWG for winding = **AWG 24**
Resistance per 1000 ft = 6.385 Ω
Current capacity = 5 A
Diameter of conductor = 0.022” = 0.5588 mm
Area of each conductor = 0.245 sq. mm

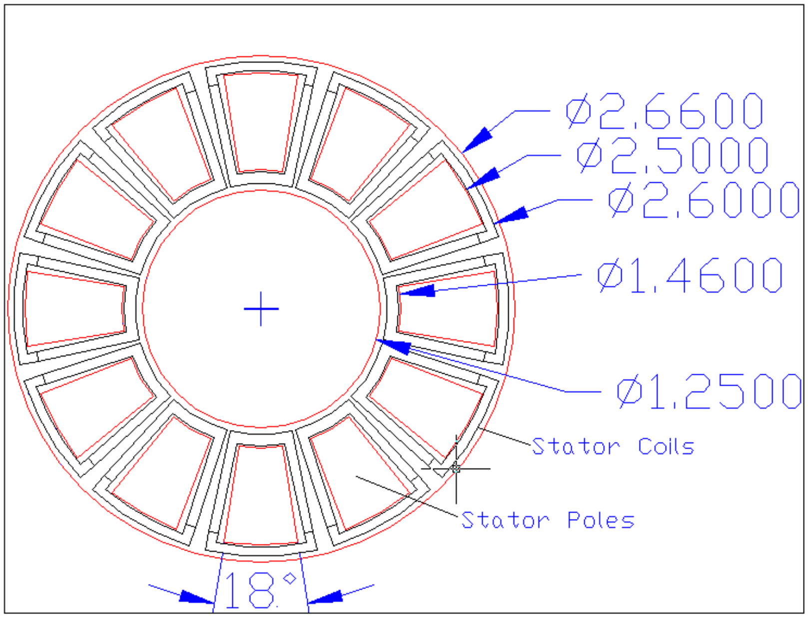
Number of conductors possible = ff x (65 / 0.245)

= ff x 265

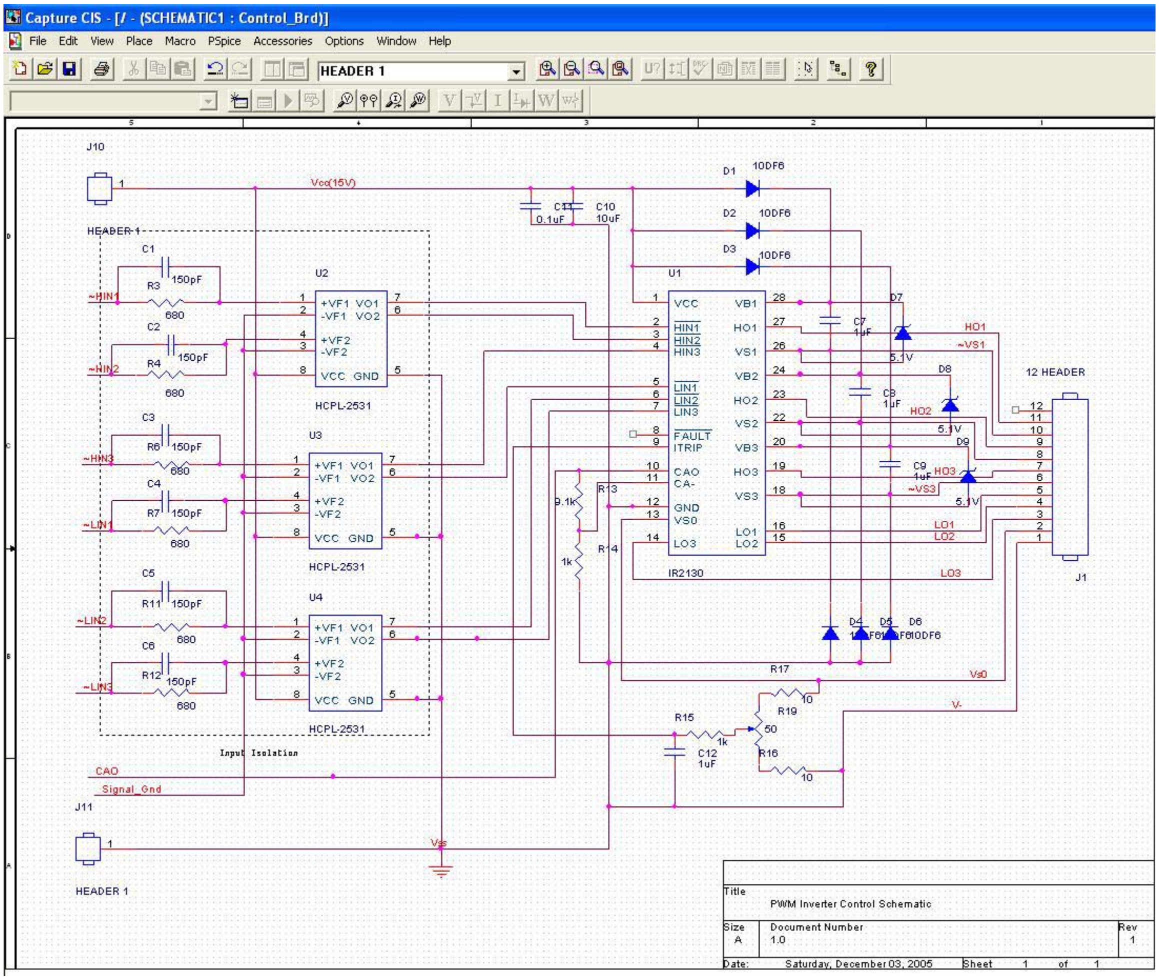
Where ff = filling factor = 0.8 (can be modified)

= 212 turns

Therefore 200 turns with 3A current can be used.



VI. CONVERTER DESIGN FOR 3 PHASE- 4- POLE PMSM

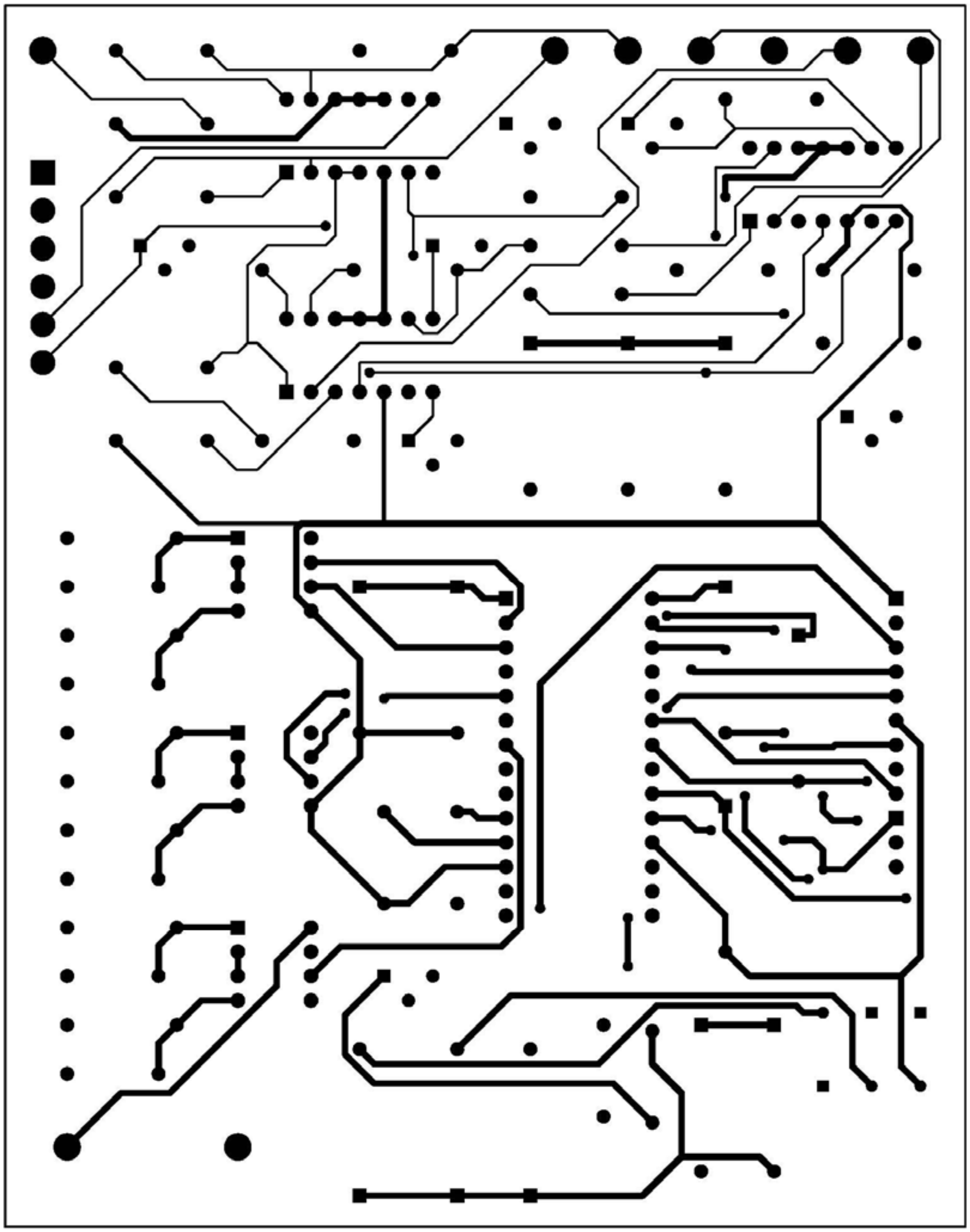


Title
PWM Inverter Control Schematic

Size A
Document Number 1.0
Rev 1

Date: Saturday, December 03, 2005
Sheet 1 of 1

Figure 6.1: Circuit design for control of 3-phase inverter.



PWM_INVERTER-3.zip
Layer: PWM_INVERTER-3.TOP

04 Dec 2005,06:26 AM

Figure 6.2: Top layer for control board PCB of 3-phase inverter.

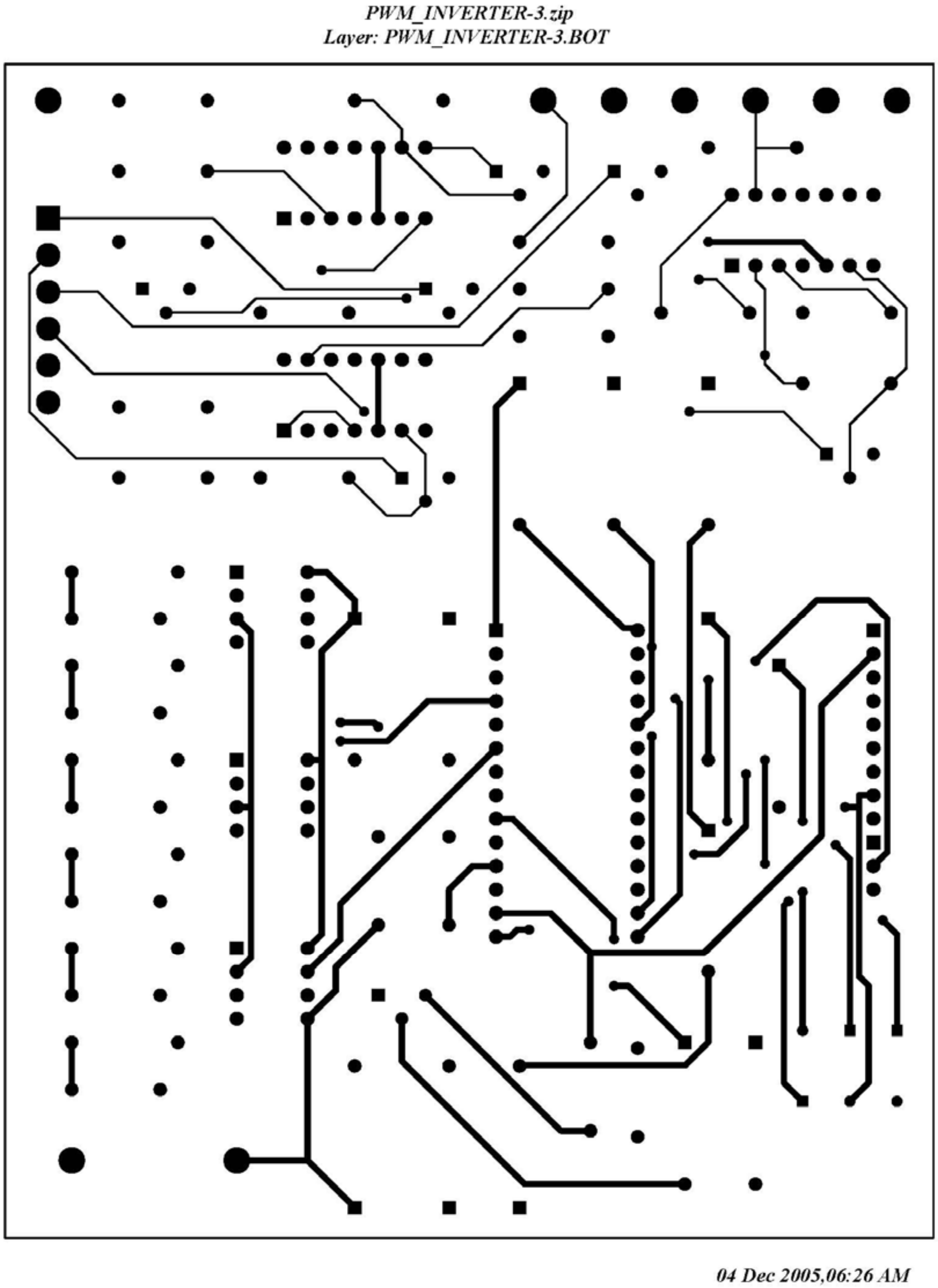


Figure 6.3: Bottom layer for control board PCB of 3-phase inverter.

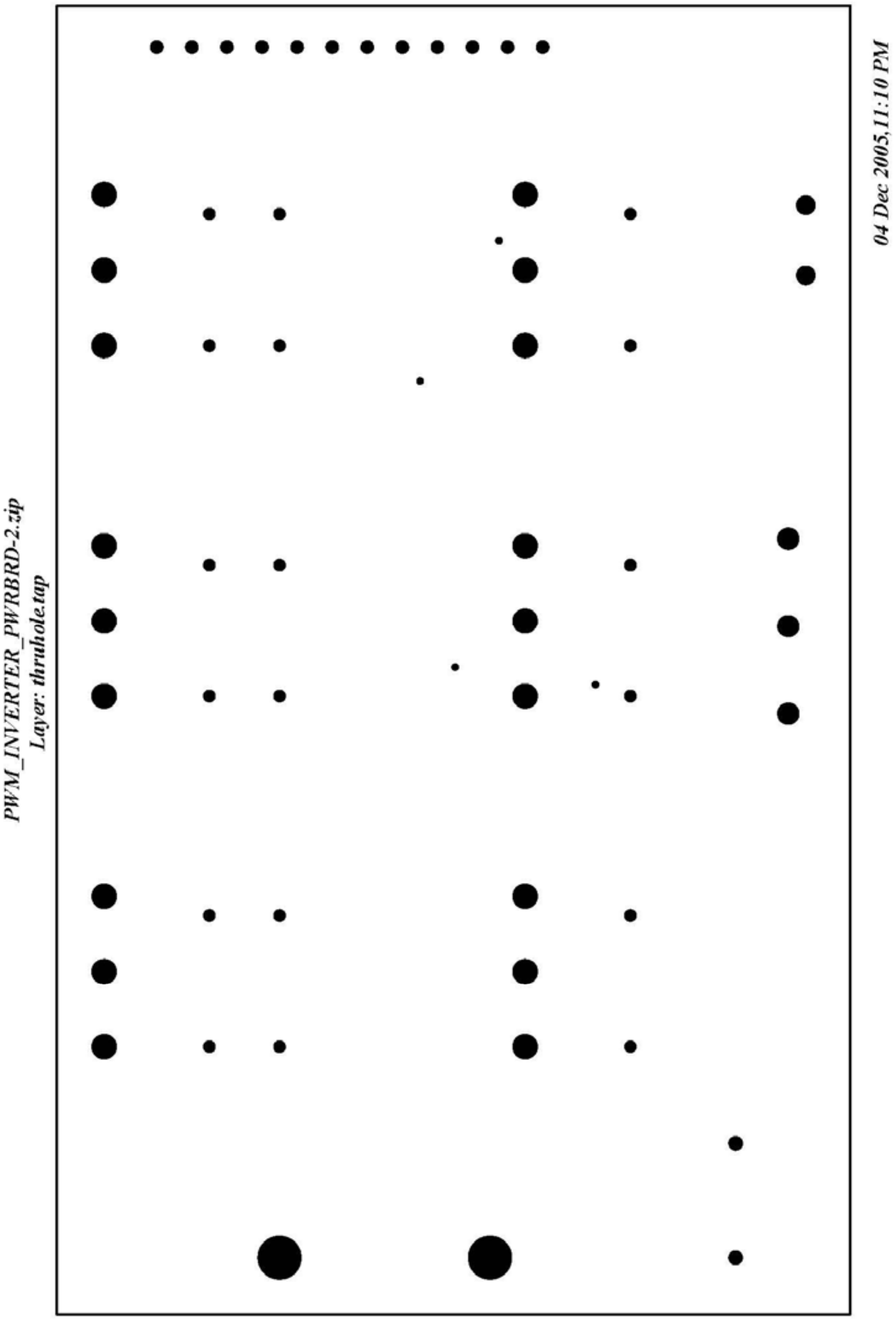
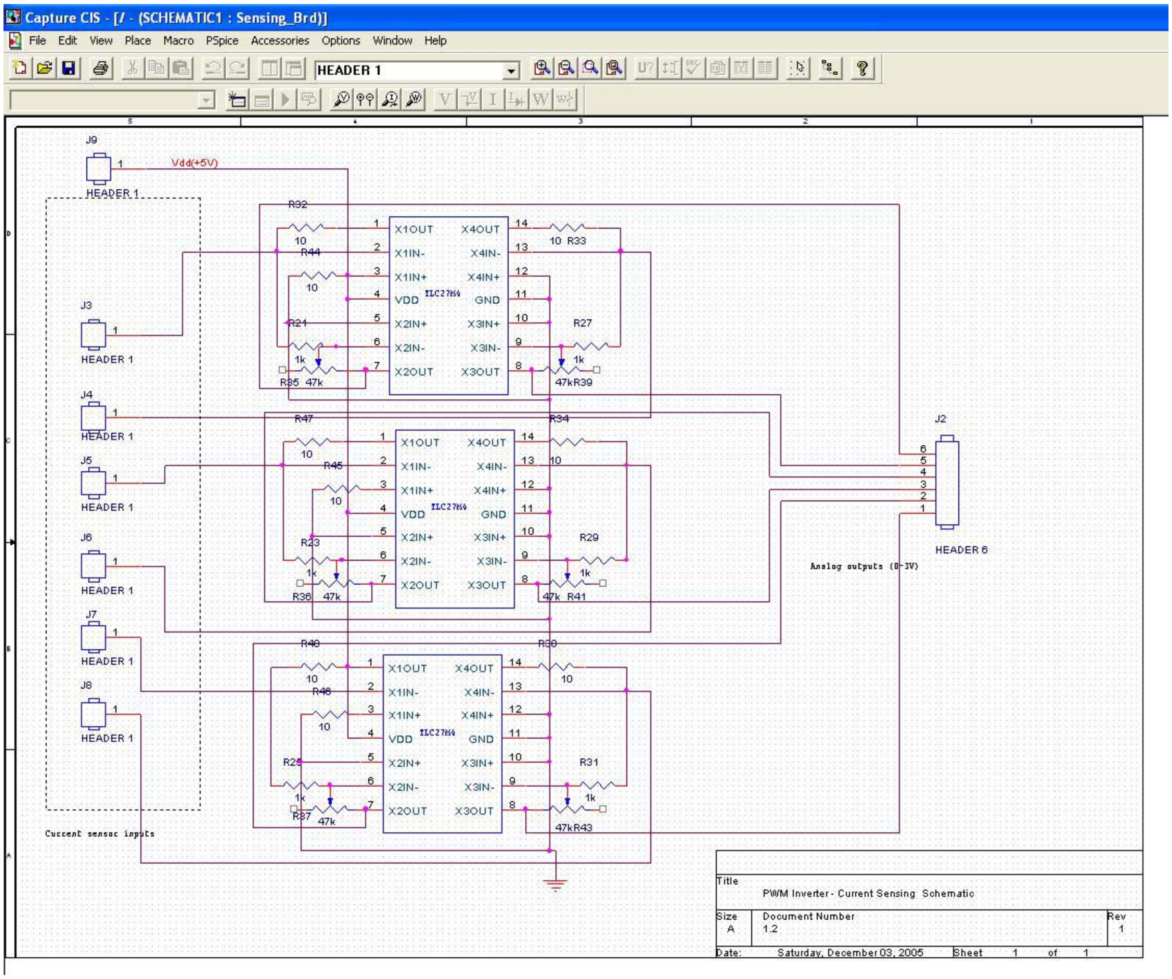
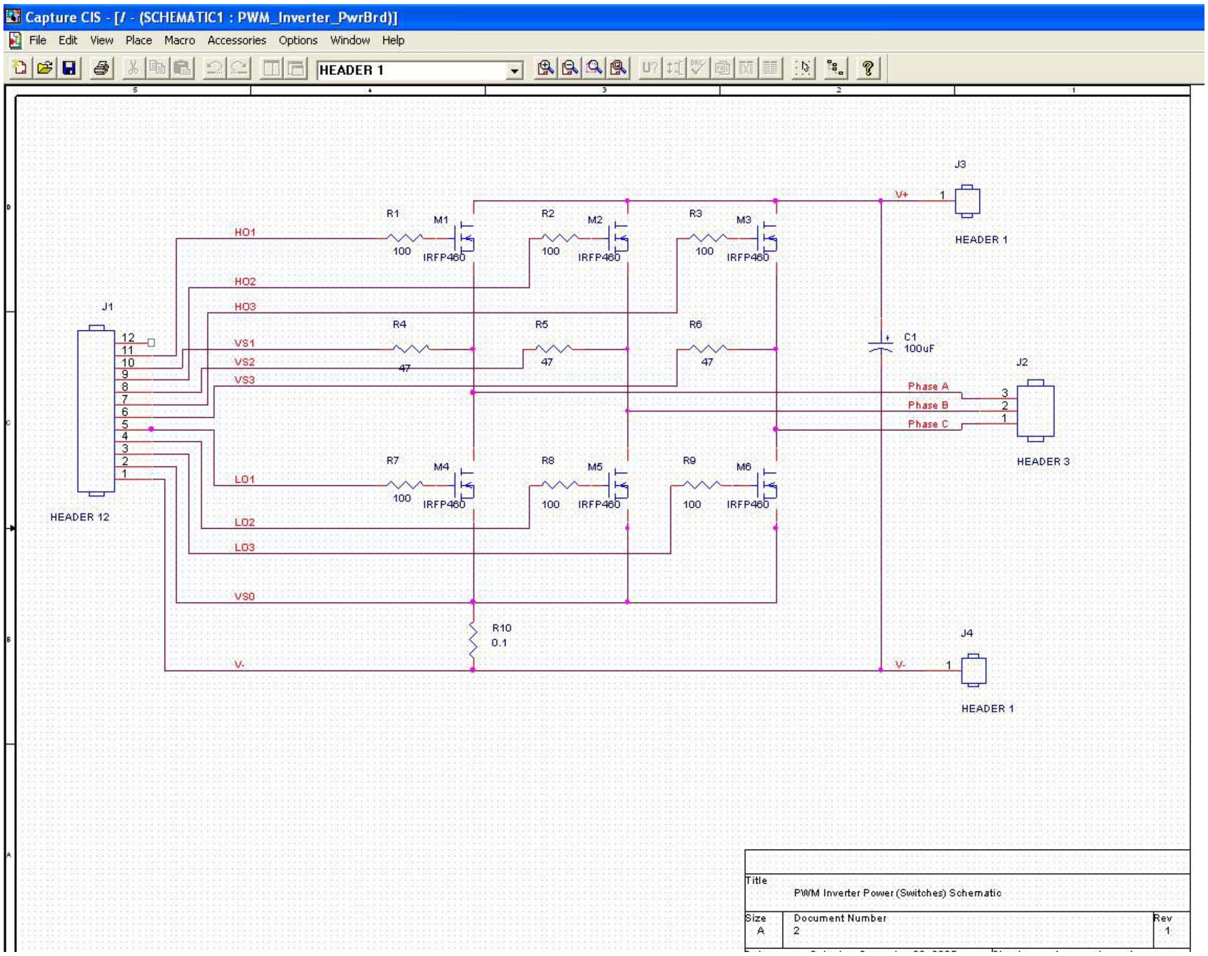


Figure 6.4: Drilling pattern for for control board PCB of 3-phase inverter.



Title
PWM Inverter - Current Sensing Schematic
Size A
Document Number 1.2
Rev 1
Date: Saturday, December 03, 2005
Sheet 1 of 1

Figure 6.5: Circuit layout for phase current sensing.



Title
PWM Inverter Power (Switches) Schematic

Size A
Document Number 2
Rev 1

Figure 6.6: Circuit layout PWM inverter power board.

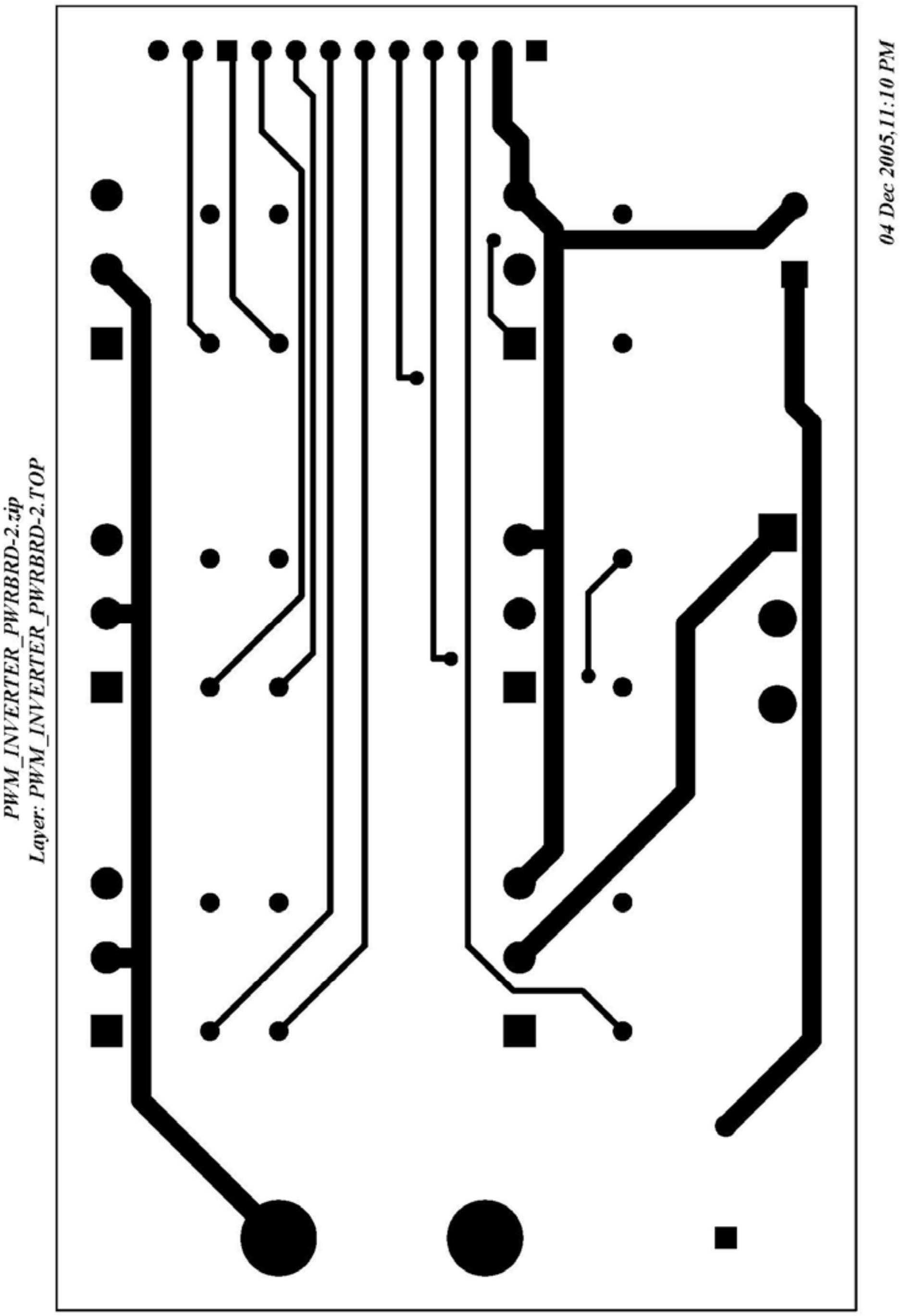


Figure 6.7: Top layer for power board PCB of 3-phase inverter.

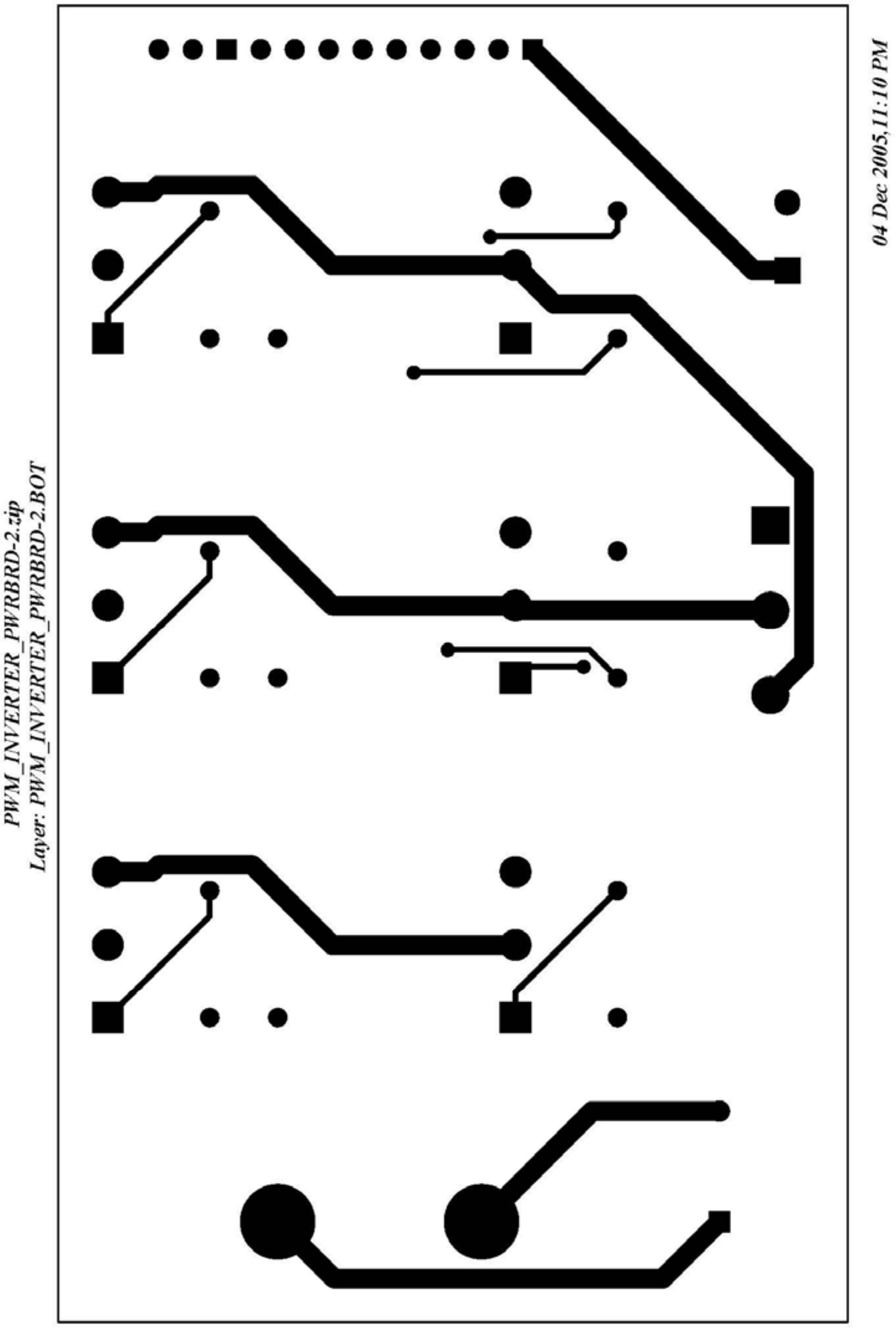


Figure 6.8: Bottom layer for power board PCB of 3-phase inverter.

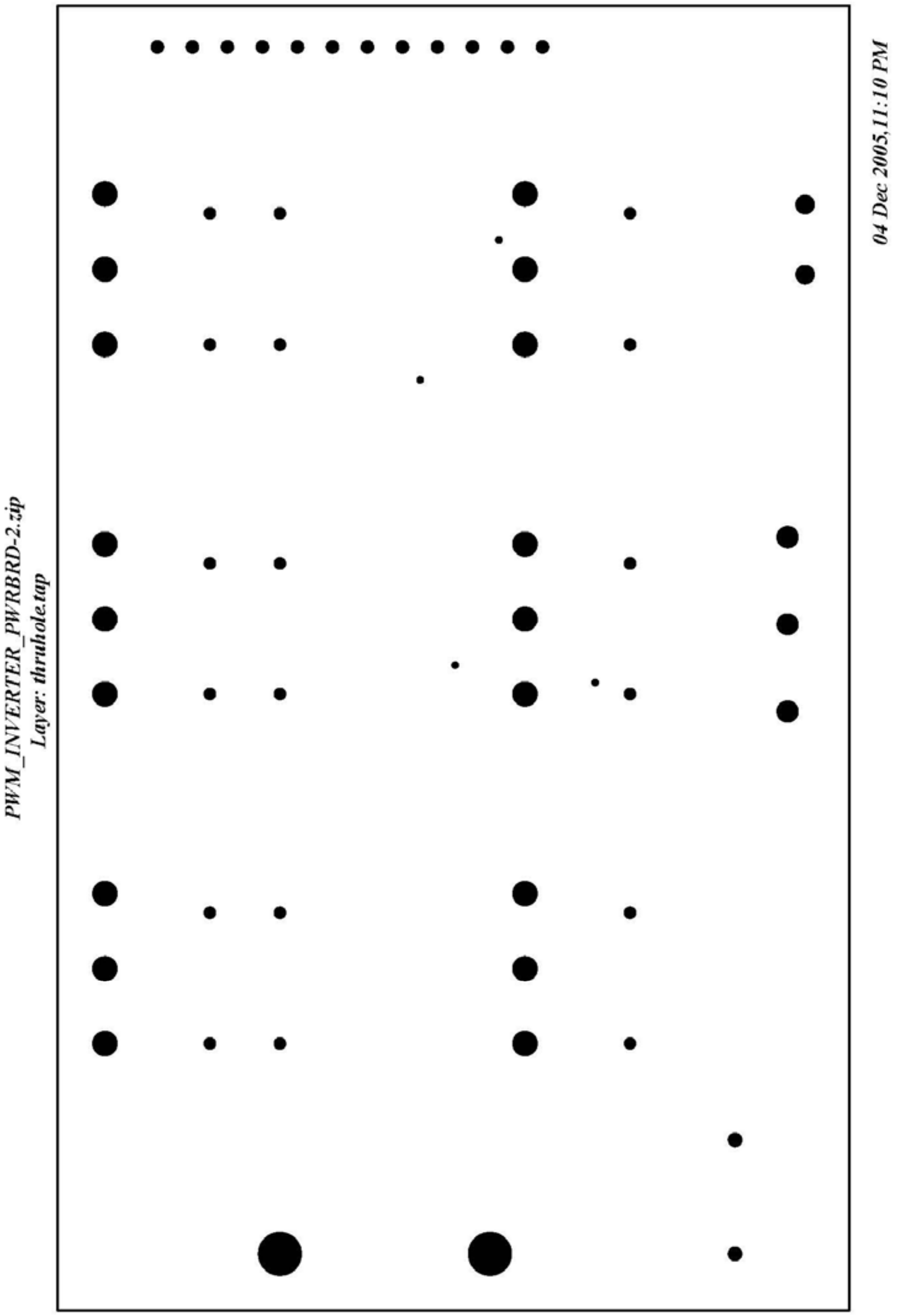


Figure 6.9: Drilling pattern for power board PCB of 3-phase inverter.

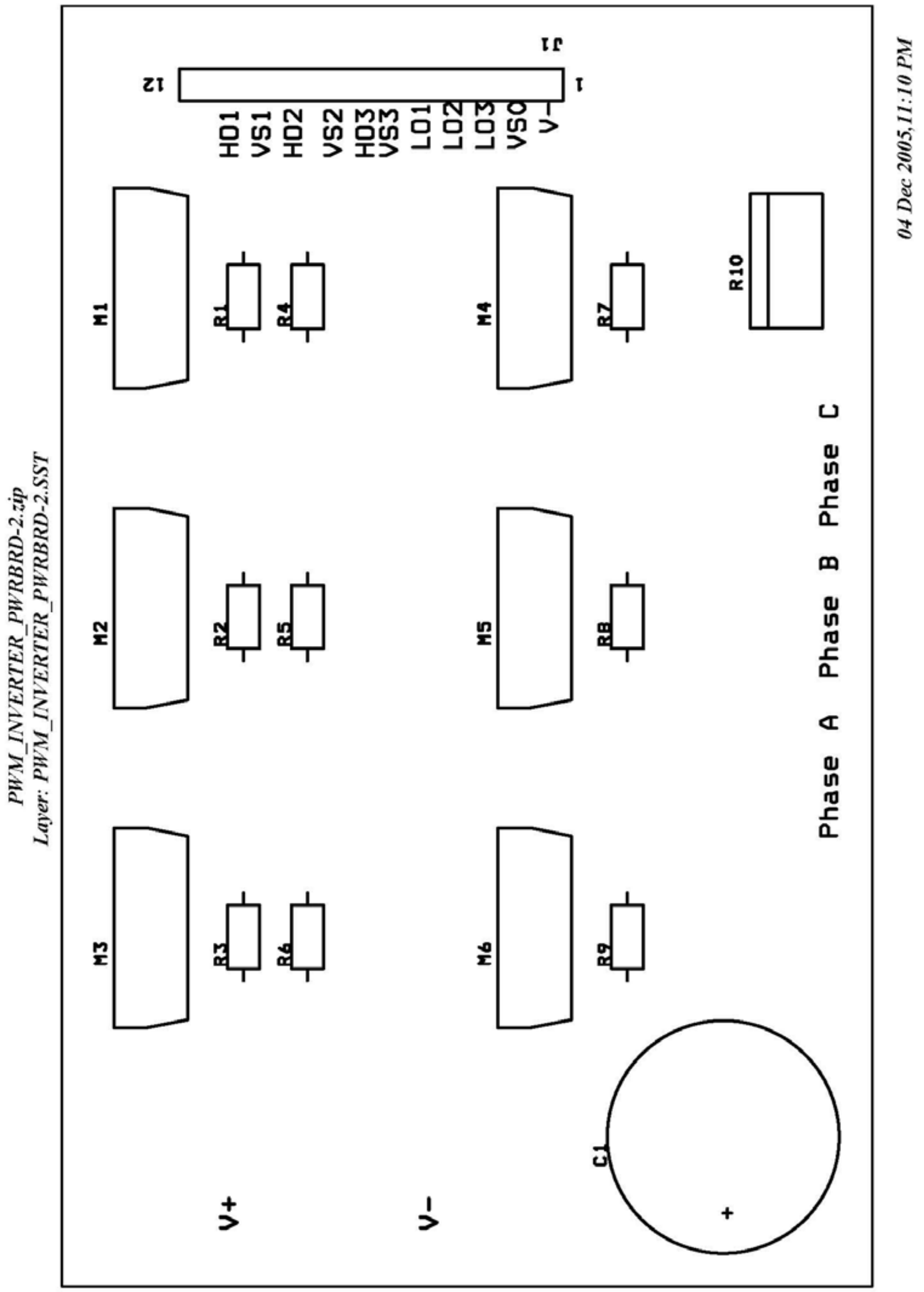


Figure 6.10: Component placement pattern for power board PCB of 3-phase inverter.

APPENDIX B

Final MatLab Structural Material Selection Listing

for an

Ultra-High Speed Electric Inverted Motor for Drilling

Material Name	Electrical Resistivity, ohm-cm	Thermal Conductivity, W/m K	Tensile Strength, Yield, PSI	Hardness, Rockwell B	Link - Click cell for complete information.
Allegheny Ludlum Type 316 Stainless Steel, UNS S31600	0.000074	14.6	29,733	95	Allegheny Ludlum Type 316 Stainless Steel, UNS S31600
Sandvik Ti grade 2 Strip Steel	0.056	16.4	52,504	???	Sandvik Ti grade 2 Strip Steel
Kaiser Aluminum Alloy 7068 T6, T6511 Rod & Bar	0.00494	190	99,061	91	Kaiser Aluminum Alloy 7068 T6, T6511 Rod & Bar
Fecralloy™ 145 Electrical Resistance Steel	0.000145	16	79,771	96	Fecralloy™ 145 Electrical Resistance Steel
Fecralloy™ 135 Electrical Resistance Steel	0.000135	16	79,771	96	Fecralloy™ 135 Electrical Resistance Steel
Fecralloy™ 134 Electrical Resistance Steel	0.000126	16	79,771	96	Fecralloy™ 134 Electrical Resistance Steel
HPA COBALT Alloy 6BH, Wear Resistant, (Co-Cr-W) (UNS R30016)	0.00012	14.8	120,961	110	HPA COBALT Alloy 6BH, Wear Resistant, (Co-Cr-W) (UNS R30016)
HPA COBALT Alloy 6B, Wear Resistant, (Co-Cr-W) (UNS R30016)	0.00012	14.8	90,068	109	HPA COBALT Alloy 6B, Wear Resistant, (Co-Cr-W) (UNS R30016)
Resistalloy 8020 Nickel Chromium Electrical Resistance Alloy	0.000109	15	65,267	87	Resistalloy 8020 Nickel Chromium Electrical Resistance Alloy
Special Metals INCONEL® Alloy 600	0.000103	14.9	44,962	90	Special Metals INCONEL® Alloy 600
AISI Type S21800 Stainless Steel tested at 24°C	0.0000982	20.7	58,160	100	AISI Type S21800 Stainless Steel tested at 24°C
AISI Type S21800 Stainless Steel 105 mm annealed bar tested at RT	0.0000982	20.7	55,985	100	AISI Type S21800 Stainless Steel 105 mm annealed bar tested at RT
Crucible 15-5 Precipitation Hardening Stainless Steel	0.000098	22.6	185,648	110	Crucible 15-5 Precipitation Hardening Stainless Steel
Crucible 17Cr-4Ni Precipitation Hardening Stainless Steel	0.000098	17.9	185,648	110	Crucible 17Cr-4Ni Precipitation Hardening Stainless Steel
Stellite® alloy 6B, solution heat-treated at 1232°C, air cooled, 1.0 mm thick sheet	0.000091	14.85	90,068	109	Stellite® alloy 6B, solution heat-treated at 1232°C, air cooled, 1.0 mm thick sheet
Allegheny Ludlum Altemp® A286 Iron-Base Superalloy, UNS S66286	0.000091	15.1	39,885	85	Allegheny Ludlum Altemp® A286 Iron-Base Superalloy, UNS S66286
AISI Type S45500 Stainless Steel, hardened at 480°C (900°F) for 4 hours, air cooled, 25 mm (1 in.) round	0.0000900	18	242,213	110	AISI Type S45500 Stainless Steel, hardened at 480°C (900°F) for 4 hours, air cooled, 25 mm (1 in.) round
AISI Type S45500 Stainless Steel, annealed at 815°C (1500°F) for 30 minutes, water quenched, 4.1 mm round	0.00009	18	134,885	107	AISI Type S45500 Stainless Steel, annealed at 815°C (1500°F) for 30 minutes, water quenched, 4.1 mm round
AISI Type S45500 Stainless Steel, annealed at 815°C (1500°F) for 30 minutes, water quenched, 100 mm (4 in.) round	0.00009	18	115,305	106	AISI Type S45500 Stainless Steel, annealed at 815°C (1500°F) for 30 minutes, water quenched, 100 mm (4 in.) round

17-7 PH Stainless Steel, RH950, bar and forgings	0.000083	16.4	149,389	110	17-7 PH Stainless Steel, RH950, bar and forgings
17-7 PH Stainless Steel, TH1050, bar and forgings	0.000083	16.4	139,961	110	17-7 PH Stainless Steel, TH1050, bar and forgings
AISI Type S20910 Stainless Steel, high strength, typical	0.000082	15.6	145,038	99	AISI Type S20910 Stainless Steel, high strength, typical
AISI Type 303 MA Stainless Steel, in bar, cold drawn, tested at RT	0.0000805	16.2	60,191	96	AISI Type 303 MA Stainless Steel, in bar, cold drawn, tested at RT
AISI Type 303 MA Stainless Steel, in bar, annealed, tested at RT	0.0000805	16.2	39,885	83	AISI Type 303 MA Stainless Steel, in bar, annealed, tested at RT
AISI Type 348 Stainless Steel, annealed and cold drawn, bar	0.0000791	16.3	65,267	94	AISI Type 348 Stainless Steel, annealed and cold drawn, bar
AISI Type 348 Stainless Steel, annealed, bar	0.0000791	16.3	34,809	83	AISI Type 348 Stainless Steel, annealed, bar
Allegheny Ludlum Stainless Steel Chromium-Nickel-Molybdenum 317L (UNS S31703)	0.000079	14.6	29,733	96	Allegheny Ludlum Stainless Steel Chromium-Nickel-Molybdenum 317L (UNS S31703)
Allegheny Ludlum Type 317 Stainless Steel, UNS S31700	0.000079	14.6	29,733	95	Allegheny Ludlum Type 317 Stainless Steel, UNS S31700
AISI Type 309 Stainless Steel, annealed, bar	0.000078	15.6	39,885	83	AISI Type 309 Stainless Steel, annealed, bar
AISI Type 309S (Cb) Stainless Steel, annealed, bar	0.000078	15.6	39,885	83	AISI Type 309S (Cb) Stainless Steel, annealed, bar
AISI Type S15500 (15Cr-5Ni) Precipitation Hardening Stainless Steel transverse direction, intermediate location, condition H925	0.000077	17.8	174,770	103	AISI Type S15500 (15Cr-5Ni) Precipitation Hardening Stainless Steel transverse direction, intermediate location, condition H925
X25CrNi2520 Austenitic Stainless Steel for medical instruments	0.000077	17.5	44,962	???	X25CrNi2520 Austenitic Stainless Steel for medical instruments
AISI Type S24000 Stainless Steel, annealed bar up to 200mm diameter, minimum acceptable properties for material specification	0.000074	15.9	55,114	92	AISI Type S24000 Stainless Steel, annealed bar up to 200mm diameter, minimum acceptable properties for material specification
X5CrNiMo17133 Austenitic Stainless Steel for medical instruments	0.000074	16.2	44,962	95	X5CrNiMo17133 Austenitic Stainless Steel for medical instruments
X2CrNiMo17133 Austenitic Stainless Steel for medical instruments	0.000074	16.2	44,962	95	X2CrNiMo17133 Austenitic Stainless Steel for medical instruments
Grade 704 Zirconium (Zr-1.5Sn)	0.000074	21.5	34,954	???	Grade 704 Zirconium (Zr-1.5Sn)
Zircaloy-2 Zirconium Alloy	0.000074	21.5	34,954	???	Zircaloy-2 Zirconium Alloy
Zircaloy-4 Zirconium Alloy	0.000074	21.5	34,954	???	Zircaloy-4 Zirconium Alloy
X2CrNiMo18164 Austenitic Stainless Steel for medical instruments	0.000074	16.2	34,809	95	X2CrNiMo18164 Austenitic Stainless Steel for medical instruments
Sandvik KANTHAL Kanthal 50 HT Thermostatic bimetal	0.0000635	20	53,664	87	Sandvik KANTHAL Kanthal 50 HT Thermostatic bimetal
Deutsche Titan Tikrutan® RT 20 Commercially Pure Titanium	0.000055	20.1	59,465	93	Deutsche Titan Tikrutan® RT 20 Commercially Pure Titanium

Deutsche Titan Tikrutan® RT 18 Commercially Pure Titanium	0.000052	22.6	50,763	87	Deutsche Titan Tikrutan® RT 18 Commercially Pure Titanium

[redacted]

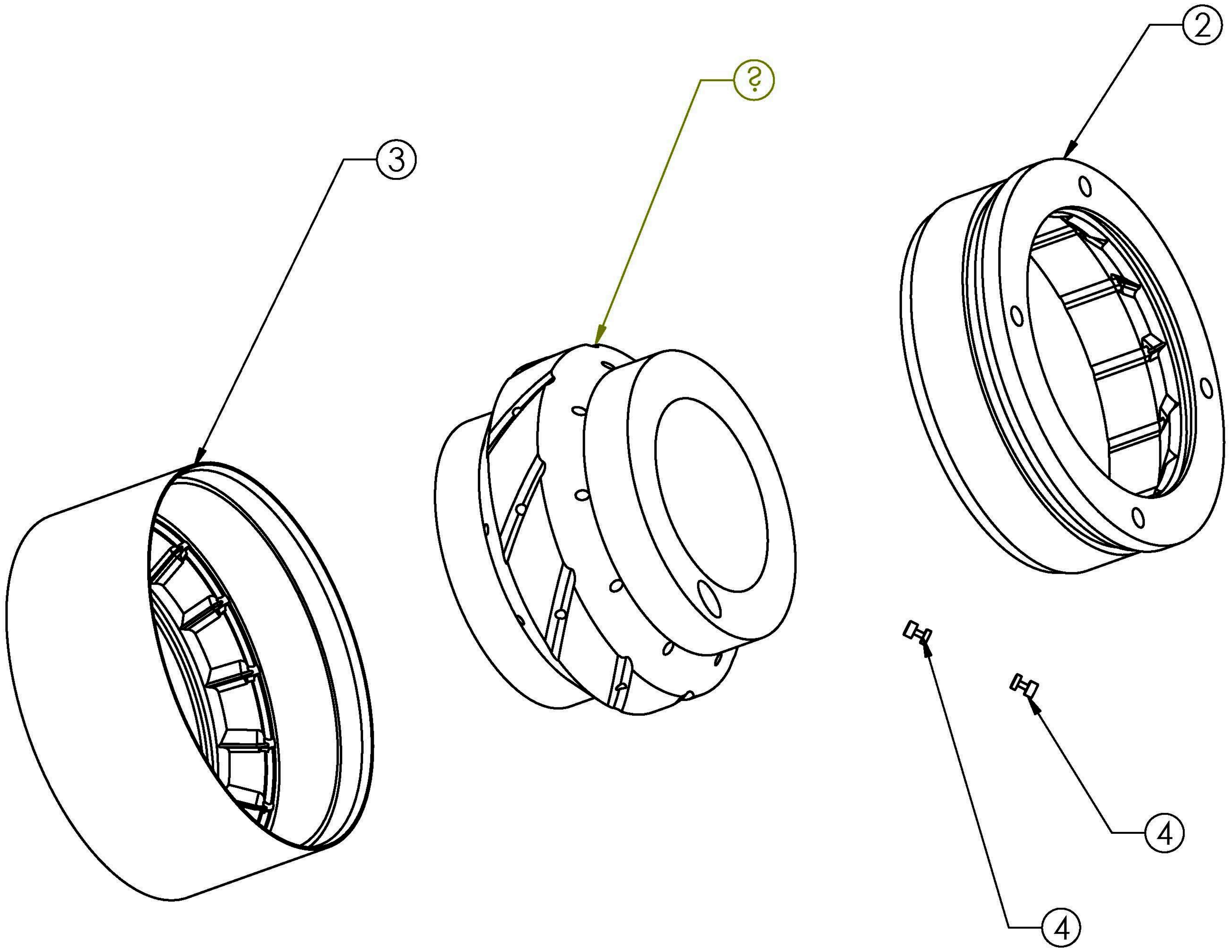
APPENDIX C

Inverted Thurst/ Journal Bearing Designs

for an

Advanced Ultra-High Speed (Electric & Inverted) Motor for Drilling

ITEM NO.	QTY.	PART NO.	DESCRIPTION
1	1	1043	RACE, INNER, BEARING, HYDRO, INVERTED, THREADED
2	1	1042	RACE, OUTER, BEARING, HYDRO, INVERTED, THREADED
3	1	1044	CAP, RACE, OUTER, HYDRO, INVERTED, THREADED
4	2	1028	PISTON, CHAMBER, EXPANSION



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/16 ANGULAR ±1° 0.0 = ±.1 0.00 = ±.03 0.000 = ±.005 0.0000 = ±.0005		
MATERIAL:		
FINISH:		

	NAME	DATE
DRAWN	MF	6-20-07
CHECKED		
ENG APPR.		

ECN #:

Impact Technologies LLC

TITLE:
BEARING, HYDRO, INVERTED, THREADED, ASSY

SIZE	DWG. NO.	REV.
A	1041	

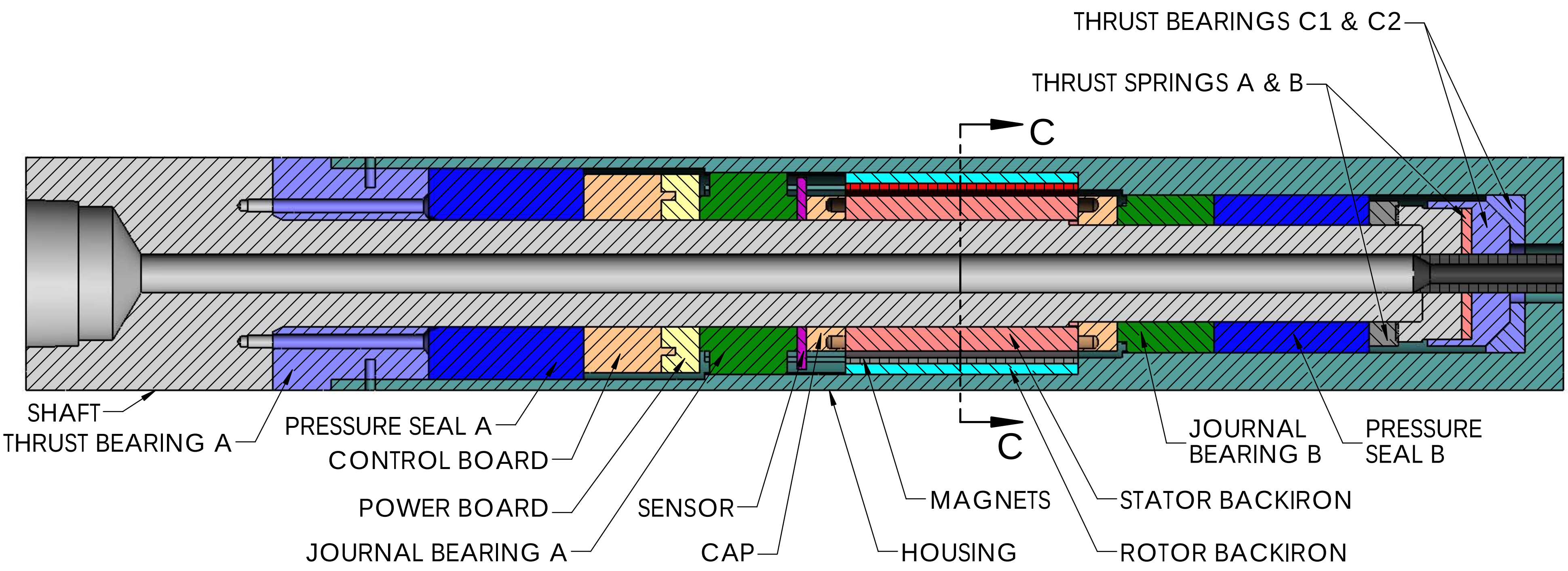
NOT TO SCALE | WEIGHT: | SHEET 1 OF 1

APPENDIX D

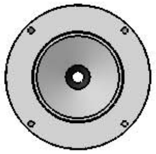
Drawings for a 6.91 cm/ 2.72 inch Radial Inverted Motor

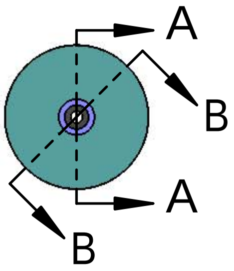
for the

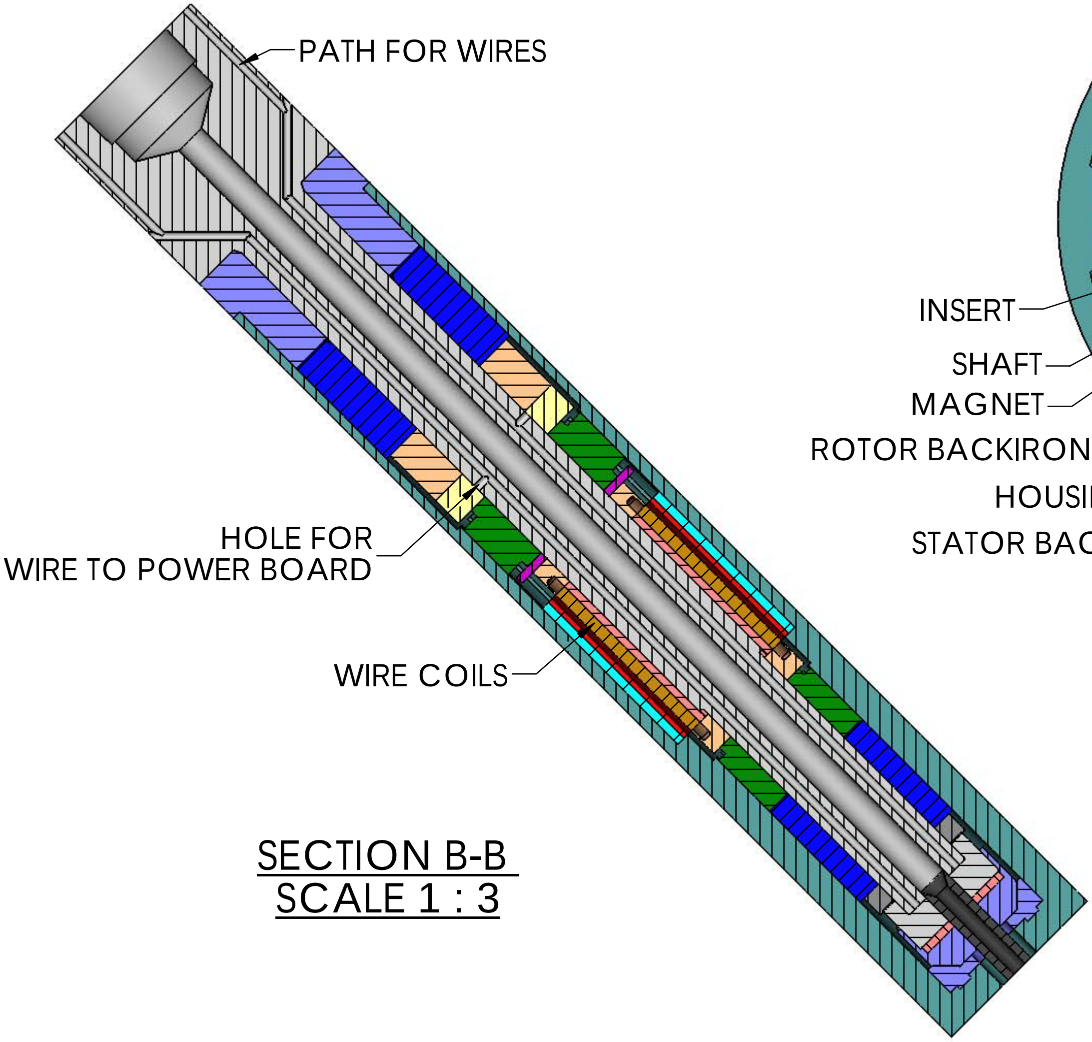
Advanced Ultra-High Speed (Electric & Inverted) Motor for Drilling Project



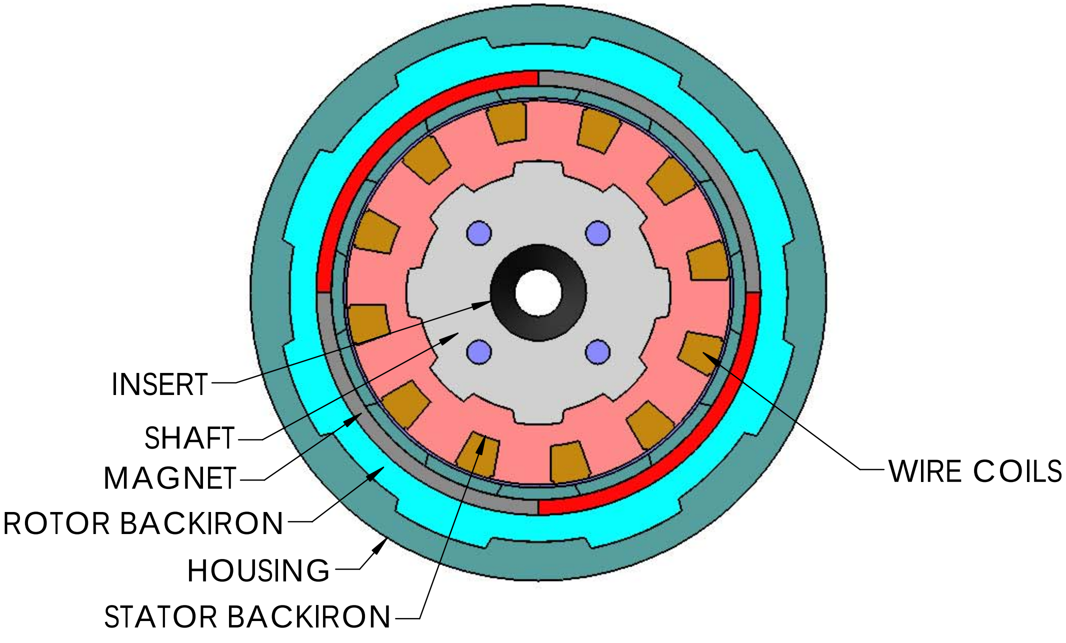
SECTION A-A
SCALE 1 : 2







SECTION B-B
SCALE 1 : 3



SECTION C-C
SCALE 1 : 1

APPENDIX E

Drawings for a
6.91 cm/ 2.72 inch
Axial Inverted Motor

for the

Advanced Ultra-High
Speed (Electric & Inverted)
Motor for Drilling
Project

03					
REV.	DESCRIPTION	DATE	MOD.	REV.	APP.
REVISIONS					

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/32
ANGULAR: ± 0.5
TWO PLACE DECIMAL ± 0.020
THREE PLACE DECIMAL ± 0.005
FOUR PLACE DECIMAL ± 0.0002

MATERIAL

FINISH

DO NOT SCALE DRAWING

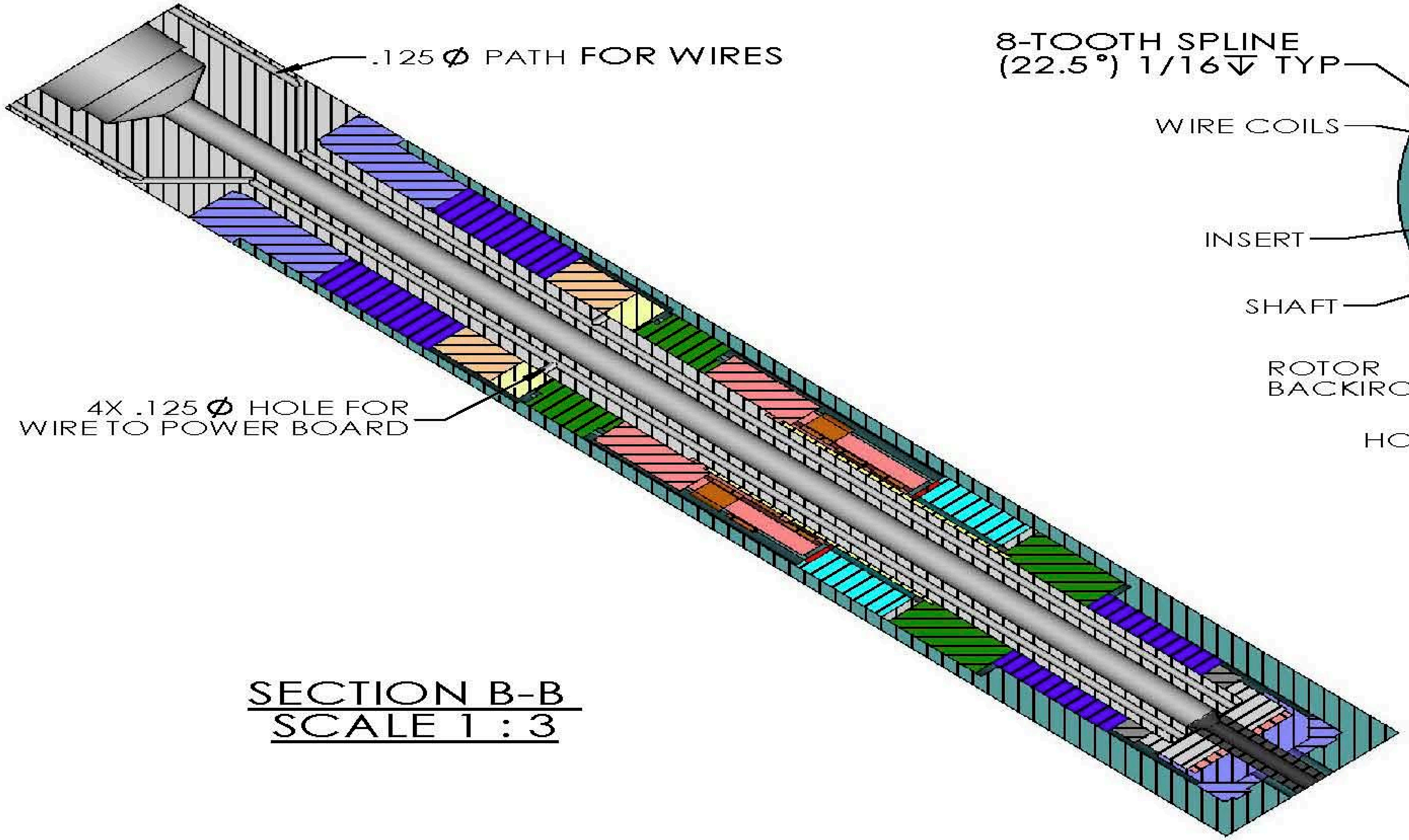
	NAME	DATE
DRAWN	JWP	11/10/06
ENG APPR.		
CHECKED BY		
MFG APPR.		
Q.A.		

COMMENTS:

DRAWING TYPE:
MANUFACTURE DRAWING

SIZE	DRW. NO.	REV.
A	**IMe-HSM (3in)_03-Axial**	03

SCALE: NOTED
FILENAME:
SHEET 1 OF 2



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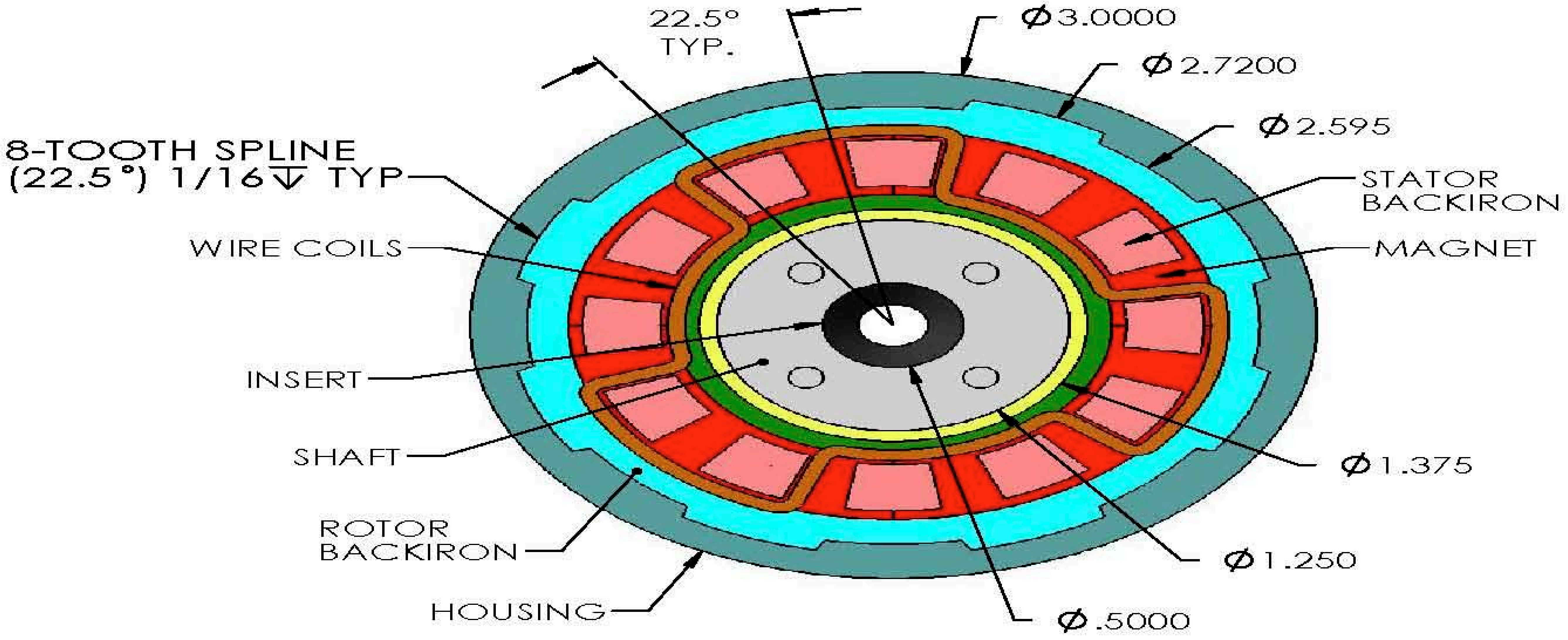
SCALE 1 : 3



SECTION C-C
SCALE 1 : 1

DO NOT SCALE DRAWING

DRAWING TYPE:
MANUFACTURE DRAWING

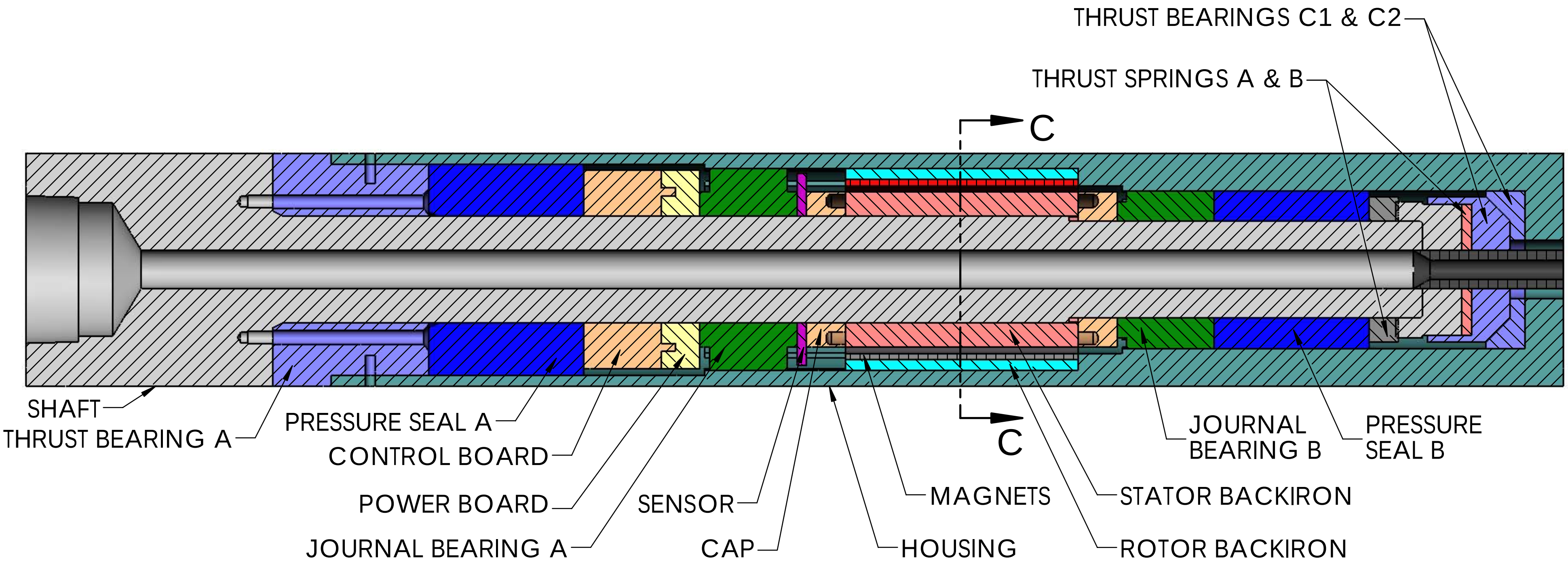
SIZE	DRW. NO.		REV.
A	**IMe-HSM (3in)_03-Axial**		03
SCALE: NOTED	FILENAME:	SHEET 2 OF 2	

APPENDIX F

Drawings for a 4.29 cm/ 1.69 inch Radial Inverted Motor

for the

Advanced Ultra-High Speed (Electric & Inverted) Motor for Drilling Project



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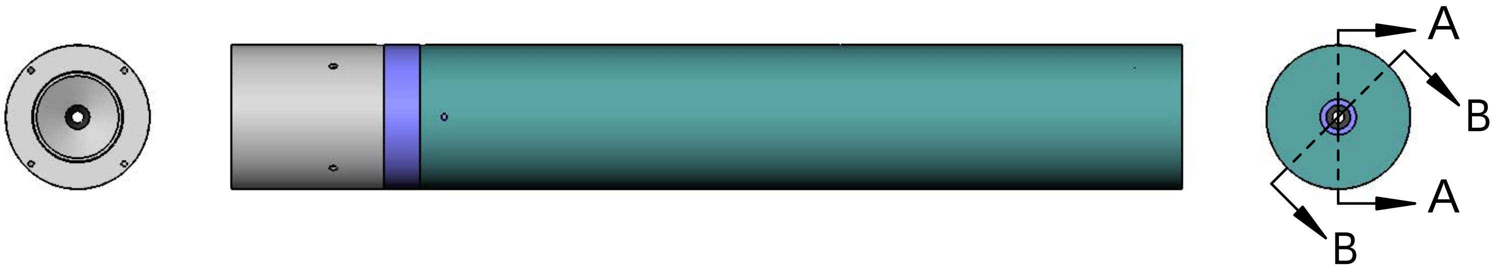
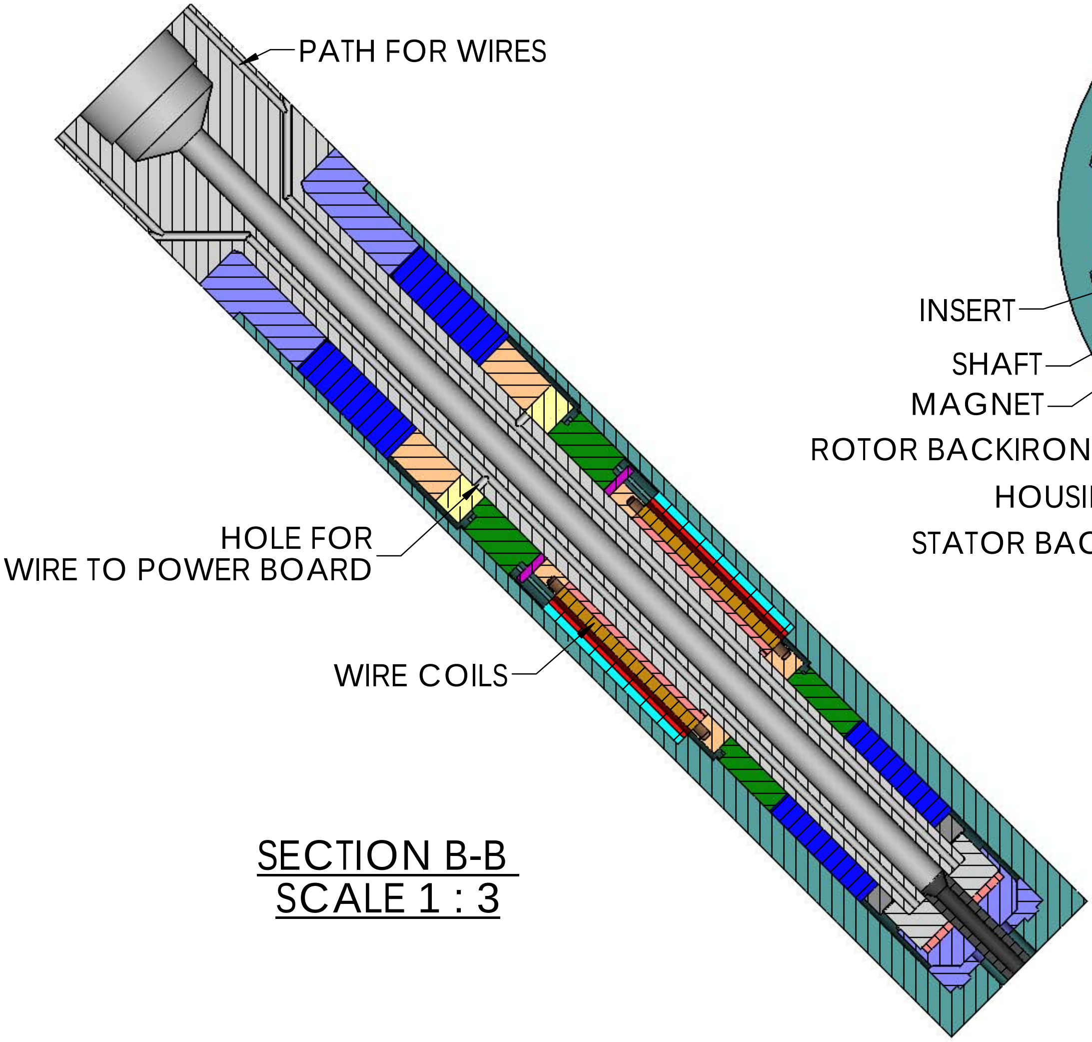
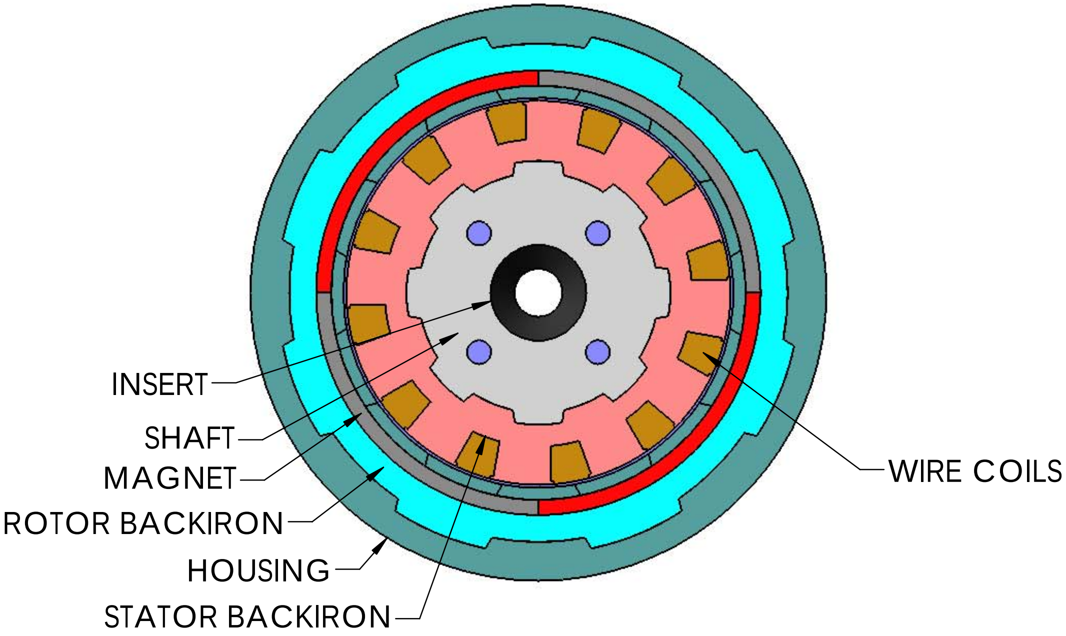




SECTION B-B
SCALE 1 : 3



SECTION C-C
SCALE 1 : 1

APPENDIX G

Technical Status Reports delivered to DOE/ NETL

for the

Advanced Ultra-High Speed (Electric & Inverted) Motor for Drilling Project

Advanced Ultra High Speed Motor for Drilling

Status Report
Report Effective 30April 2005

DOE Award Contract Number DE-FC26-04NT15502

by
Kenneth D Oglesby, Impact Technologies LLC,
Principal Investigator
Dr. Babak Fahimi, University of Texas-Arlington
Dr. Shari Dunn-Norman, University of Missouri-Rolla

Report Issued 5 May 2005

Disclaimer

Abstract

The project focus has been on determining the drilling feasibility and torque/ power of a 10,000 rpm electric motor in an inverted design. Initial study focus was on available bits for 10,000rpm drilling service and their performance characteristics. Only natural diamonds, PDC and TSP cutting materials come close to the necessary properties, but no or minimal data exists at these ultra high speeds. The second focus was the unit size to design and make the motors, nothing in the literature nor in industry could be found to answer this question, thus maximum power for a 1 foot motor was utilized. A study of power systems showed that 300VAC (at the motor) power transmission and motor feed was considered best for this application. A 300VDC motor with permanent magnets and controllers was considered best for the inverted motor configuration and application. Radial motor designs have been made on both a 1.687" OD and a 3.00" OD inverted motor. Axial motor designs are now being studied on both motor sizes. Remaining concerns are bending with the small air gaps between moving parts, seals, bearings, heating/ cooling, vibration and harmonics.

Table of Contents

Not utilized for status report

Executive Summary

The project focus has been on determining the drilling feasibility and torque/ power of a 10,000 rpm electric motor in an inverted design. Initial study focus was on available bits for 10,000rpm drilling service and their performance characteristics. Only natural diamonds, PDC and TSP cutting materials come close to the necessary properties, but no or minimal data exists at these ultra high speeds. The second focus was the unit size to design and make the motors, nothing in the literature nor in industry could be found to answer this question, thus maximum power for a 1 foot motor was utilized. A study of power systems showed that 300VAC (at the motor) power transmission and motor feed was considered best for this application. A 300VDC motor with permanent magnets and controllers was considered best for the inverted motor configuration and application.

Radial motor designs have been made on both a 1.687” OD and a 3.00” OD inverted motor. Axial motor designs are now being studied on both motor sizes. Remaining concerns are bending with the small air gaps between moving parts, seals, bearings, heating/ cooling, vibration and harmonics.

Report Details

Key Dates:
6Dec04 meeting TerraTek presentation at NETL on ultra high speed PDC tests
14Dec04 HSM Kick off meeting in Tulsa
4Jan05 Shop experiments on rotational drag
5Jan2005 report by Dr. Fahimi on initial 1.68"OD radial inverted motor design results
28Feb05 report by Dr. Fahimi on updated 1.68"OD radial motor results
28April 2005 report by Dr. Fahimi on 3.0" OD radial motor design results

Discussion and Results:
The motor concept is based on a patent pending configuration by Ken Oglesby. The basis of which is that the internal shaft is attached to the drill string and does not rotate. The outer housing rotates with the bit/ mill/ cutting surface attached to it. The motor resides between the fixed shaft and rotating housing, driving the housing to rotate. A channel(s) exists in the fixed shaft that allows fluids to flow through the motor without contact of any powered components. These fluids can be at any pressure and type since they will only contact the internal channel at high pressure and outside of the outer housing at lower pressure. Higher rotating mass and abrasive jetting can also be of benefit with this configuration of electric motor.

Initial concerns in the project were to determine the characteristics of the cutting elements to be used at these ultra high speeds. The problem is the ultra high tip velocities developed and the large amount of heat generated. Few materials can stand the expected temperature, impact and abrasive wear. Very little data is available, and only natural diamonds, TSP (thermally stable polycrystalline diamond) and PDC (polycrystalline diamond) materials have been identified as potentially useable at these ultra high speeds. Only TerraTek's DOE work with small (less than 1"OD), core style, natural diamond bits comes closest. While the TerraTek work sheds some light on the benefits, little other data was obtained. Discussion with several bit manufacturers revealed only that lighter weight-on-bits and less torque would be expected.

The next step was to quantify the unit power of motor needed to do the smallest drilling tasks. This included the simple tasks of just overcoming simple drag in the hole and lifting of the bottom hole assemble in a horizontal hole. Again, a literature search shed no light on this issue. To get some handle on the minimum power needed some experiments in Impact's Tulsa shop showed that on bare steel to steel friction, there is less than 4 ft-lbs over 110" of linear contact. It is expected that a motor, bit and related tools may be up to 36" long with a broader contact area than tested. A 400% safety factor would put this startup torque at about 16 ft-lbs. This converts to about 3 horsepower at startup speeds (100rpm). With little data available it was decided to simply develop the maximum horsepower/ torque in a one foot unit length of motor for all designs. The lengths can be reduced later.

The two motor sizes selected were 1.6875" OD and 3.00" OD, full dimensions are given in Figures 1 and 2 for radial design motors. The smaller OD was selected to fit into the microhole range of work. The tip velocities on smaller diameter bits is proportionally lower with smaller bit sizes…requiring smaller motors as well. This smaller size would allow passage through standard 2-3/8” tubing (1.995” drift ID) and useable with 1.875” to 2.75” bits / mills. The larger size was targeted for passage through 4-1/2” tubulars and with 3.5” to 4.75” bits/ mills. Larger sizes can be designed and made later.

The system voltage selection process considered insulation materials, transmission, control, depth, temperature and power density generated in the motor. It was determined that 300VDC brushless drive in the motor with a maximum operating temperature of 270 defree F. With this motor selection, the shaft must be of non-magnetic materials. System power transmission for 5000 feet will be 300 VAC to allow for maximum power, minimum magnetic field generated and BHA/ control signals to be imbedded in the power wave.

Motor analysis will look at both a radial and axial design for both OD sizes. A modified / hybrid design was discussed for future designs. This radial motor study utilized a two dimensional, transient Finite Element Analysis (FEA) with various magnetic configurations. The main purpose of this phase of the project is to estimate the highest torque and mechanical power that can be obtained using a radial design. In order to achieve this goal various permanent magnets and ferromagnetic steel laminations have been considered and the best results have been reported. Moreover, a field oriented control strategy has been incorporated in our transient FEA. This has been done for both motor OD sizes. Figures 3 and 4 show the basic power and torque designs for these radial systems. All motor designs will require a disc for converting AC to DC and a second disc for controlling the motor to obtain optimum performance.

In Figures 1 and 2 for radial design motors, the outer housing is the external segment, permanent magnets lie inside and are kept in place by centrifugal forces during operation. an airgap exists between the PMs and an internal shaft. The outer portion of the shaft contains the coils/ armature. The internal portion of the shaft is the channel for fluid flow and cooling. Cooling, in fact, occurs both on the inside and outside of the motor.

The 1.68”OD motor in a radial design resulted in 2.36 Hp, 1.24 ft-lbs per foot of motor length at 10,000 rpm with good power over the full rpm range. In fact, start up torque is estimated at 1.75 ft-lbs without surging the input power.

The 3.0” OD radial motor design shows 4.53 Hp, 2.38 ft-lbs per foot of motor length at 10,000 rpm. Startup torque was estimated at 6.47, 3.4 ft-lbs per foot of motor length.

Figures 3 and 4 show typical performance of such radial motors. Figures 5 , 6 and 7 are for a 3.0”OD radial motor. Figure 8 is for a 1.6875” OD radial motor. In these simulations, red indicates higher heat generation which will require cooling from the nearby internal flow channel or return flow on the outside of the rotating housing. Note that ll figures have been taken out of interim reports from Dr Fahimi.

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Axial designs for both motor sizes are now being studied by Dr Fahimi at UT-Arlington.

Both metal-metal and PDC bearing surfaces have been investigated for this motor configuration. Dennis Oil Tools, Houston, was visited concerning their expertise in the PDC bearings. Other designers will be visited to choose the optimal bearing materials.

Bending concerns will have to be addressed as it related to shaft size / strength and the air gap thickness between the motor's moving parts. Seal assembly is also of concern and will be addressed. Balancing of all motor parts and induced harmonic vibrations must also be investigated. Cooling of the motor is also of concern in that a minimum flow rate is required and must be known.

Conclusions for the project:

1. The inverted motor configuration with an electric motor seems favorable for drilling;
2. Power generation in the motors (based on radial only at this time) with the electrical system chosen (300V) seems feasible and adequate for drilling with both sizes motors chosen;
3. The Axial motor design looks promising in generating higher power density than the radial design and this work continues;
4. Bearing and seal investigations must continue to obtain optimal designs;
5. Side force FEA must be performed to determine bending and address airgap and shaft strength concerns; and
6. Heat generation and transfer FEA must be performed once the final motor design is selected to determine minimum fluid flow for cooling.

Graphical Materials

(note that all graphics were taken from reports from Dr. Fahimi)

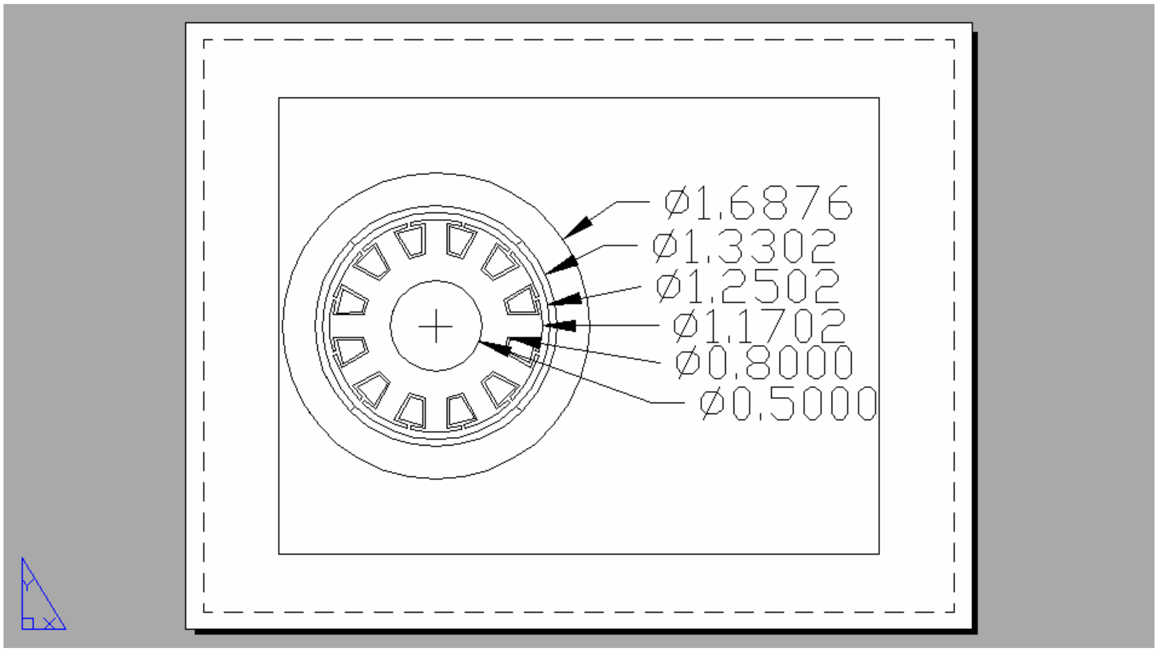


Figure 1 Modified dimensions of the smaller OD motor- radial design

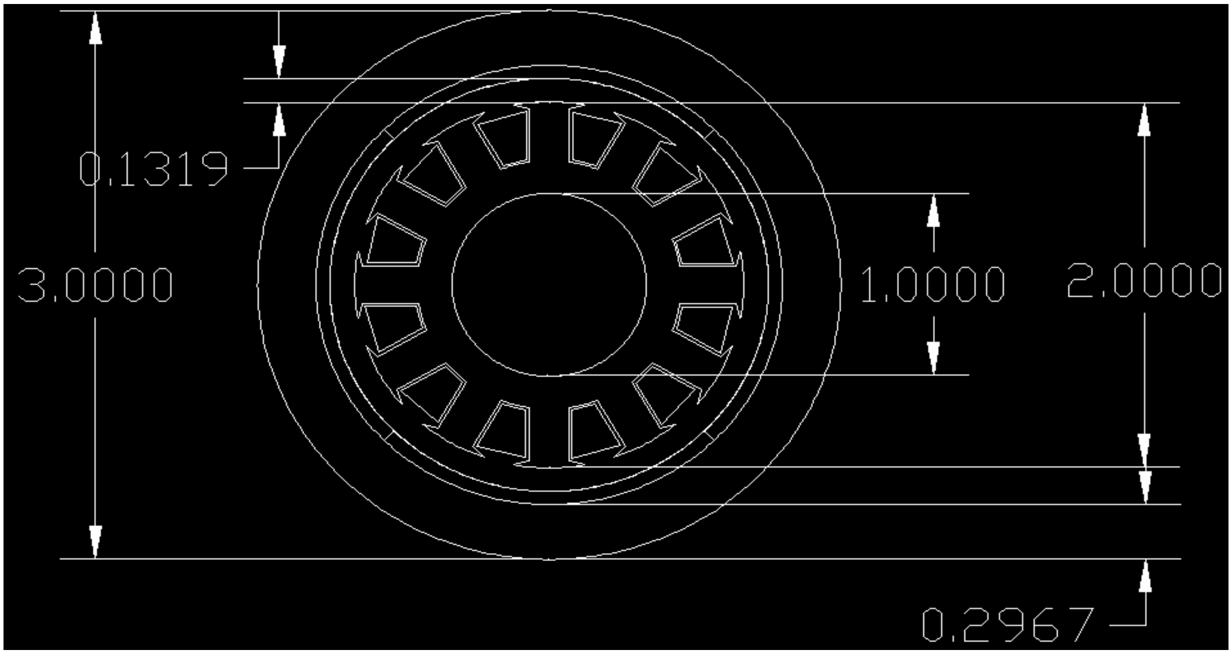


Figure 2- Modified dimensions of the larger OD motor- radial design

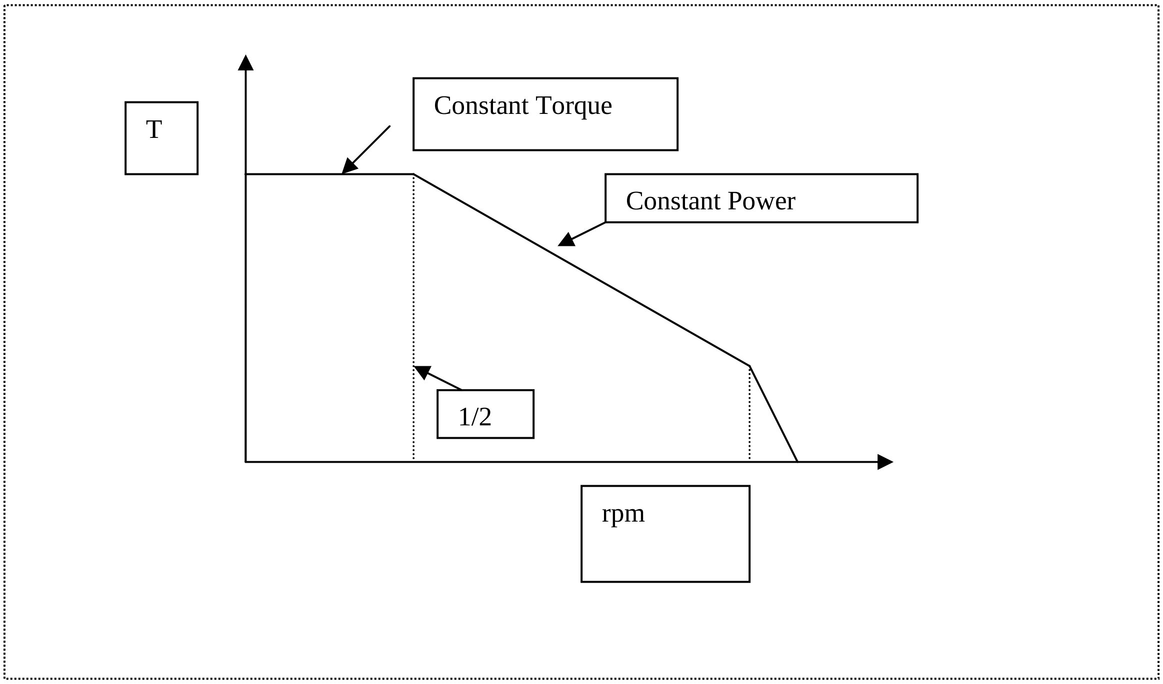


Figure 3- Basic Torque Profile versus RPM for the chosen radial motor designs

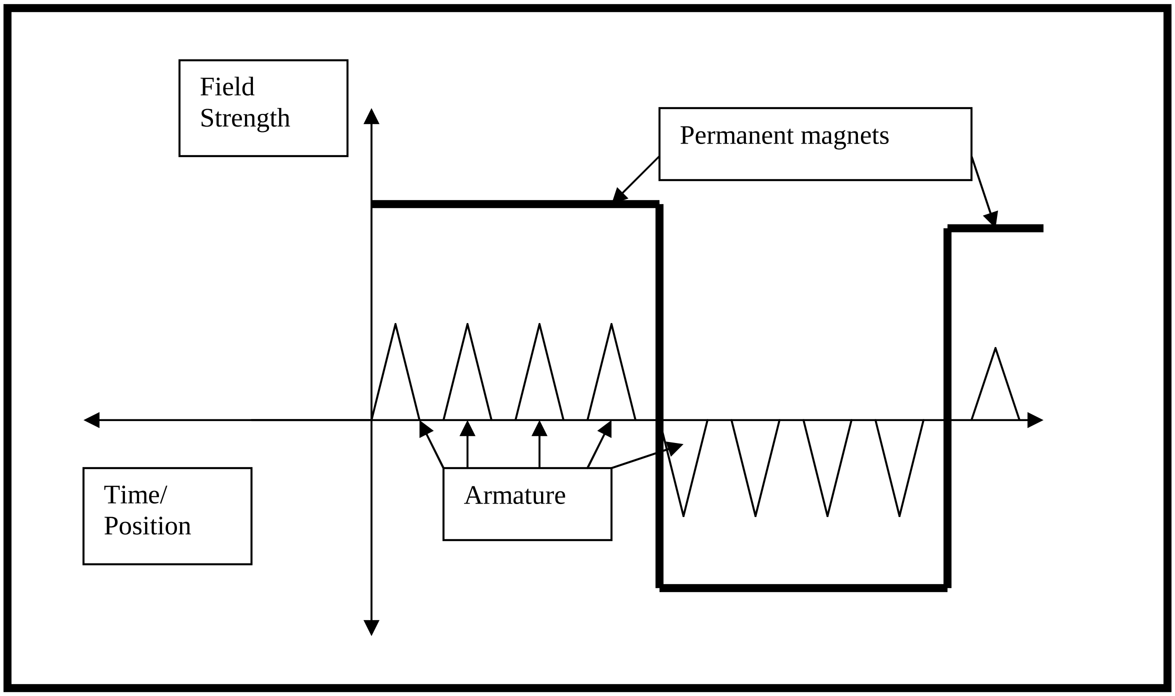


Figure 4- Basic Field Strength versus Time / position for a Strong PM and Weak Armature

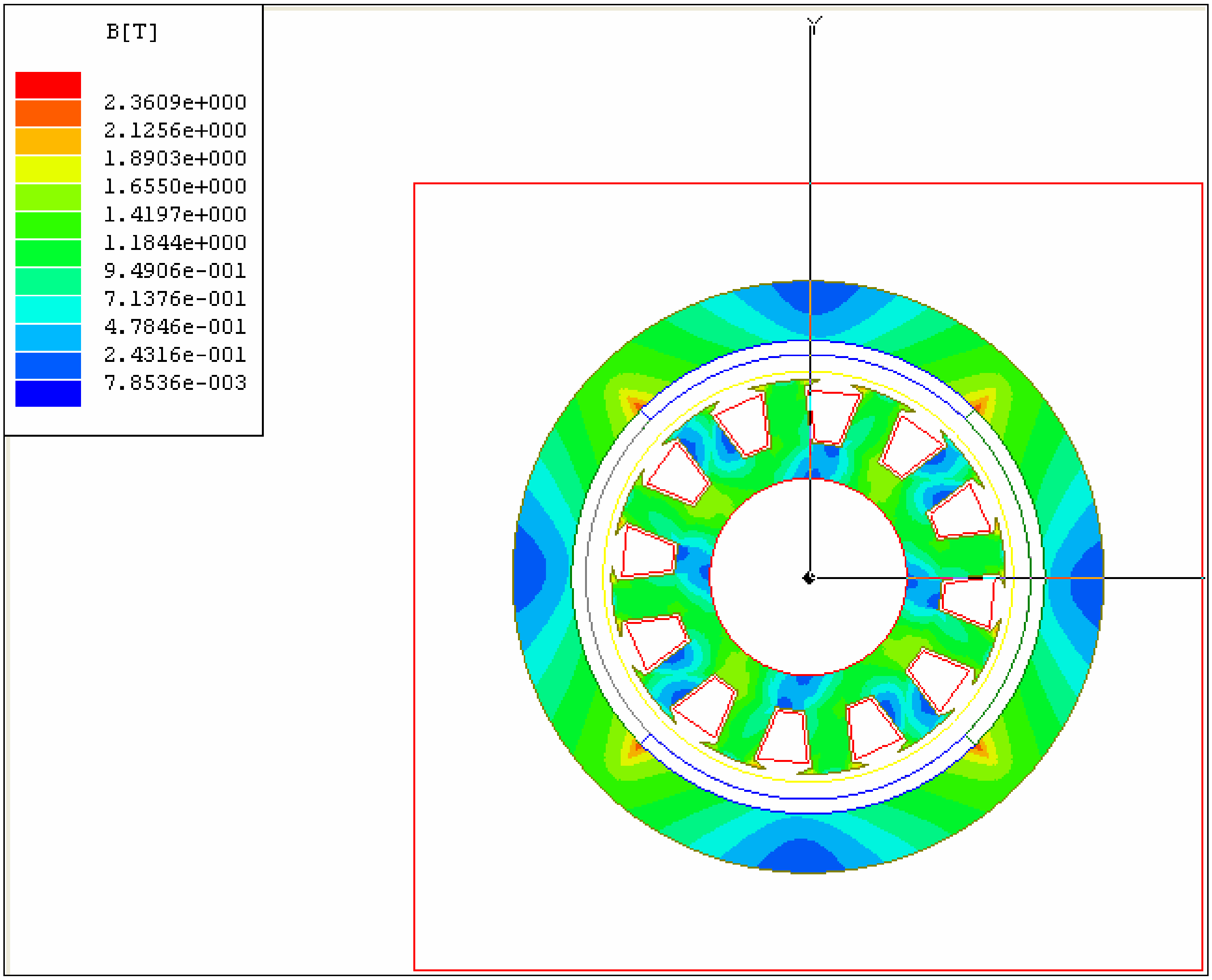


Figure 5. Flux density distribution in iron for 130AT in the stator for a 3.0” Radial Motor design.

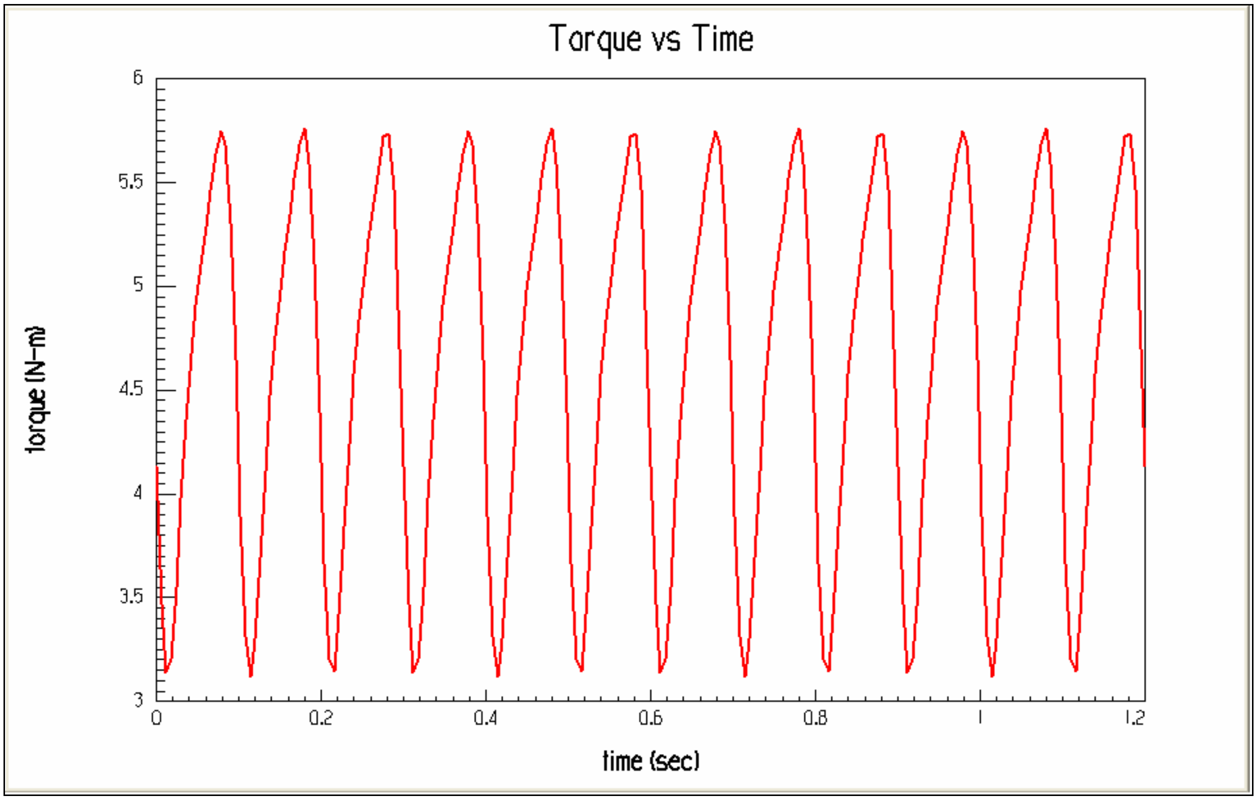


Figure 6- . Torque at Maximum allowable current, 50 rpm for 3.0" radial motor design. Average = 4.61N-m

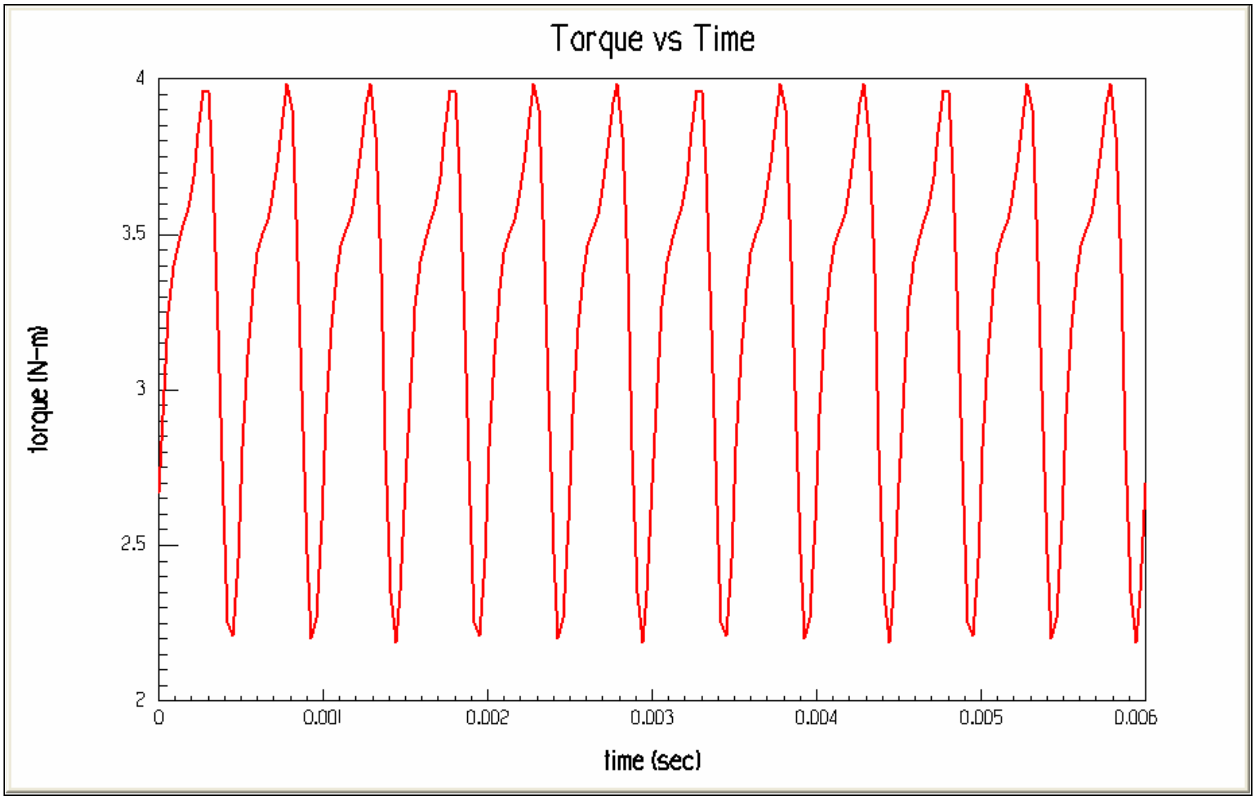


Figure 7 -. Torque at Maximum allowable current, 10,000 rpm for 3.0"OD Radial Motor. Average 3.23806 N-m

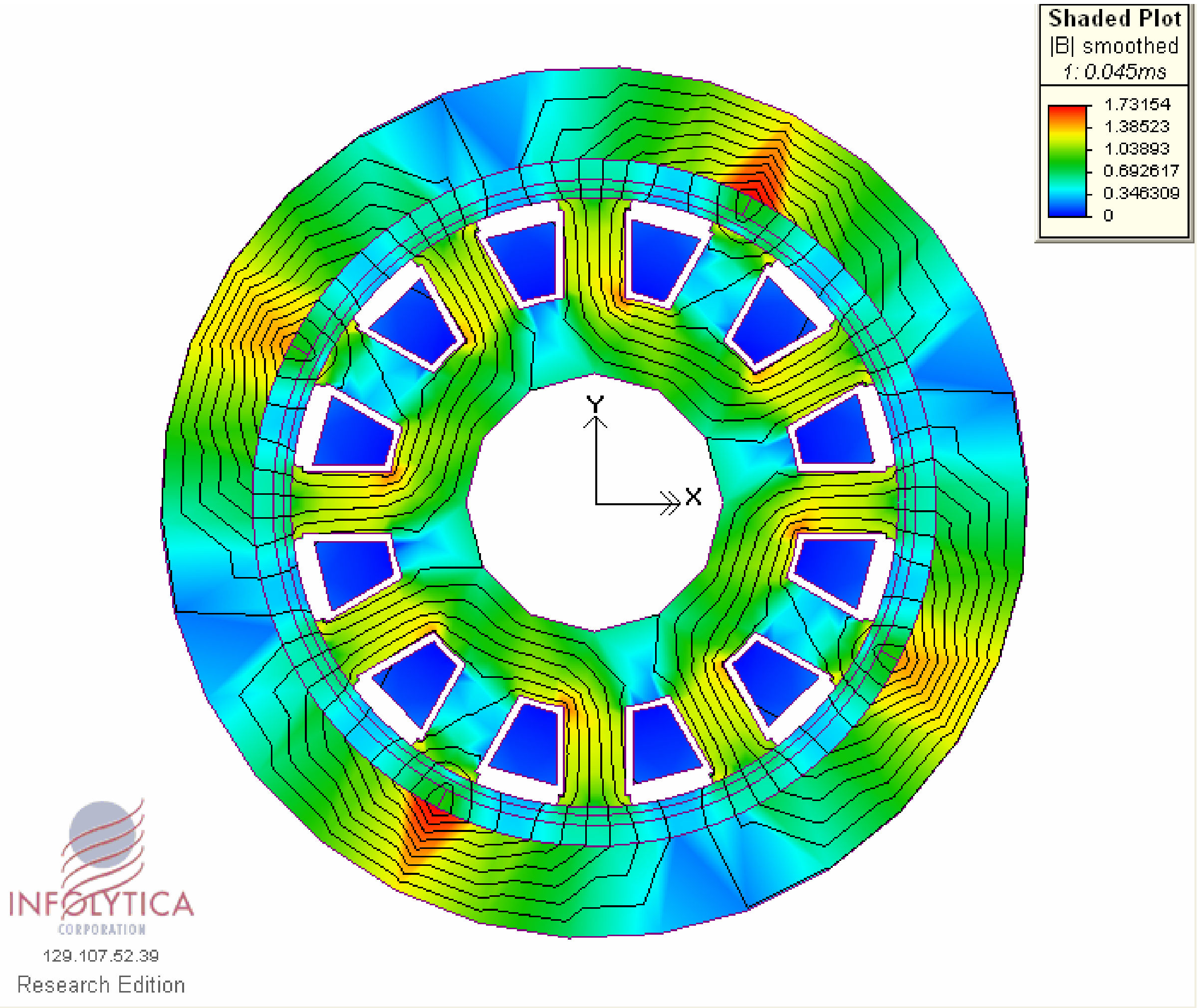


Figure 8- Magnetic Flux Density Plot at 50 rpm for 1.6875” OD Radial Design

References

None given for this status report

Bibliography

None given for this status report

List of Acronyms, Abbreviations, Conversions and Equations

Horsepower = Torque(lb-ft) * rpm/ 5252

Watts = Torque(lb-ft) * rpm/ 7.04

Foot-Pound Torque = Newton-Meters Torque * 0.7376

NOYB = None of Your Business (as in confidential or proprietary information)

Appendices

None given for this status report

Advanced Ultra-High-Speed Motor for Drilling

DE-FC26-04NT15502

Program

This project was selected in response to DOE's Oil Exploration and Production solicitation DE-PS26-04NT15450-1. The objective of this section of the solictation was to develop high-speed downhole motors suitable for drilling with high-speed bits in the harsh downhole drilling environment.

Project Goal

The project goal is to design ultra-high-speed (10,000 rpm) electric inverted configured motors in two sizes for drilling microholes.

Performers

Impact Technologies LLC
Tulsa, OK

University of Texas-Arlington
Arlington, TX

Project Results

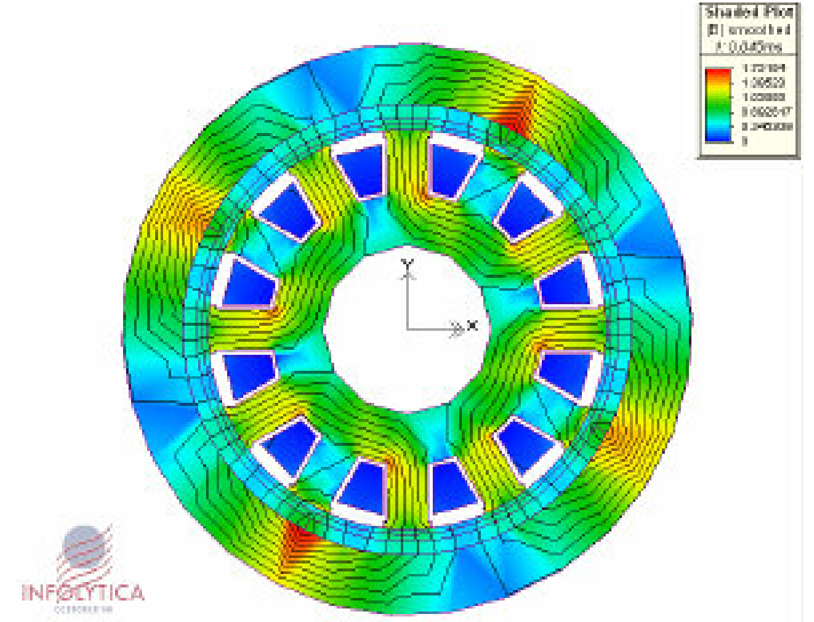
Researchers have developed electromagnetic designs for radial and axial motors in 2 outer diameters (OD) for speeds up to 10,000 rpm. Magnetic saturation and power/torque estimations have been made at various speed and loading conditions. Bearing and seal materials have been studied, but their final design must wait until the electromagnetic motor design has been finalized.

Benefits

A new motor and drilling process combination will benefit oil and gas exploration and production by finding new reserves as a result of lower finding costs and increased production from existing wells with horizontal drilling applications. The drilling method is applicable to extremely hard or deep reservoirs that are difficult to drill with current technology. The gas storage industry can benefit from horizontal drilling in storage fields, which allows enhanced deliverability. Significant benefits are expected for the trenchless utility (telephone, fiber-optics, communications, water, sewer, etc.) and pipeline installations across roads and rivers.

Background

Drilling boreholes at ultra-high speeds (>10,000 rpm) has been shown to penetrate faster than at lower speeds. Using abrasive and/or acidic fluids at high pressures also has been shown to increase drill rate. Employing an electric motor in the new "inverted" configuration allows the combination of these two mechanisms (ultra-high speed and high-pressure fluids) to be used for even faster and more efficient drilling.



Magnetic field distribution in a small, ultra-high-speed electric motor.

Project Summary

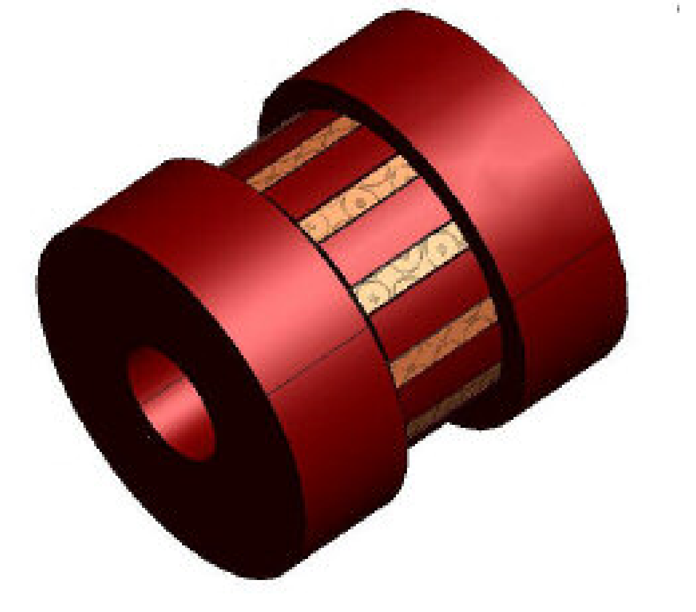
This project initially focused on drillbits that are to be used in ultra-high-speed drilling applications. This was important to determine the required load, torque, horsepower, and sizes. From this study, it was found that few cutter elements and bits can withstand the generated heat, abrasiveness, and shock of this environment, although current work in this area is encouraging.

Based on this work, the motor requirements were set as a first pass for the electromagnetic design. Two sizes planned for initial design were 1.69 inches and 3 inches OD, with the lengths variable and motor power sections stackable. The chief benefit of an "inverted motor" configuration vs. an electrical motor is that the internal high-pressure fluids are not in contact with the electrical components. The weaker permanent magnets are lined inside the outer rotating housing and thus are supported from the extreme centrifugal forces generated by such high speeds. The internal and external flows can efficiently cool the electrical/magnetic-induced heat load. Air gap clearances and magnetic-strength saturation are ongoing concerns.

Radial designs have been finished. The more complicated axial design is ongoing and looks favorable relative to the radial design. Seals and bearing design will come out of the final electrical-magnetic design selected. Polycrystalline diamond, diamond, and other coatings are being considered for bearing surfaces. Ultra-high-speed seal materials will be selected last, based on the heat and pressure ranges required by the final design.

Current Status (August 2005)

Researchers are finalizing the electromagnetic design of the motor. The current focus is on electric-magnetic axial design of a 3-inch OD motor for microhole drilling and on bearing materials and design. The next steps are to mate final electromagnetic mechanical designs with appropriate bearings and seals perform heat-transfer analysis of final designs, and prepare final machine drawings for prototyping.



Layout of a small, ultra-high-speed electric motor designed for drilling micro-bores.

Publications
Technical status reports have been generated. A technical paper abstract has been submitted and accepted as an alternate by the Society of Petroleum Engineers. Budget period semi-annual reports are available from NETL, 918-699-2000.

Project Start: October 1, 2004
Project End: March 31, 2006

Anticipated DOE Contribution: $165,882
Performer Contribution: $55,441 (25% of total)

Contact Information
NETL – Rhonda Jacobs (rhonda.jacobs@netl.doe.gov or 918-699-2037)
Impact Technologies – Ken Oglesby (oakk@aol.com or 918-627-8035)

Advanced Ultra High Speed Motor for Drilling

Status Report
Report Effective 30March2006

DOE Award Contract Number DE-FC26-04NT15502

by
Kenneth D Oglesby, Impact Technologies LLC,
Principal Investigator
and
Dr. Babak Fahimi, University of Texas-Arlington
Co-Investigator

Report Issued 31March 2006

Disclaimer

Abstract

A 300VDC pulse modulated PMSM (permanent magnet synchronous machine) axial motor in the patented inverted configuration was chosen for this drilling application at 10,000 rpm. Materials were selected and both 3.0" and 1.69" OD motors of this type have been electro-mechanical designed and FEA modeled. PCB board designs are now ongoing. Manufacturer seal data have been reviewed and manufacturers met with, but not selected. Engineering designs for layout and manufacturing have been made and nearing final. Concerns remaining are bending with the 1mm air gaps between moving parts (rotor-stator), sealing, journal bearing spacing, heating/ cooling, vibration/ harmonics and manufacturing ease. Some bearing and seal parts many be purchased for testing.

Table of Contents

Not utilized for status report

Executive Summary

Initial steps in this project included a review of the literature on high speed drilling, cutting elements for 100ft/sec operation to determine WOB and torque requirements. Based on the limitation of available cutters, microhole sizes of 1.69" and 3.0" OD were selected. Voltages for the downhole motor were set at 300VAC. Radial versus Axial motor designs were compared and the axial design selected due to the higher power density possible. A 300VDC pulse modulated PMSM (permanent magnet synchronous machine) axial motor in the patented inverted configuration was chosen for this drilling application at 10,000 rpm. Materials were selected and both 3.0" and 1.69" OD motors of this type have been electro-mechanical designed and FEA modeled. PCB board designs are now ongoing. Manufacturer seal data have been reviewed and manufacturers met with, but not selected. Engineering designs for layout and manufacturing have been made and nearing final. Remaining concerns are bending with the 1mm air gaps between moving parts (rotor-stator), sealing, journal bearing spacing, heating/ cooling, vibration/ harmonics and manufacturing ease. Some bearing and seal parts many be purchased for testing.

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4Feb05 Fahimi visit to Tulsa
28Feb05 report by Dr. Fahimi on updated 1.69”OD radial motor results
28Apr05 report by Dr. Fahimi on 3.0” OD radial motor design results
30Apr05 status report to Rhonda Jacobs
15Jun05 Fahimi report on 3.0” axial design
22July05 Oglesby visit to UTA lab, review status
27July05 presentation to DOE/ Rhonda Jacobs
17Aug05DOE MHT presentation in Houston
18Aug05 Meeting in Houston with Kalsi Seals
16Sep05 University of Tulsa Graduate Seminar presentation
9Jan06 Hired EngATech to prepare Engineering Drawings of HSM 3”
10Jan06 Meeting with EngATech on HSM 3” physical layout and design
3Mar06 Fahimi to Tulsa for review of motor physical layout and design
22Mar06 DOE Microhole Meeting in Houston, visit with TerraTek on use of motor
31Mar06project no cost extension to 31Sep06
31Mar06Project manager change from Rhonda Jacobs to Paul West
25Mar06 ICEM2006 paper No.245 entitled "Comparative Evaluation of Axial Flux versus Radial Flux Permanent Magnet Synchronous Machines" authored by M. Krishnamurthy, B. Fahimi and K. D. Oglesby was accepted for presentation

Financial Status as of 31March06-

Original Authorization-	$ 221,323
Invoice to DOE-	$ 140,661
Remaining Balance-	$ 80,662
Contract end date-	31Sept06

Discussion and Results:

The motor concept is based on a patent pending configuration by Ken Oglesby. The basis of which is that the internal shaft is attached to the drill string and does not rotate. The outer housing rotates with the bit/ mill/ cutting surface attached to it. The motor resides between the fixed shaft and rotating housing, driving the housing to rotate. A channel(s) exists in the fixed shaft that allows fluids to flow through the motor without contact of any powered components. These fluids can be at any pressure and type since they will only contact the internal channel at high pressure and outside of the outer housing at lower pressure. Higher rotating mass and abrasive jetting can also be of benefit with this configuration of electric motor.

Initial concerns in the project were to determine the characteristics of the cutting elements to be used at these ultra high speeds. The problem is the ultra high tip velocities developed and the large amount of heat generated. Few materials can stand the expected temperature, impact and abrasive wear. Very little data is available, and only natural diamonds, TSP (thermally stable polycrystalline diamond) and PDC (polycrystalline diamond) materials have been identified as potentially useable at these ultra high speeds. Only TerraTek's DOE work with small (less than 1"OD), core style, natural diamond bits comes closest. While the TerraTek work sheds some light on the benefits, little other data was obtained. Discussion with several bit manufacturers revealed only that lighter weight-on-bits and less torque would be expected.

The two motor sizes selected were 1.6875" OD and 3.00" OD, full dimensions are given in Figures 1 and 2 for radial design motors. The smaller OD was selected to fit into the microhole range of work. The tip velocities on smaller diameter bits is proportionally lower with smaller bit sizes…requiring smaller motors as well. See Figure 1. This smaller size would allow passage through standard 2-3/8" tubing (1.995" drift ID) and useable with 1.875" to 2.75" bits / mills. The larger size was targeted for passage through 4-1/2" tubulars and with 3.5" to 4.75" bits/ mills. Larger sizes can be designed and made later.

The next step was to quantify the unit power of motor needed to do the smallest drilling tasks. This included the simple tasks of just overcoming simple drag in the hole and lifting of the bottom hole assemble in a horizontal hole. Again, a literature search shed no light on this issue. To get some handle on the minimum power needed some experiments in Impact's Tulsa shop showed that on bare steel to steel friction, there is less than 4 ft-lbs over 110" of linear contact. It is expected that a motor, bit and related tools may be up to 36" long with a broader contact area than tested. A 400% safety factor would put this startup torque at about 16 ft-lbs. This converts to about 3 horsepower at startup speeds (100rpm). With little data available it was decided to simply develop the maximum horsepower/ torque in a one foot unit length of motor for all designs. The lengths can be adjusted later.

The system voltage selection process considered insulation materials, transmission, control, depth, temperature and power density generated in the motor. It was determined that 300VDC. System power transmission for 5000 feet will be 300 VAC to allow for maximum power, minimum magnetic field generated (as in DC transmission) and BHA/ control signals to be imbedded in the power wave. Voltage and power losses were determined to be acceptable, depending on the number of motor stages required and other instrumentation. The actual power consumption and losses will be determined after motor designs are finalized.

Transient 3D Finite Element Analysis (FEA) with various magnetic configurations. All motor designs will require a control disc at the motor for converting AC to DC and a second disc at the motor for controlling the motor to obtain optimum performance (speed versus torque versus power).

Figures 2 and 3 show the diference between conventional motors and inverted motors. For more information go to www.impact2u.com, since this has been covered before. Both radial and axial motor were studien in the inverted configuration. The basic difference between a conventional and the new inverted motor is described below and shown in Figures 1 and 2 and at www.impact2u.com.

Conventional radial motors (any type or design) for drilling utilize a motor housing affixed to the drillstring; the motor housing is non-rotating relative to the drillstring; the internal shaft floats on bearings and is actuated (rotated) by an internal radial motor (of any type or design); a drill tool (bit) is directly attached to the internal motor shaft. Fluid flow goes from the drillstring, through the housing/rotor annulus (motor) then crosses over back into a shaft channel to exit the end of the shaft/ tool/ bit. Full fluid flow bypass of the motor would require an upstream/ motor high pressure rotating seal and stronger bearings. Installing electrical/ optical wiring through a rotating shaft cannot be done realistically.

New Inverted Motor configuration (any type or design) inverts those basic element functions. The shaft is now affixed to and non-rotating relative to the drillstring. The housing now rotates around the shaft. The internal motor (electric in this project) now actuates/rotates the housing. The drill tool is attached to or is part of the motor housing. The shaft can contain any number of internal channels for flow or wiring. Such channels can be completely non-communicated to the exterior of the channel through the motor. The shaft can extend to or beyond the housing or drill tool for attachment of additional tools or instruments.

In addition to the benefits of conventional electric motors reported earlier by GE and XL Technology, several new benefits are expected with this new inverted motor design (listing limited to electric versions):

- Multiple liquids (hydraulic), gases (pneumatic), multiphase (energized) power fluids, slurries with solids, bases, acids, and other nasty fluids can be utilized for drilling due to the mechanically sealed internal channel.
- High Pressure fluids can be utilized for the drilling process. The internal channel <u>allows for high pressure and nasty fluids to fully bypass the motor section – this is required for an electric version.</u>
- High Temperature applications are also possible with selected motor materials.
- Directional hydraulic and abrasive jetting is also possible utilizing an offset-directed nozzle attached to the end of the fixed, non-rotating shaft. Movement of the drillstring or shaft would control and redirect this cutting stream.
- Multiple Motors can be placed at any point in the drillstring. These IM motors can be fully independent of each other or tied together for series or parallel power output. These IM motors can turn in either direction and at different speeds allowing for balanced net radial forces (i.e., Torque) to the drillstring- permitting smaller (diameter and material) drillstrings / coiled tubing.
- Multiple Motor Types (Gerotor, Progressive Cavity, Roller Vane, Turbine, Wing, Electric, others) can be can be used in the same drill string.
- Multiple Bends in the fixed non-rotating pipe sections between motors can be used to augment directional drilling for very sharp turns.
- Measurement While Drilling (MWD- realtime measurement and reporting of key drilling conditions) and Logging While Drilling (LWD- realtime measurement of key rock/ formation conditions) at/near the bit can be wired through Inverted Motor(s) to the surface, via the internal fixed, non-rotating motor shaft channel-

allowing bi-directional high data stream rates. In conventional systems these measurements are made 30-100’ above the bit, due to motor limitations (primarily).

- Ultra-short Turning Radii in directional drilling possible due to the very compact motors (short motors due to the high power density per motor length), directed hydraulic/ abrasive cutting at the drilling tip, ability to divide the drilling power requirements to multiple motors instead of only one and the ability to have multiple bends between motors/ tools.
- Enhanced Hole Cleaning with attached drilling tools (screws, cams) on multiple IM Motor housings allows pipe movement without drillstring rotation. Also due to the fact that motor speed is not independent to hole cleaning requirements.
- Smart Drilling Systems (fully electric, automated, fully instrumented and controlled- surface and downhole) are possible since all fluids can fully bypass (yet still cool) the motor section and the full assembly can be wired to the surface for bi-directional signals.
- Low/ No WOB Drilling Systems can be considered- important for thinner walled coiled tubing drilling.
- Retrievable Motors/ Bit Assemblies through the drillstring are possible

An axial PMSM motor’s torque-speed response or performance curve is shown in Figure 4. This shows that as the motor loads up or slows down, the torque increases- the direction to maintain speed- a very favorable relationship for drilling. Also, maximum torque is seen at stall and near stall conditions. Sort power surges can temporarily ncrease torque if needed.

Radial motor designs in the 1.69” OD inverted configuration motor resulted in 2.36 Hp, 1.24 ft-lbs per foot of motor length at 10,000 rpm with good power over the full rpm range. In fact, start up torque is estimated at 1.75 ft-lbs without surging the input power. The 3.0” OD inverted radial motor design shows 4.53 Hp, 2.38 ft-lbs per foot of motor length at 10,000 rpm. Startup torque was estimated at 6.47, 3.4 ft-lbs per foot of motor length. Radial designs were dropped from further study due to the much stronger axial designs.

Axial designs for both motor sizes were studied by Dr Fahimi at UT-Arlington. Three D models and FEA results are shown in Figure 5. The results of this work for the 3” motor indicates that a 5’ motor would yield 59 Hp at 10,000rpm and would have a stall torque of 99ft#. The 1.69” motor at a 5’ length would have 12 Hp at 10,000rpm and 74ft# at stall. These are considered conservative.

Dr Fahimi will still need to prepare the cascading programs that will reside on the control board at the motor which will control the torque and speed of the motor. This can be seen in Figure 6. However, this work cannot be finalized until motor components are available.

Based on the motor electro-mechanical design by Dr. Fahimi, the physical motor layout was made using SolidWorks. This engineering modeling allows consideration of machining fit, assembly and other fabrication and operations concerns. See Figure 7 for a single stage. Dynamic 3D FEA of key components will be performed once the final design is set.

As a side note- a 3” OD PMSM motor for 0-2000 rpm was designed in a separate study with Dr Fahimi. This motor will use the same basic bearings and seals as the 3” HSM motor. Since we have been conservative on the motor section, we expect in excess of 9Nm (6.7 ft-lbs) of torque per 0.5 ft of power section length at 1000rpm.

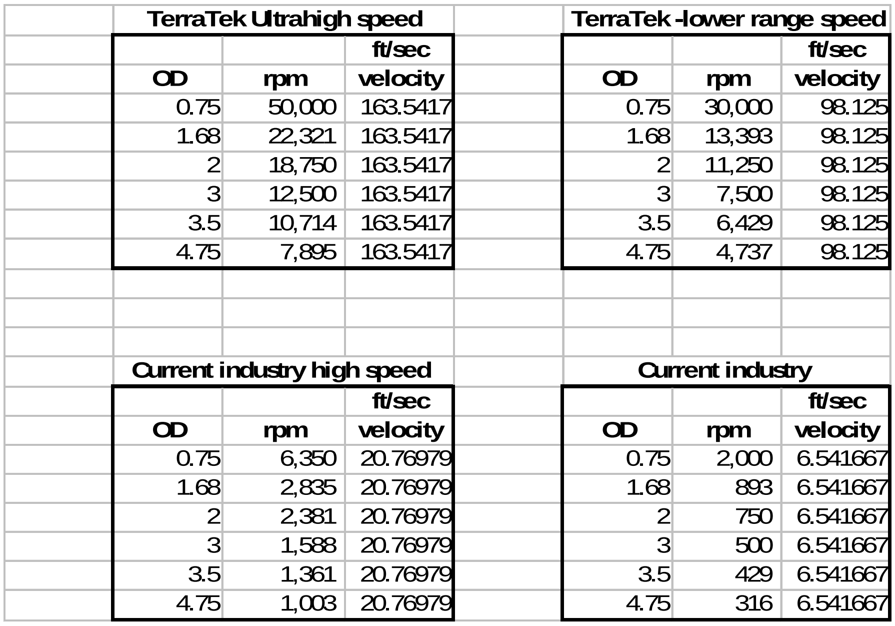
Both metal-metal and PDC bearing surfaces have been investigated for this motor configuration. Dennis Oil Tools, Houston, was visited concerning their expertise in the PDC bearings. Manufacturer catalogs have been studied for other options and these will be visited to choose the optimal bearing materials. Non-metal bearings would perform well under the low load conditions expected in this motor, however material contamination is of concern.

Heating concerns will be addressed. Bending concerns will have to be addressed as it related to shaft size / strength and the air gap thickness between the motor’s moving parts. Seal assembly is also of concern and will be addressed. Balancing of all motor parts and induced harmonic vibrations must also be investigated. Cooling of the motor is also of concern in that a minimum flow rate is required and must be known.

Dr Fahimi is not contacting vendors for manufacturer availability and cost estimates.

Graphical Materials

(note that all graphics were taken from reports from Dr. Fahimi)



TerraTek Ultrahigh speed

OD	rpm	ft/sec velocity
0.75	50,000	163.5417
1.68	22,321	163.5417
2	18,750	163.5417
3	12,500	163.5417
3.5	10,714	163.5417
4.75	7,895	163.5417

TerraTek -lower range speed

OD	rpm	ft/sec velocity
0.75	30,000	98.125
1.68	13,393	98.125
2	11,250	98.125
3	7,500	98.125
3.5	6,429	98.125
4.75	4,737	98.125

Current industry high speed

OD	rpm	ft/sec velocity
0.75	6,350	20.76979
1.68	2,835	20.76979
2	2,381	20.76979
3	1,588	20.76979
3.5	1,361	20.76979
4.75	1,003	20.76979

Current industry

OD	rpm	ft/sec velocity
0.75	2,000	6.541667
1.68	893	6.541667
2	750	6.541667
3	500	6.541667
3.5	429	6.541667
4.75	316	6.541667

Figure 1 Cutting Tip Velocities

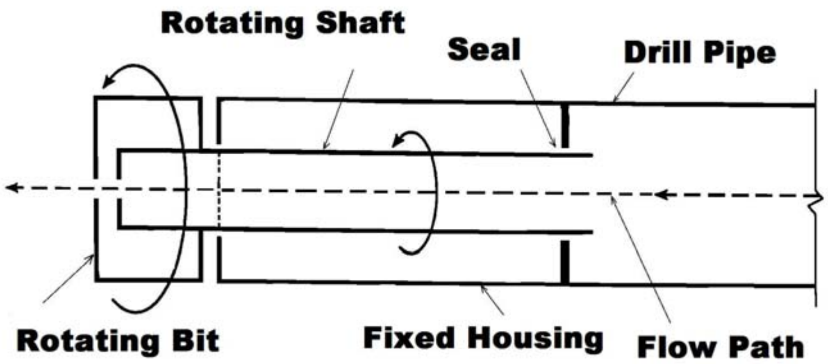


Fig. **2**

Conventional Electric Motor

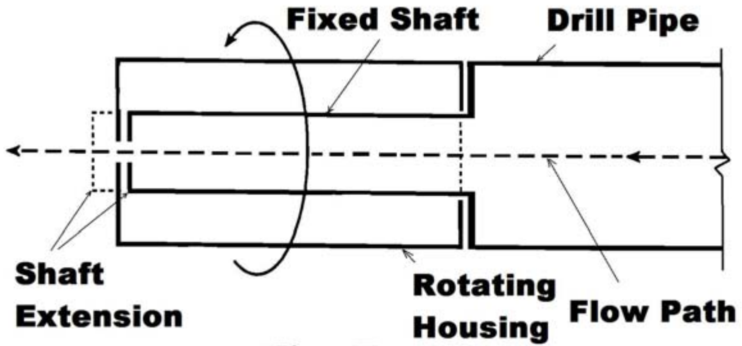


Fig. 3

Inverted Electric Motor

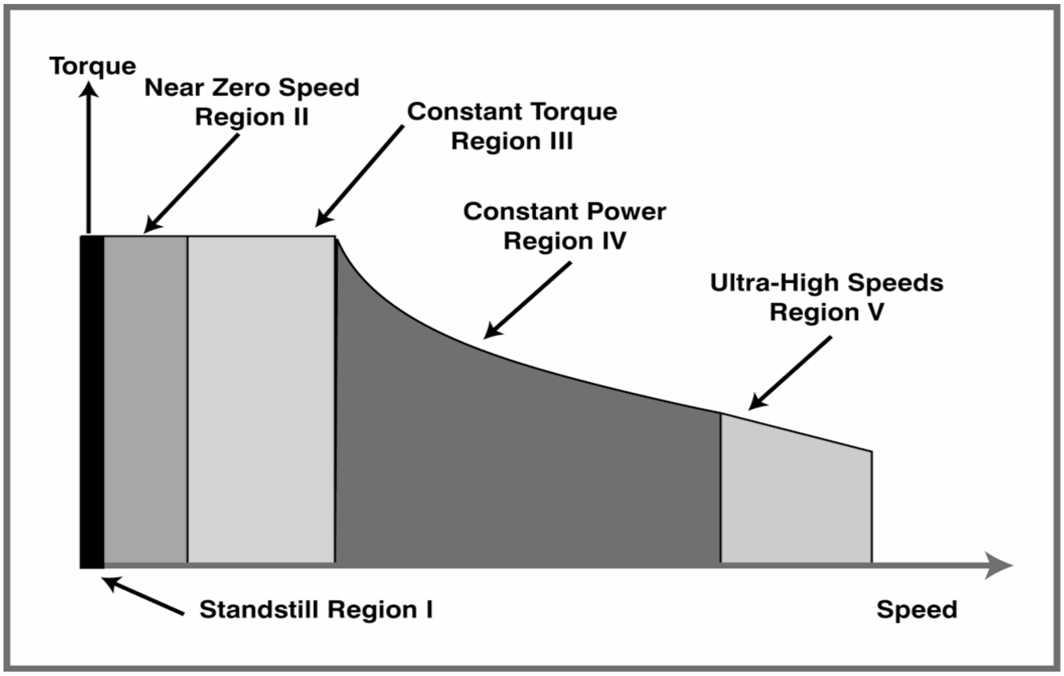


Figure 4- PMSM Torque-Speed Response Curve

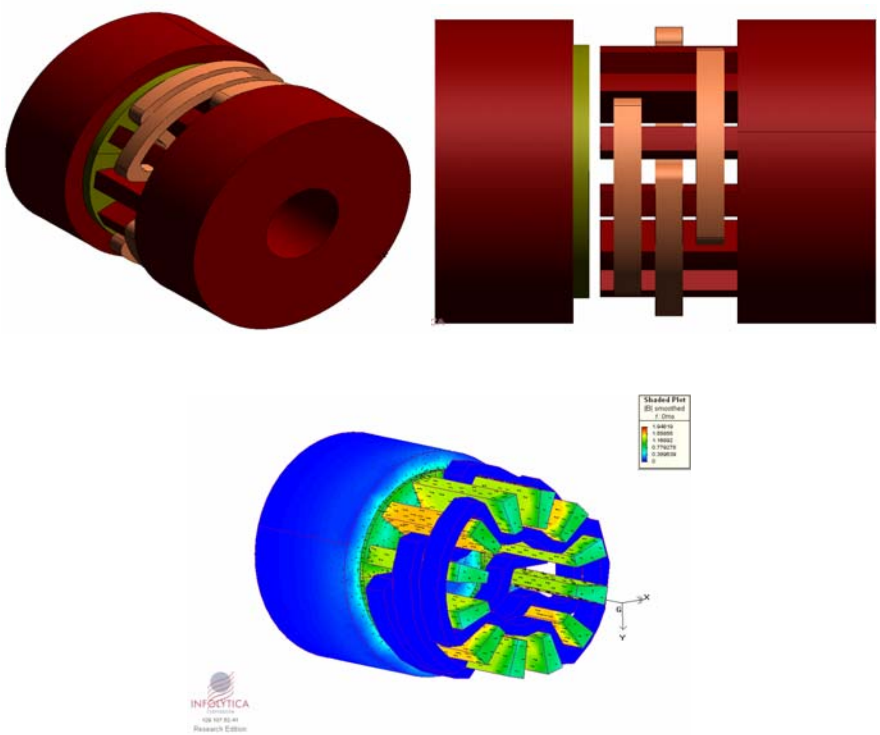


Figure 5- 3” OD PMSM models (2 3D views) and 3D FEA analysis

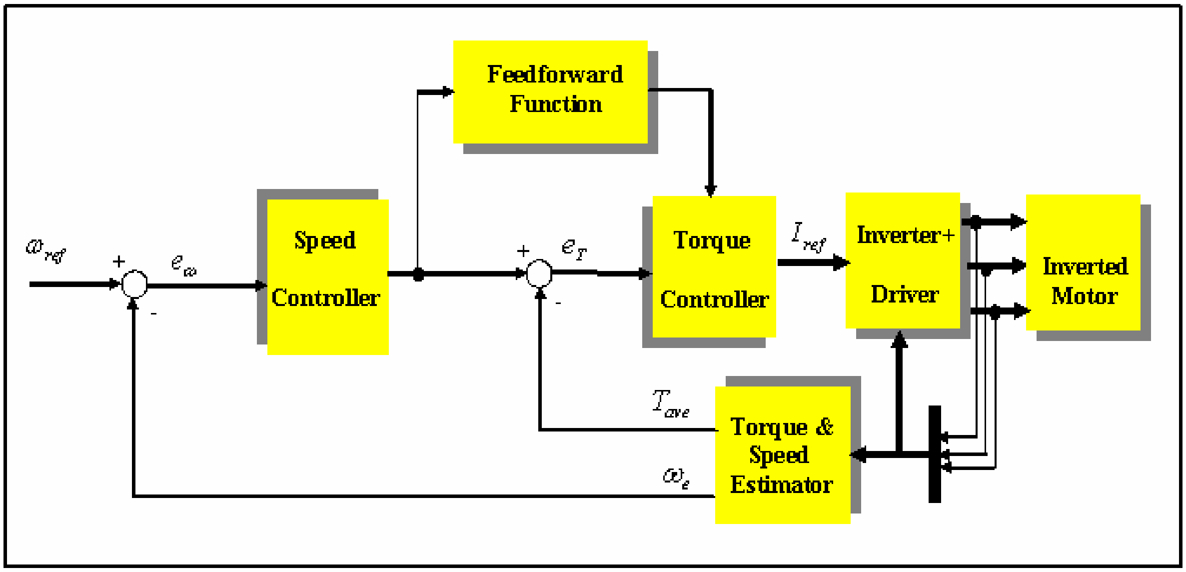


Figure 6- Cascading Control Loop for PMSM

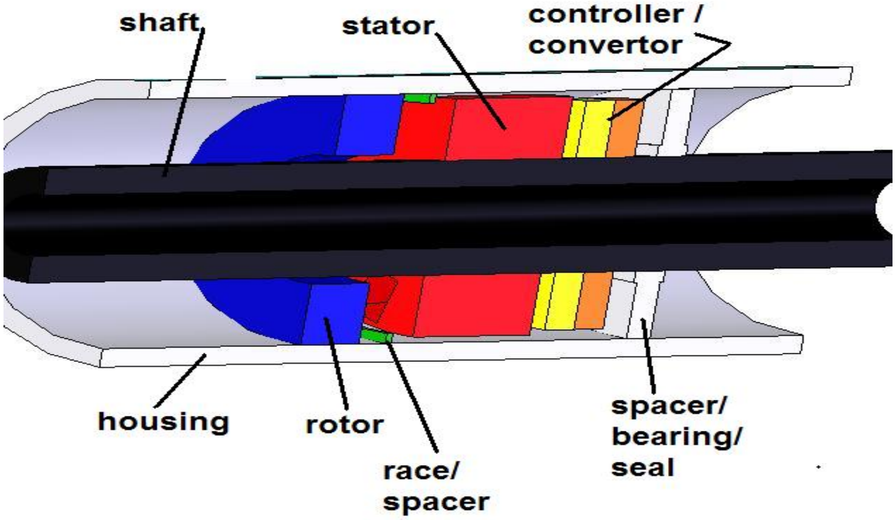


Figure 7 - 3” OD PMSM Engineering Design- single stage

References

None given for this status report

Bibliography

None given for this status report

List of Acronyms, Abbreviations, Conversions and Equations

Horsepower = Torque(lb-ft) * rpm/ 5252

Watts = Torque(lb-ft) * rpm/ 7.04

Foot-Pound Torque = Newton-Meters Torque * 0.7376

NOYB = None of Your Business (as in confidential or proprietary information)

Appendices

None given for this status report

Advanced Ultra-High Speed Motor for Drilling

Contract : DE-FC26-04NT15502

Goal : The project goal is to design two sizes of ultra-high speed (10,000 rpm) electric inverted configured motors for drilling.

Performers:
Impact Technologies LLC, Tulsa, OK and University of Texas, Arlington, TX

Results :
Researchers have developed electromagnetic designs for radial and axial motors in 2 outer diameters (OD) for rotational speeds up to 10,000 rpm. Magnetic saturation and power/torque estimations have been made at various speed and loading conditions. Bearing and seal materials have been studied and manufacturers contacted. The project milestones completed to date are:

- Review and analysis of ultrahigh-speed cutters and bits to set motor requirements;
- Selection of motor diameters and torque / horsepower requirements;
- Electric-magnetic radial motor design of 1.69-inch OD;
- Electric-magnetic radial motor design of 3.0-inch OD;
- Electric-magnetic axial motor design of 3.0-inch OD;
- Electric-magnetic axial motor design of 1.69-inch OD; and
- Review of materials, methods and manufacturers for ultra-high speed seals and bearings.

Benefits:
Ultra-high speed drilling, as enabled and powered by this patented configured motor, has the potential to provide a step change over current drilling and boring processes. Its application to deep, hard rocks and/ or with microhole drilling will allow drilling of targets that are not currently possible or uneconomic to attempt. This will result in lower costs to drill and/ or find new reserves. It has applications in the oil and gas (exploration, drilling, completion and production); gas storage industry (enhanced deliverability); geothermal (injectivity); road boring; resource mining; utility trenchless installations (telephone, fiber-optics, communications, water, sewer, etc.); pipeline installations across roads and rivers; and job / fabrication shops.

Background:
Drilling boreholes in materials at ultra-high speeds (>10,000 rpm) has been shown to penetrate faster than at lower speeds. Utilization of ultra-high pressures (excess of 10,000 psi), abrasive and/or corrosive fluids or other high-energy processes has also been shown to further increase penetration rate. A newly configured and patented motor design can utilize all the above mentioned advanced drilling techniques for drilling difficult materials on the surface and in the earth. The chief benefit of this “inverted” motor configuration over conventional motors is that the internal high-pressure fluids, wires or

cables are not in contact with the motor power components. This new configured motor is being deployed in this project as an electric motor to drive cutters at these ultra-high speeds. With this motor it will be possible that some extremely hard and/or deep geological rocks and materials now can be drilled, where currently they cannot be drilled efficiently, economically or even at all.

Summary

This project began in October 2004 and initially focused on the applications and bits that are to be used in these ultrahigh-speed drilling applications. This was important to determine the required or estimated load, torque, horsepower, and sizes of the motors. From this study, it was found that few cutter elements and bits can withstand the generated heat, abrasiveness, and shock of this environment, although current work in this area is encouraging. A separate DOE project with TerraTek is studying cutting elements at these ultra-high speeds.

Based on this initial work, the motor requirements were set as a first pass for the electromagnetic design. The two motors sizes selected were 1.69 inches and 3.0 inches OD, with the lengths variable and motor power sections stackable. The internal and external fluid flows can efficiently cool the electrical/magnetic-induced heat load. Air gap clearances is ongoing concerns and proper spacing is required. Based on the simulations made, axial motor designs were found to be superior to radial designs based on unit power generated. Both power control and power inverter boards have been designed.

Materials, methods and manufacturers of bearings and seals have been identified and contacted. Final selection of these has not been made. Of specific concern is the no leak requirement of the internal gas phase at 5000ft operating depths.

Current Status (June 2006):

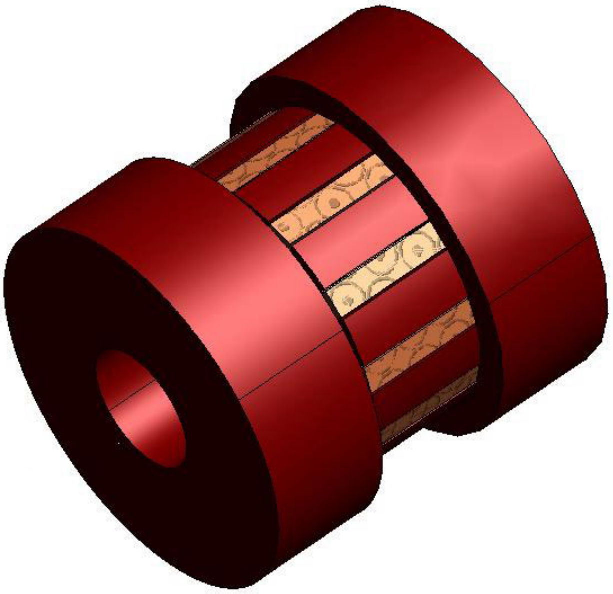
Researchers are focusing on bearing and seal materials and design. Remaining to be done are engineering stress analysis of the shaft and other key elements, limited heat transfer analysis of the final designs, and preparation of final machine drawings for prototyping.

Funding :
This project was selected in response to DOE's Oil Exploration and Production solicitation DE-PS26-04NT15450-1, Microhole II Breakout.

Project Start: October 1, 2004
Project End: September 31, 2006

Anticipated DOE Contribution: $165,882
Performer Contribution: $55,441 (25% of total)

Contact Information
NETL – Rhonda Jacobs (rhonda.jacobs@netl.doe.gov or 918-699-2037)
Impact Technologies, LLC – Ken Oglesby (kdo@impact2u.com or 918-627-8035)



3D Visualization of a compact, powerful ultra-high-speed electric motor designed for drilling.

Advanced Ultra-High Speed Motor for Drilling

DE-FC26-04NT15502

Goal

The project goal is to design two sizes of an ultra-high speed (10,000 rpm), inverted configured, electric motor specifically for drilling.

Performers

Impact Technologies LLC,
Tulsa, OK

University of Texas
Arlington, TX

Results

Researchers have developed PMSM (Permanent Magnet Synchronous Machine) electromagnetic designs of both radial and axial motors for rotational speeds up to 10,000 rpm in 2 outer diameters (OD). Finite Element Analyses of the magnetic saturation and power/torque output have been made at various speed and loading conditions. Mechanical 3D models have been prepared based on those designs. Bearing and seal materials have been studied and manufacturers contacted. The project milestones completed to date are:

- Review and analysis of ultrahigh-speed cutters and bits to set motor requirements;
- Selection of motor diameters and torque / horsepower requirements;
- Electric-magnetic design (including FEA) of 1.69-inch OD radial motor;
- Electric-magnetic design (including FEA) of 3.0-inch OD radial motor;
- Mechanical 3D SolidWorks model of 3.0-inch OD radial motor.
- Electric-magnetic design of 3.0-inch OD axial motor;
- Electric-magnetic design of 1.69-inch OD axial motor;
- Mechanical 3D SolidWorks model of 3.0 inch OD axial motor; and
- Review of materials, methods and manufacturers for ultra-high speed seals and bearings.

Benefits

Ultra-high speed drilling, as enabled and powered by this patented configured motor, has the potential to provide a step change over current drilling and boring processes. Its application to drill deep, hard rocks and/ or with microhole sized holes will allow drilling of targets that are not currently possible or uneconomic to attempt. This will result in lower costs to drill and/ or find new reserves. It has applications in the oil and gas (exploration, drilling, completion and production); gas storage industry (enhanced deliverability); geothermal (injectivity); road boring; resource mining; utility trenchless installations (telephone, fiber-optics, communications, water, sewer, etc.); pipeline installations across roads and rivers; and job / fabrication shops.

Background

Drilling boreholes in materials at ultra-high speeds (>10,000 rpm) has been shown to penetrate faster than at lower speeds. Utilization of ultra-high pressures (in excess of 5,000 psi), abrasive and/or corrosive fluids or other high-energy processes has also been shown to further increase penetration rate. A newly configured and patented motor design can utilize all the above mentioned advanced drilling techniques for drilling difficult materials on the surface and in the earth. The chief benefit of this “inverted” motor configuration over conventional motors is that the internal high-pressure fluids are not in contact with the internal motor power components, wires or cables. An electric version of this new configured motor is being deployed in this project to drive cutters at these ultra-high speeds. With this motor it will be possible that extremely hard and/or deep geological rocks and materials now can be drilled, where currently they cannot be drilled efficiently, economically or even at all.

Summary

This project began in October 2004 and initially focused on the applications and bits that can be used for these ultra-high speed drilling applications. This was important to estimate the required load, torque, horsepower, and sizes of the motors. From this study, it was found that few cutter elements and bits can withstand the generated heat, abrasiveness, and shock of this environment, although current work in this area is encouraging. A separate DOE project with TerraTek is studying cutting elements at these ultra-high speeds.

Based on this initial work, the motor requirements were set as a first pass for the electromagnetic design. The two motors sizes selected were 1.69 inches (pass through standard 2-3/8” tubing) and 3.0 inches (pass through standard 4.5” casing) ODs, with the lengths variable and motor power sections stackable to meet any required power requirement. The internal and external fluid flows can efficiently cool the electrical/ magnetic and bearing/seal friction induced heat load, thus a minimum flow rate will be required. Air gap clearance is an ongoing concern and proper spacing (via design and bearings) is required. Based on the simulations made, axial motor designs were found to be superior to radial designs based on unit power generated. Both power control and power inverter boards have been designed. The motor can be variably speed controlled. Power and torque output of the motor is very favorable over its full speed range.

Materials, methods and manufacturers of bearings and seals have been identified and contacted. Final selection of these has not been made. We have recently dropped the internal gas requirement in favor of a non-conducting internal fluid. Internal designs will be modified to minimize turbulence effects. This change has allowed seal to be designed, where otherwise (with internal gas) they could not be designed for no –seepage and ultra-high speeds.

Current Status (January 2007)

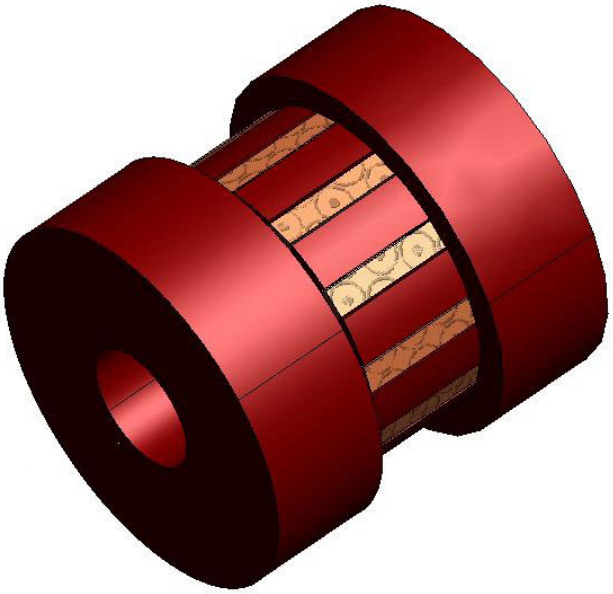
Electro-Mechanical designs have been made. Base mechanical models have been prepared. Remaining are- Internal model design revisions will be made to accomodate non-conducting liquid in the internal motor power section; . Final seal selections and designs; Final bearing selections and designs; FEA for stress analysis of the shaft and other key elements; Limited heat transfer analysis of the final designs to set minimum flow requirements; preparation of final machine drawings; and preparation of the Final Report.

Funding
This project was selected in response to DOE's Oil Exploration and Production solicitation DE-PS26-04NT15450-1, Microhole II Breakout.

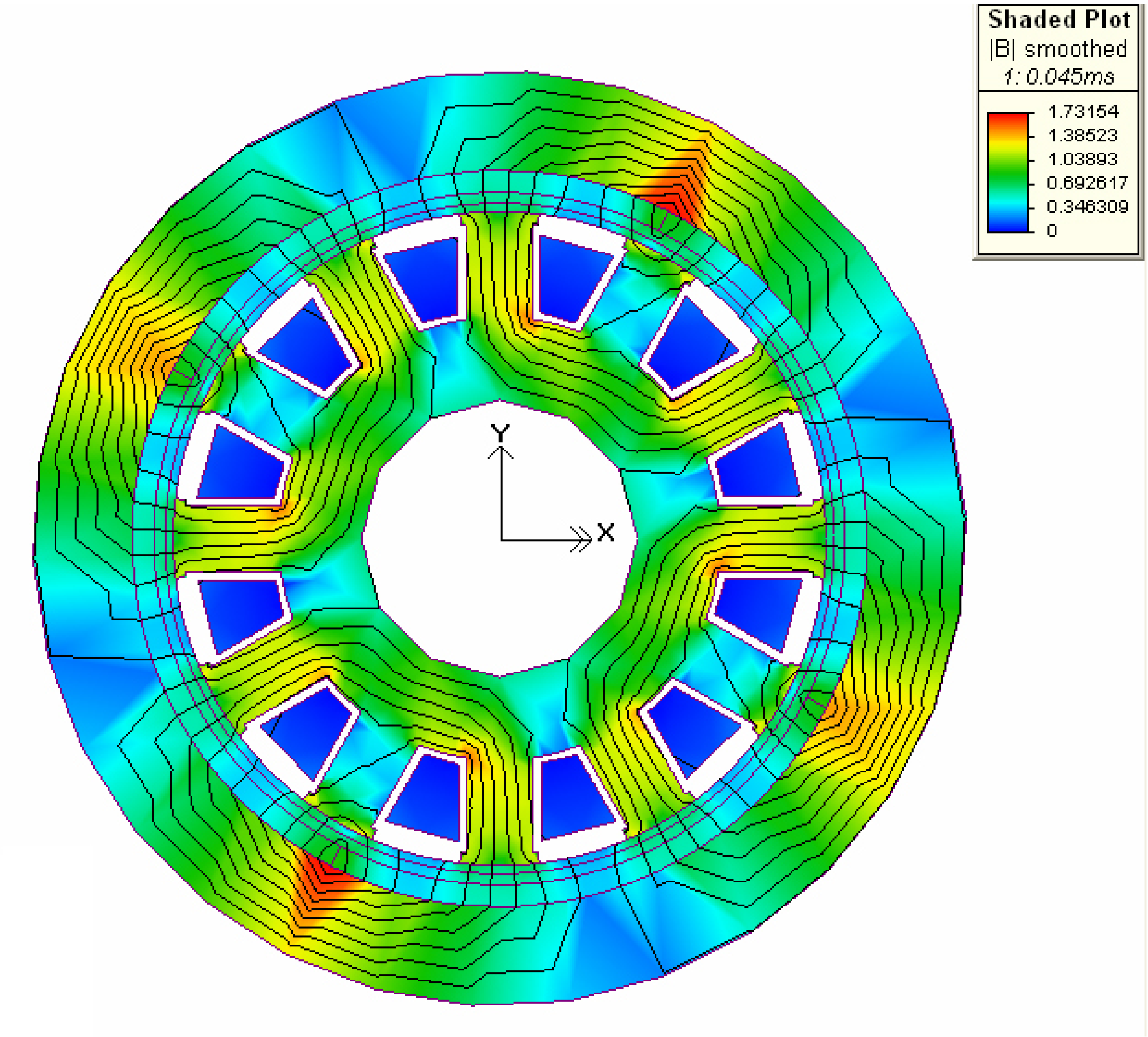
Project Start: October 1, 2004
Project End: September 30, 2006

Anticipated DOE Contribution: $165,882
Performer Contribution: $55,441 (25% of total)

Contact Information
NETL – Virginia Weyland (virginia.weyland@netl.doe.gov or 918-699-2041)
Impact Technologies, LLC – Ken Oglesby (kdo@impact2u.com or 918-627-8035)



3-D Visualization of a compact, powerful ultra-high speed electric motor specifically designed for drilling.



Magnetic field distribution in a small, ultra-high speed electric motor.

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APPENDIX H

Technical Presentations delivered for DOE/ NETL

for the

Advanced Ultra-High Speed (Electric & Inverted) Motor for Drilling Project

Advanced Ultra High Speed Motor for Drilling
DE-FC26-04NT15502
01Oct04 through 31March06

27 July 2005
Project Update

For
Rhonda Jacobs
US Department of Energy

By
Ken Oglesby
IMPACT TECHNOLOGIES LLC
and
Dr Babak Fahimi
University of Texas at Arlington

Advanced Ultra High Speed Motor for Drilling Summary

At 10 months into 18 month project

- Accomplished-
  - Set motor specifications (dimensions/ voltage/ Hp)
  - Made Electro-Magnetic-Mechanical design for radial and axial designs for 1.69” and 3.0”OD motors
  - Investigated various bearings and seals for ultra high speed applications- awaiting final EMM design
- Remaining-
  - Mate final EMM designs with appropriate bearings and seals
  - Perform heat transfer analysis of final designs
  - Prepare final machine drawings for prototyping

Advanced Ultra High Speed Motor for Drilling Outline of Discussion

- Contract Requirements
- Inverted Electrical Motor Configuration
- Motor Specifications
- Electro-Magnetic-Mechanical Designs
- Bearing / Seal Options

Advanced Ultra High Speed Motor for Drilling Contract Requirements

- Design only
- Electric motor for drilling
- 10,000 rpm speed
- Two diameter sizes
- Inverted configuration of motor
- Final designs ready for prototype manufacture

Advanced Ultra High Speed Motor for Drilling Inverted Motor Configuration

- Basic design
  - Shaft connected to drillstring and not rotating (stator)
  - Housing rotates (rotator) with bit attached
  - Shaft has channels for flow and wires
- Benefits
  - Allows advanced drilling techniques
    - Ultra high pressure / Abrasives / Acids/ bases
  - Directional and Logging (GR, resistivity) tools at bit
  - Multiple motors
  - Fits into Microhole Project sizes and CT capabilities
  - Ultra short radius turns
- Drawbacks
  - New, not tested
  - Shaft only now holds motor and lower string / tools

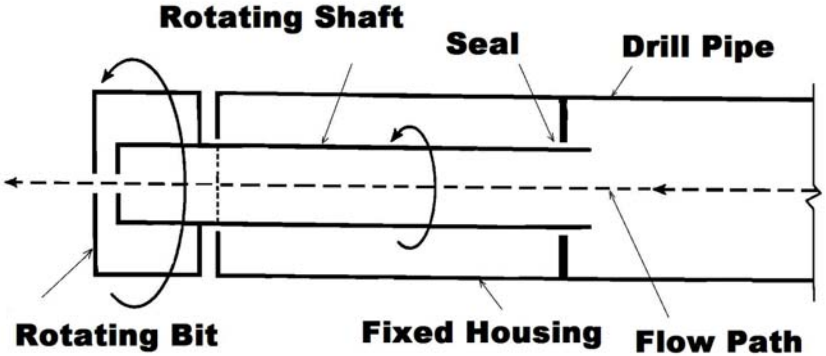


Fig. **2**

Conventional Electric Motor

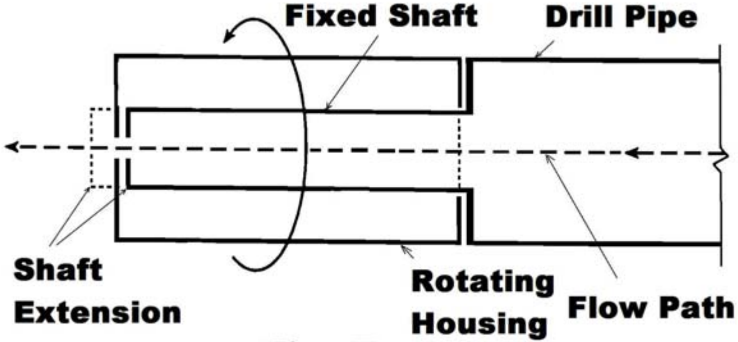


Fig. 3

Inverted Electric Motor

Advanced Ultra High Speed Motor for Drilling
Electric IM Drilling System Elements

1. Drill string with connected to motor shaft;
2. Electric (300VAC, 1-2 wire) power cable connected to motor' power converter;
3. Converter disc to convert 1phase AC to DC;
4. Controller disc to monitor the motor position and pulse the proper DC current to the stator coils;
5. Wired coils embedded in a stator (axial- disc, radial disc) and attached/wired to the non-rotating shaft;
6. Shaft (non magnetic) with flow and electrical wire channels,
7. Permanent magnets attached to outer housing (axial-disc, radial-inner lining);
8. Journal Bearings (non magnetic) between Shaft – Rotors and Stator-Rotors;
9. Thrust bearings on both ends of housing;
10. Keepers on both ends of housing; and
11. Bit connected to Housing

Advanced Ultra High Speed Motor for Drilling
Motor Specifications-Background

- Literature Review on DC machine fundamentals
  - Electric Machinery Fundamentals by SJ Chapman, ISBN 0-07-246523-9
  - Electrical Motion Devices by PC Krause, ISBN 0-07-035494-4
- Research into ultrahigh speed cutters
  - Ultra high rpms/ velocities generate high temps causing thermal cracking
  - PDCs, diamonds
  - Smith Premium HOT PDC cutters
  - Thermally Stable Polyrystalline Diamond Cutters- Bob Radkte / Technology International/ DOE work
  - TerraTek / Arnis Judzis, Alan Black/ DOE work on testing cutters for ultra high speeds
- Research into bearings
  - Mahlon Dennis/ Dennis Oil Tools- PDC-PDC bearings
  - NASA metal-metal coatings
  - Kalsi
  - Fahimi source
- Research into seals- Kalsi / Weatherbee

Advanced Ultra High Speed Motor for Drilling TerraTek Motor Comparison

- TerraTek motor specifications (used for Lab testing of high speed cutters) are:
  - Koford Hall Effect motor
  - 120VAC at 10 amps
  - Slottless, brushless DC, 2 pole (?) motor
  - 1.6”   OD???
  - 51,000rpm no load maximum speed
  - Stall torque 788oz-in==== 4.1 ft-lbs
  - Continuous torque is 80 oz-in=== 0.42ft-lbs
  - Peak output is 7383 watts===9.9 Hp
  - Continuous output 2700 watts===3.6 Hp
  - Maximum current utilized is 9 amps

Advanced Ultra High Speed Motor for Drilling
Motor Specifications- Setting

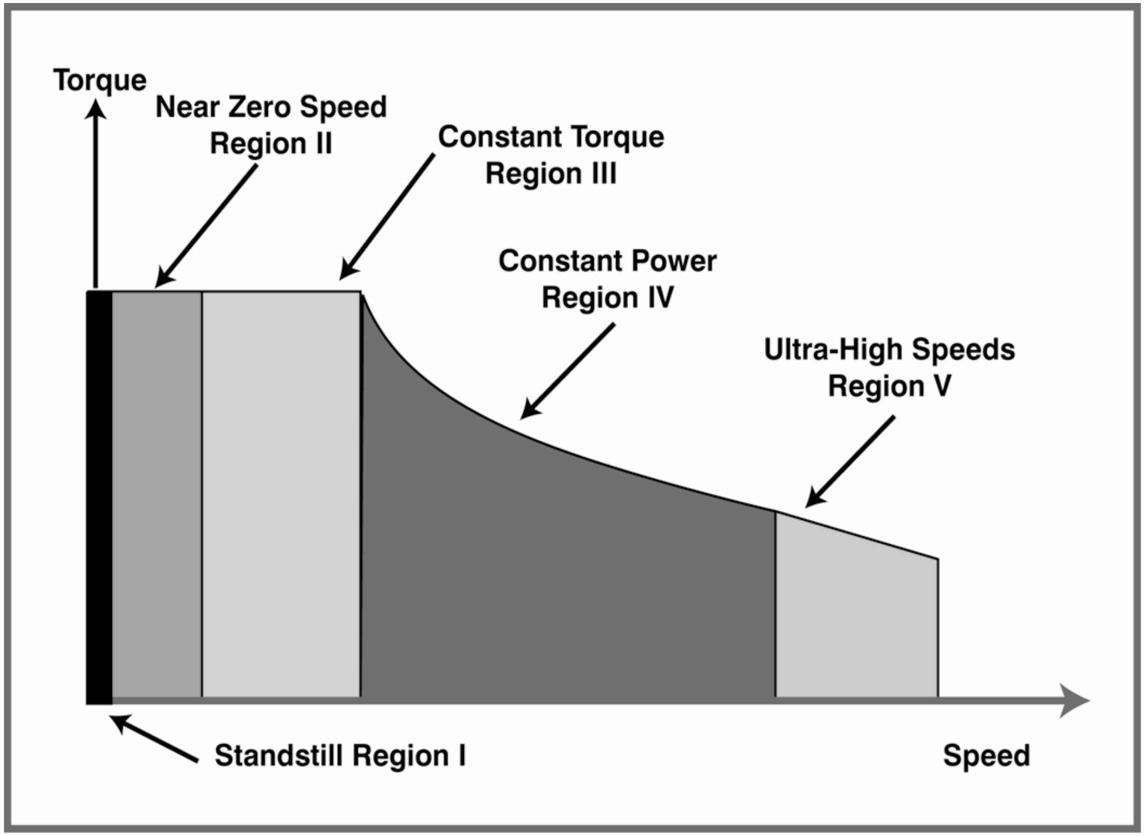
- Set Dimensional specifications
  - DOE Microbore Effort
  - 1.69” OD with 0.5” shaft OD
  - 3.0” OD with 1.0” shaft OD
  - Each power section 1 fool long
- Set Voltages and current type- 300 VDC motor with 220VAC 1phase line feed (at motor),
  - Line loss DC power- 10 amp 300VDC 5000’ length - 9.3Volt loss, 279 watt loss
  - Line loss AC power - 8.5 amps 208VAC - 304 watt loss. With AC can embed keys on AC signal for control of motor
  - Requires 2 lines for power transmission (only 1 if drillstring is used)
  - Higher voltages require special and /or thicker insulation and equipment
- Set Horsepower and Torque-
  - Bench Test Drag study showed 16 ft-lbs drag in horizontal position (400% SF)
  - Torque= 0.5*Bit diameter (inches) * WOB (#) * formation hardness factor (range 0.2-0.4)/ 12
    - Unknown source, estimated at +/- 25% accuracy
  - Estimate 2.0 - 10 ft-lbs required for WOB and sizes anticipated,
  - Target 3Hp stackable motor power sections within housing
  - maximum 1 ft length due to bending

- Set Airgap requirements/ concerns -1mm too small, target 3mm.
- Flow requirements for cooling due to heat generated by electronics in motor, bearings under loads, cutters in action

Advanced Ultra High Speed Motor for Drilling Electro-Magnetic-Mechanical Design Points

- Permanent Magnet Synchronous Motor, brushless
- Radial or Axial or Modified/ Hybrid
- Fully adjustable for speed and direction by key embedded in AC current
- Current gives power/ torque, but limited by metal type and amount,
- Voltage gives rpm capabilities
- Nonmagnetic materials required for spacers, journal bearings, shaft
- Stackable power sections to meet HP requirements
- 10amps per mmXX2 area is design with 80-90 utilization factor. Can go to 15amps/mm2 for surge of higher power
- Power sections set at maximum 1 ft in length or 3 Hp , whichever is shorter
- Back emf voltage is induced by motion of PMs
- Field weakening is used to keep power up at higher rpms
- Available PM materials are SMCO alloy good for 100C / NDFEBR for 150C
- Cogging is not a problem at high speeds, just low speeds. This is just resistance to motion when PM are much stronger that induced field
- Anything on the outside of the housing will not impact motor performance (cutters,…)

Advanced Ultra High Speed Motor for Drilling



Advanced Ultra High Speed Motor for Drilling Electro-Magnetic-Mechanical Design

Accomplished

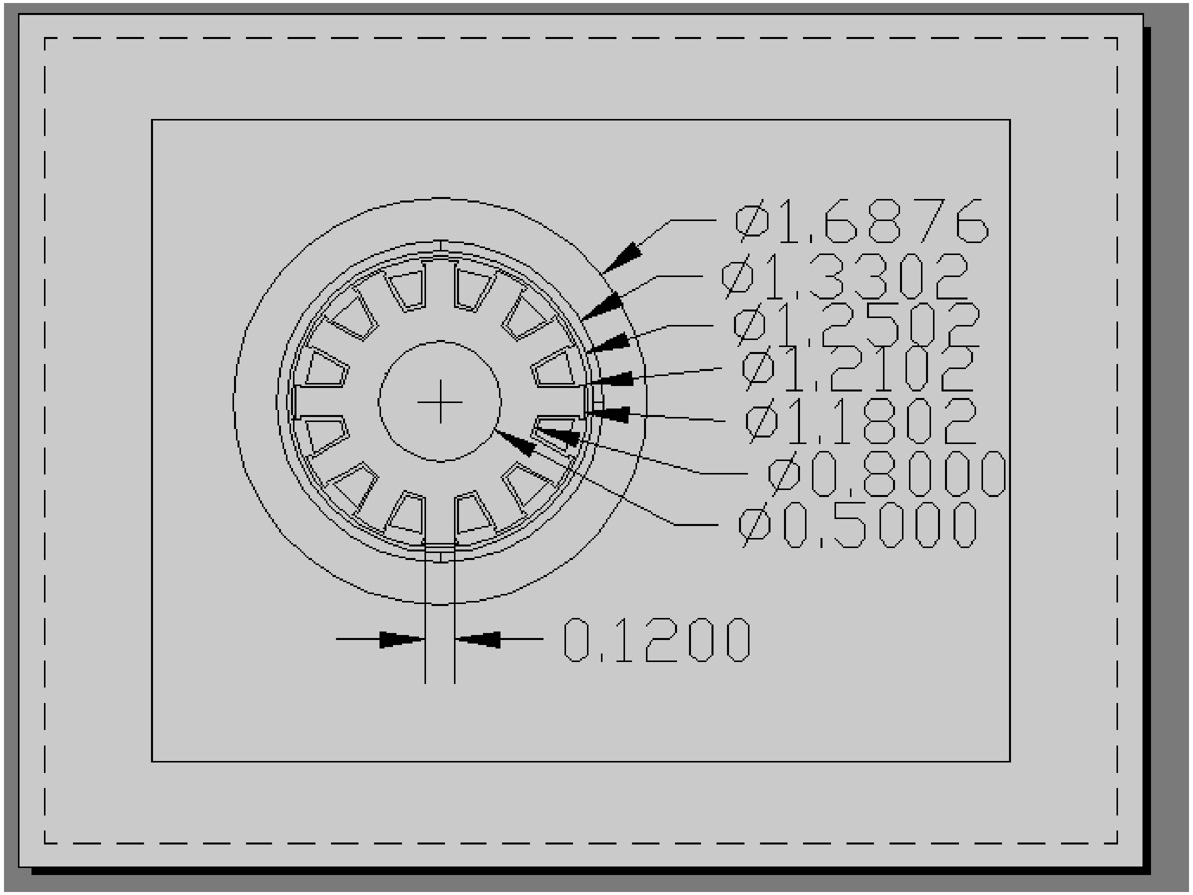
- Finite Element Modeling of Radial Design, 1.69”OD
- Finite Element Modeling of Radial Design, 3.0” OD
- Finite Element Modeling of Axial Design, 3” OD
- Non-magnetic requirements of shaft, bearings, spacers
- Settled on Axial design as best for optimization
- Estimated Core losses in Axial Design is 35W out of 2000W or 1.75% losses

Remaining

- Heat Generation and Distribution
- Power Convertor Disc Design
- Controller Disc design and Programing

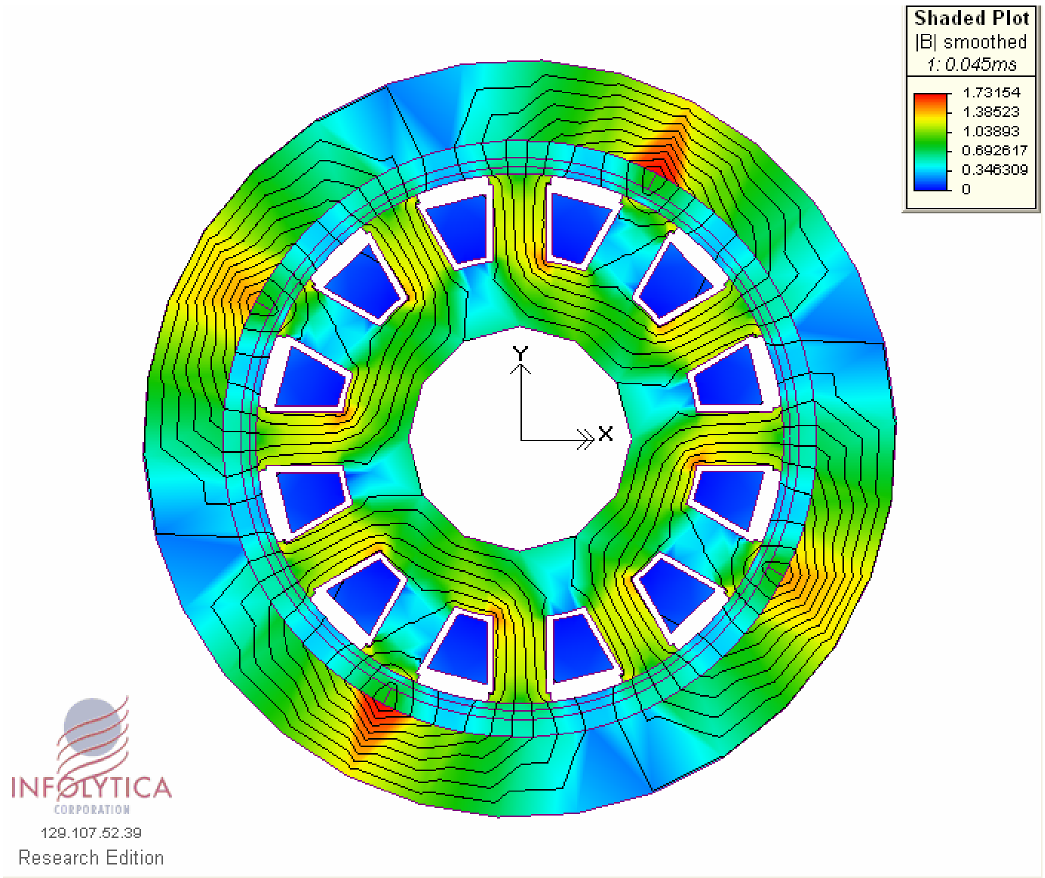
Advanced Ultra High Speed Motor for Drilling

Finite Element Modeling of Radial Design, 1.69inOD



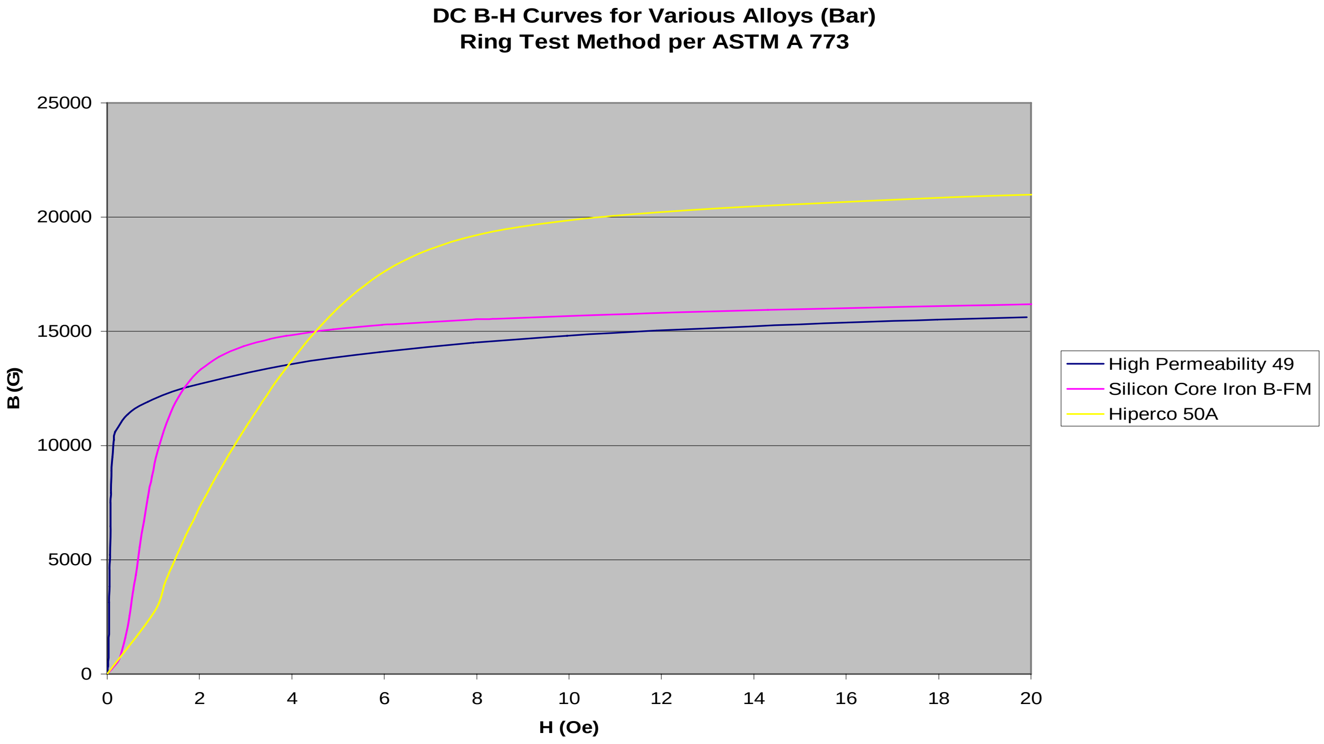
Advanced Ultra High Speed Motor for Drilling

Finite Element Modeling of Radial Design, 1.69in OD



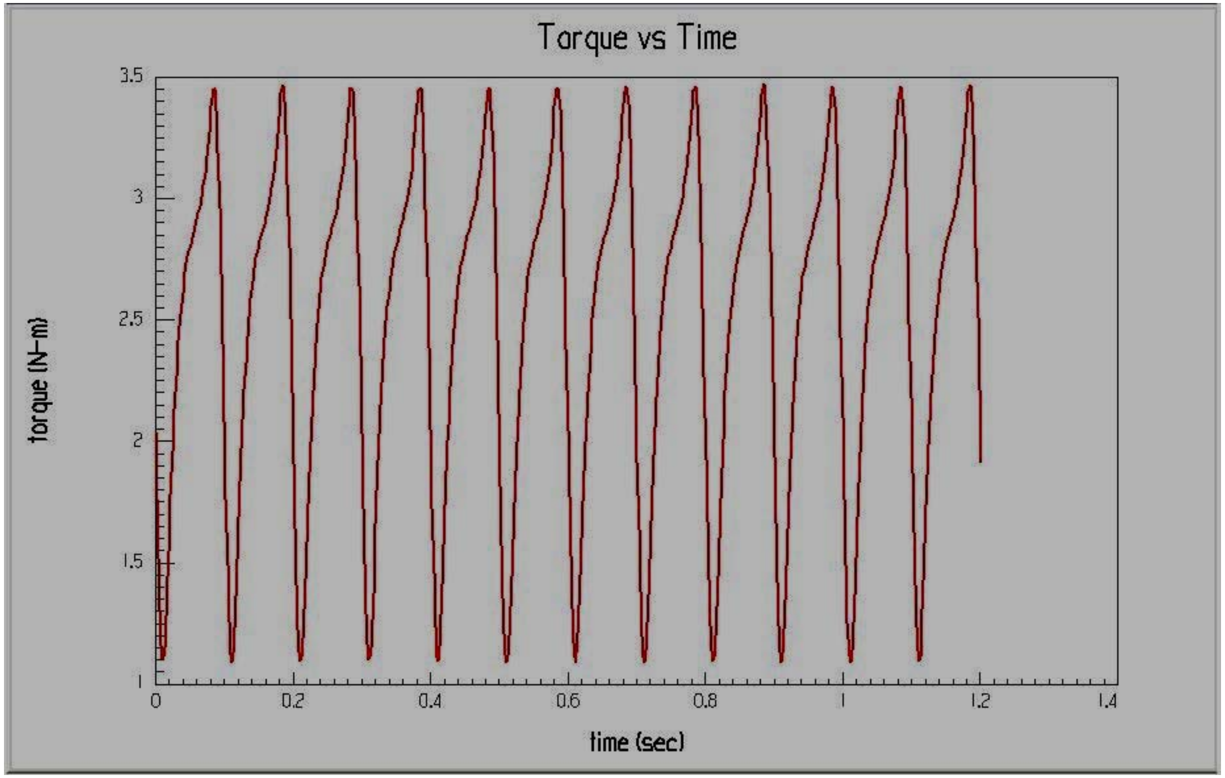
Advanced Ultra High Speed Motor for Drilling

Finite Element Modeling of Radial Design, 1.69”OD



Advanced Ultra High Speed Motor for Drilling

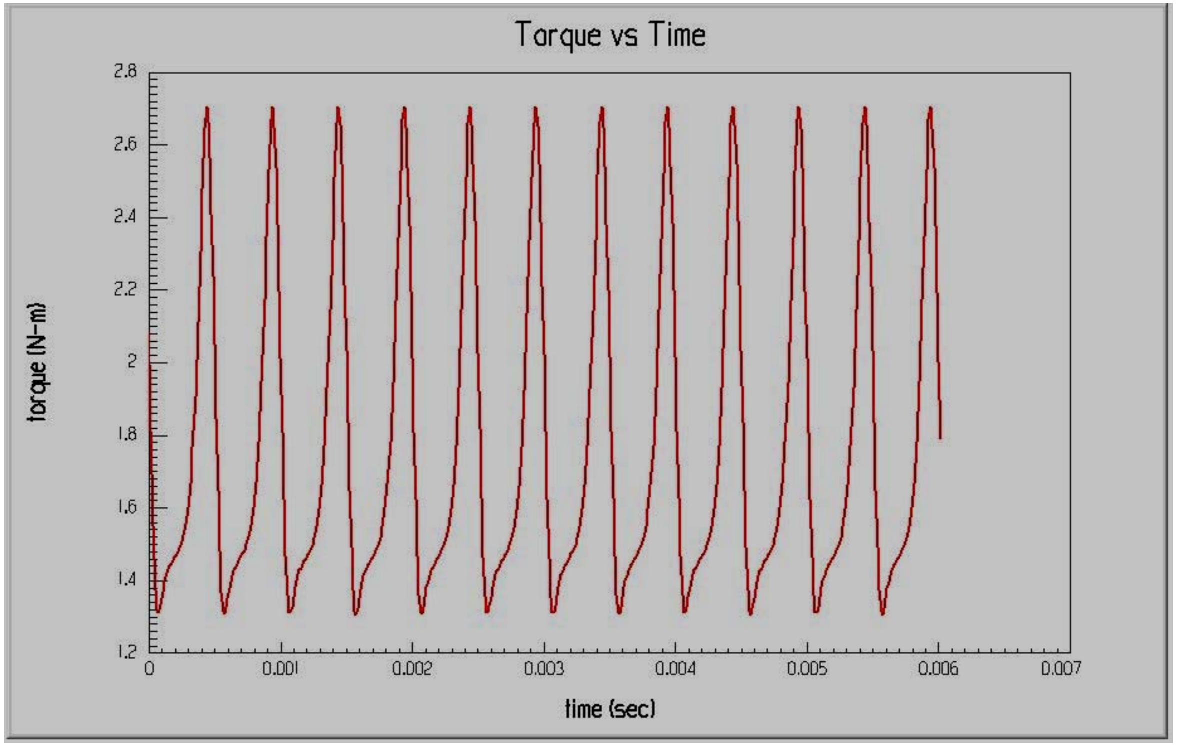
Finite Element Modeling of Radial Design, 1.69”OD



Torque profile at 50 r.p.m.—2Nm=1.48ft# , 0.013 Hp

Advanced Ultra High Speed Motor for Drilling

Finite Element Modeling of Radial Design, 1.69”OD

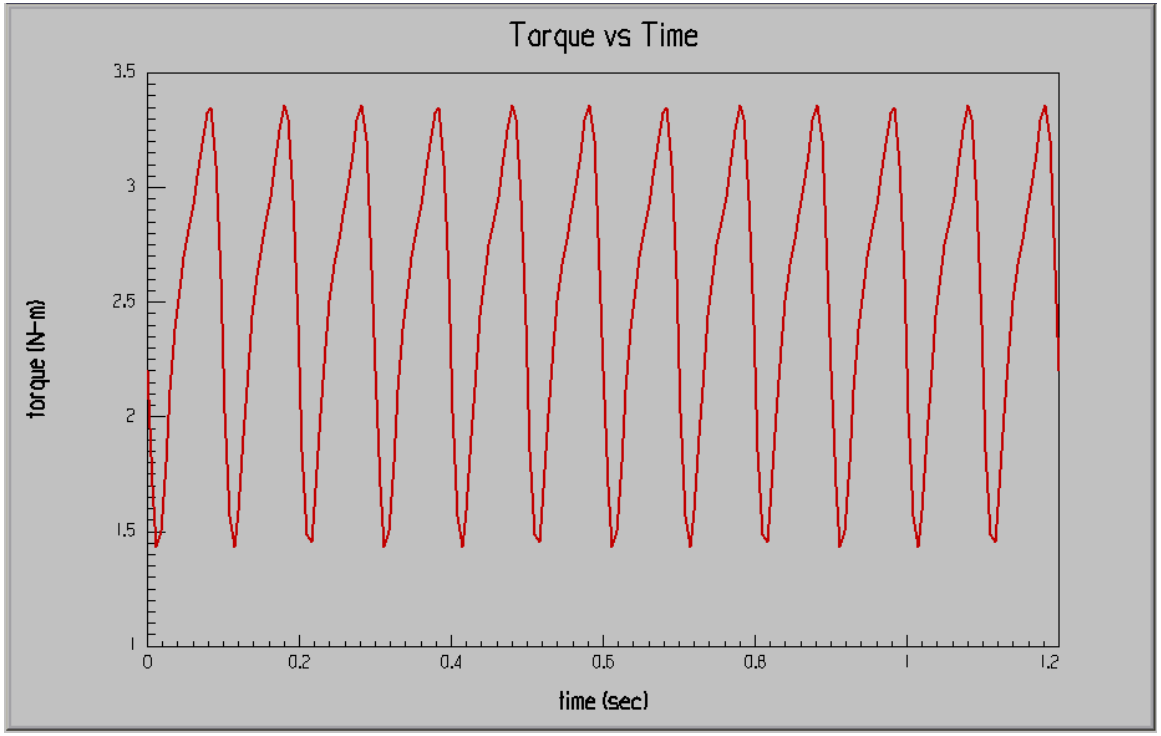


Torque profile at 10000 r.p.m.- 2 Nm=1.48ft-#, 2.68 Hp

Advanced Ultra High Speed Motor for Drilling

Finite Element Modeling of Radial Design, 3.0”OD

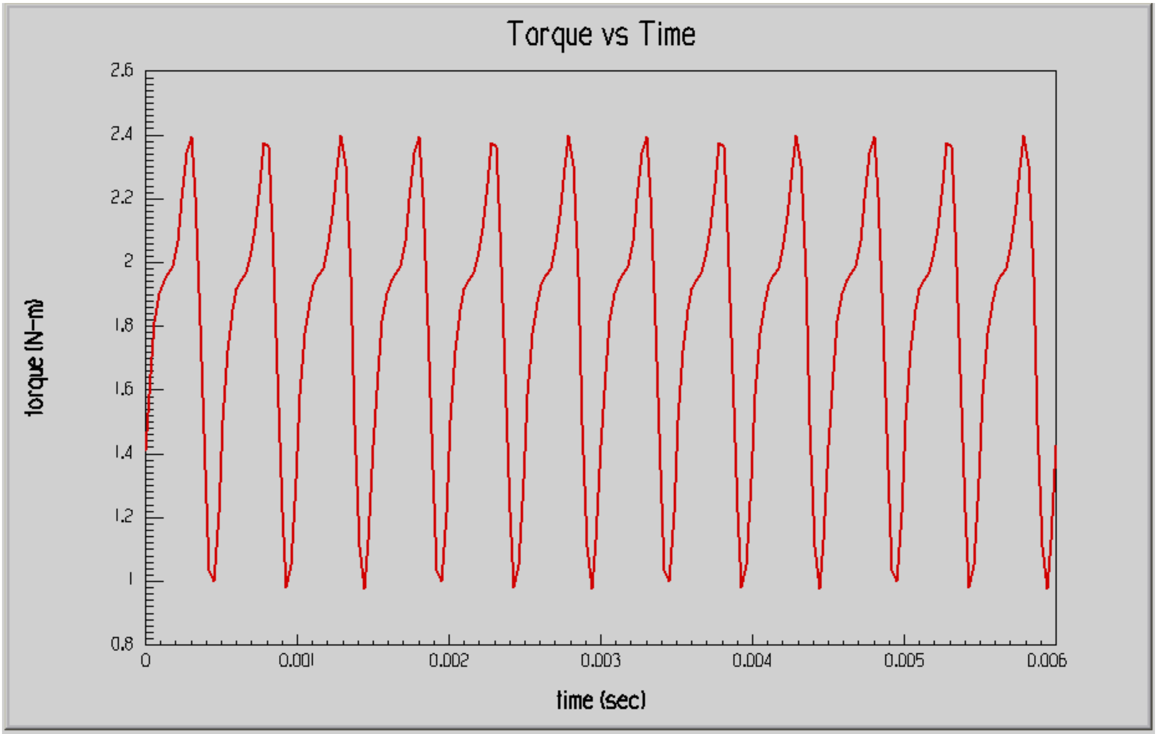
1.Torque profile for speed of 50 rpm. The current=2A, No. of turns=65.
2.Average value of torque generated is 2.51548 N-m= 1.8 ft-#



Advanced Ultra High Speed Motor for Drilling

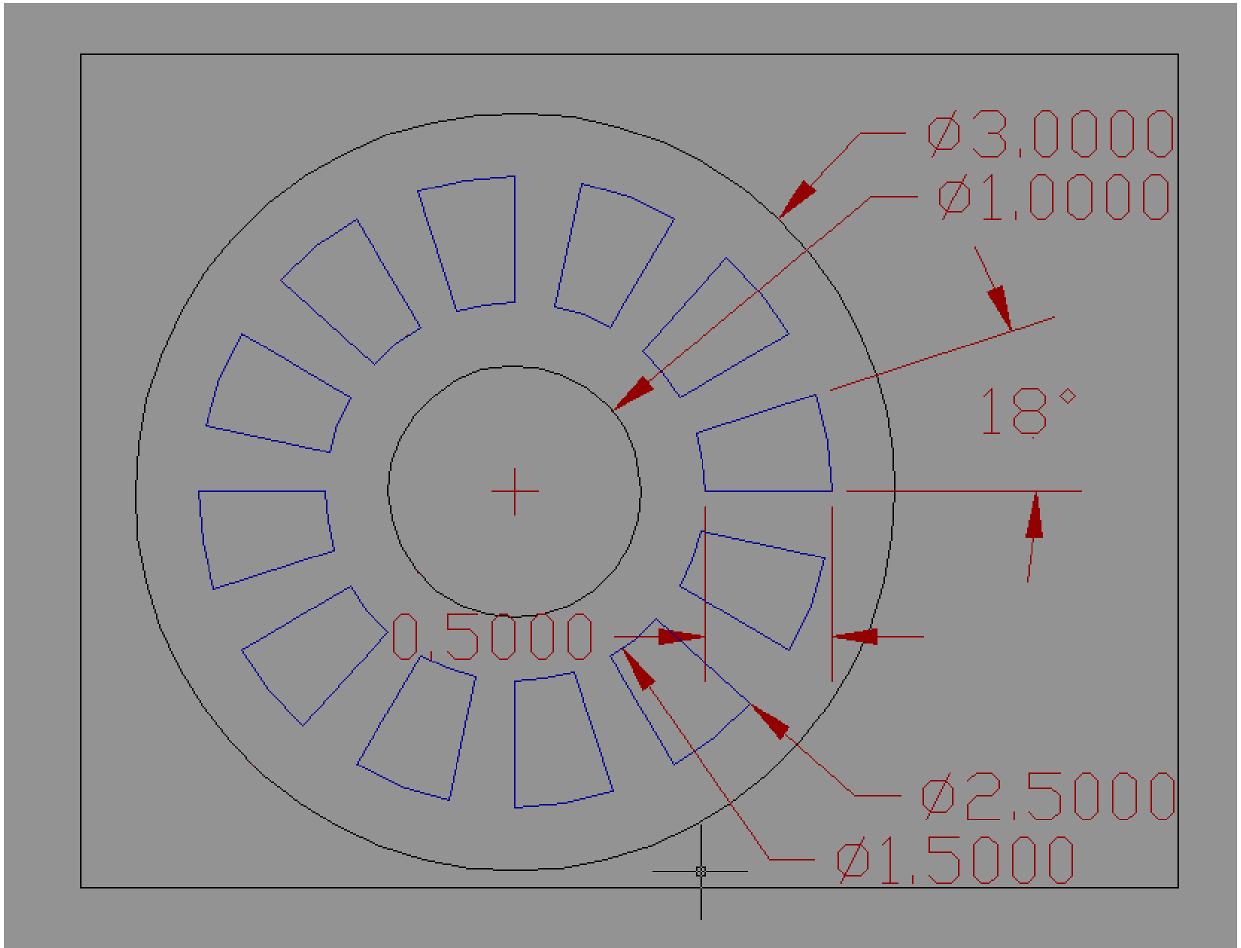
Finite Element Modeling of Radial Design, 3.0”OD

Torque profile for speed of 10000 rpm. The current=2A, No. of turns=65.
Average value of torque generated is 1.79018 N-m = 1.33 ft-#



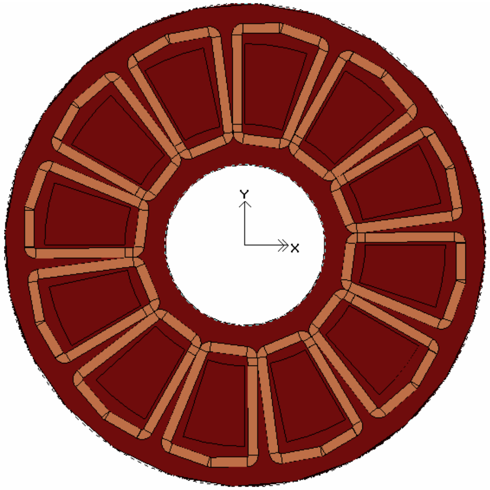
Advanced Ultra High Speed Motor for Drilling

Stator of 3.0 inch OD in Axial Design

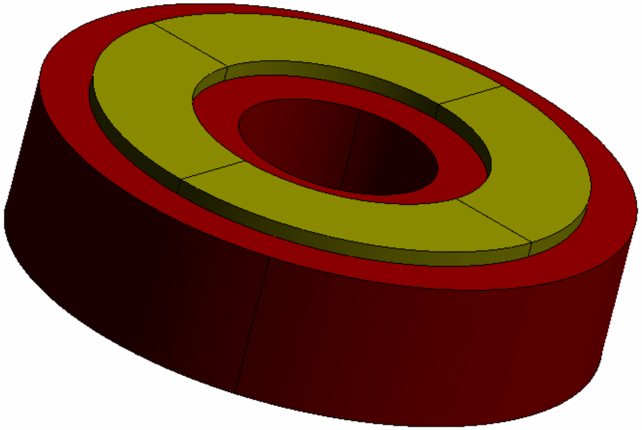


Advanced Ultra High Speed Motor for Drilling

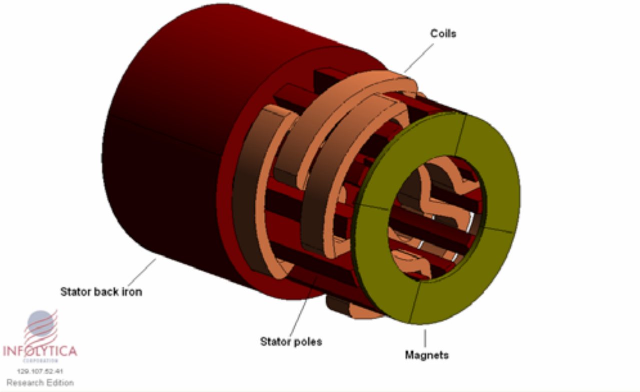
Finite Element Modeling of Axial Design



STATOR WINDING AS SEEN FROM THE ROTOR

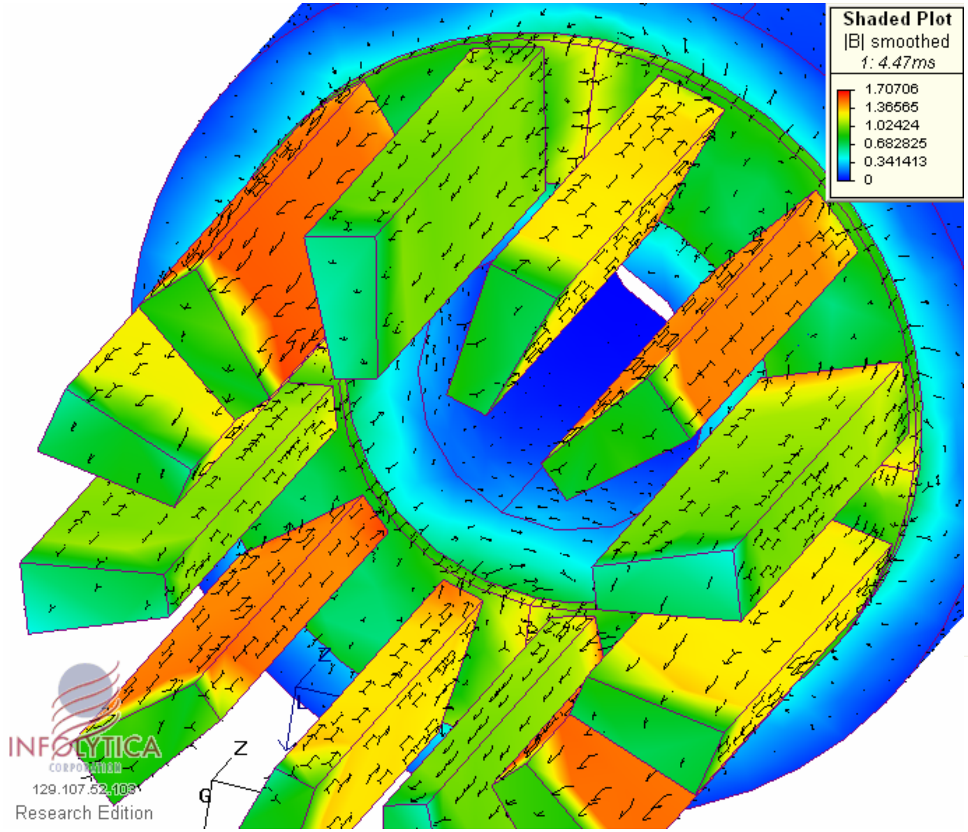


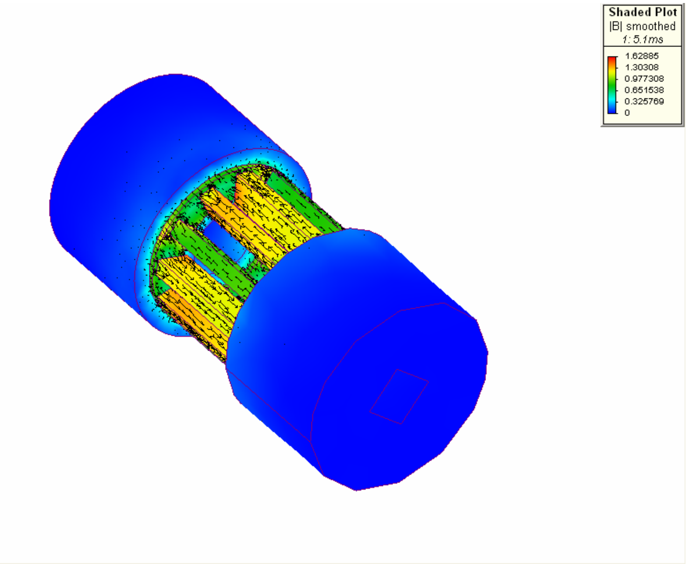
MAGNET ARRANGEMENT ON ROTOR



Advanced Ultra High Speed Motor for Drilling

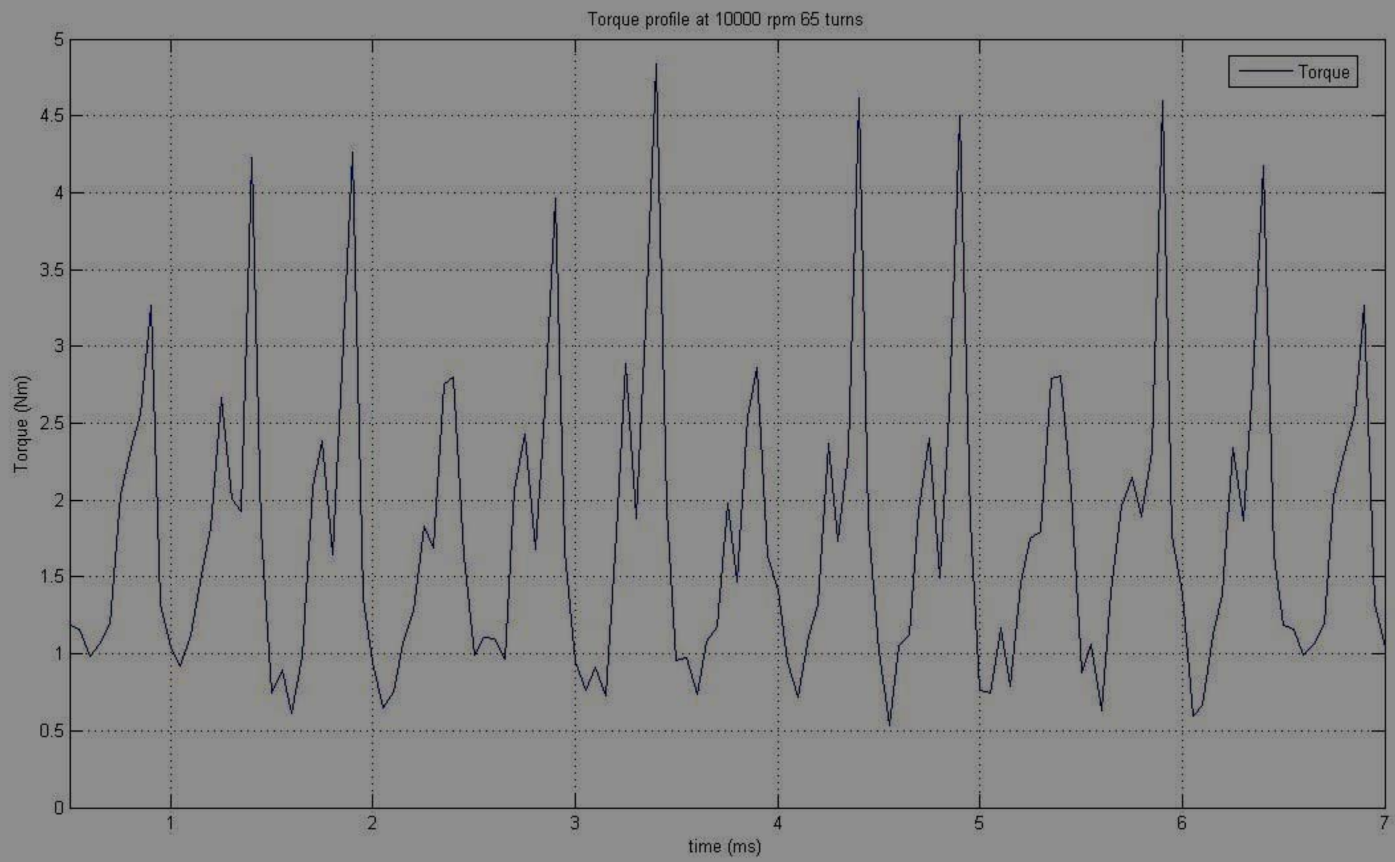
Finite Element Modeling of Axial Design





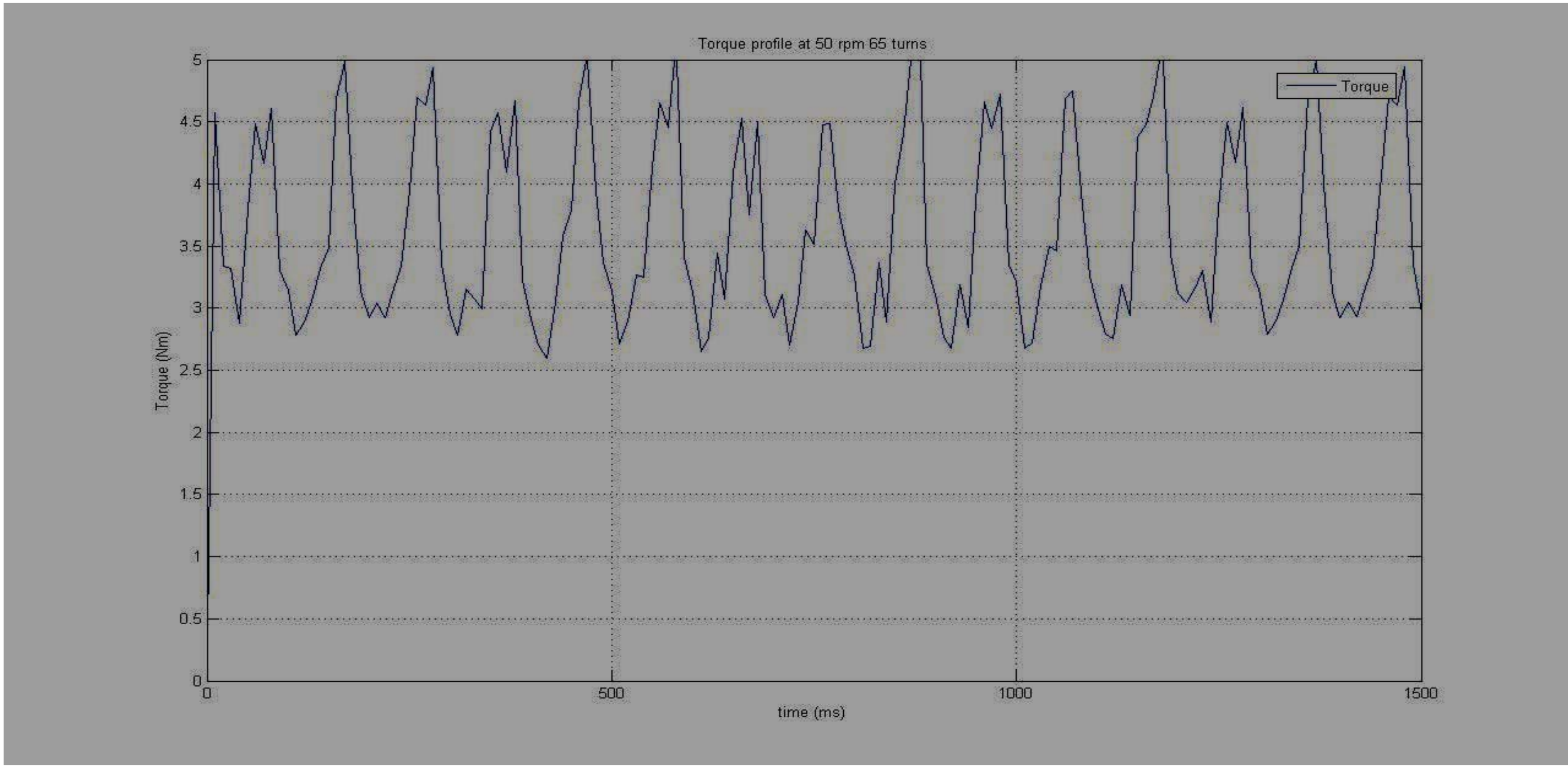
Advanced Ultra High Speed Motor for Drilling

Finite Element Modeling of Axial Design, 10Krpm,65AT
Torque 1.8 Nm = 1.34 ft-#, 0.4 Hp



Advanced Ultra High Speed Motor for Drilling

Finite Element Modeling of Axial Design, 3”OD, 50rpm,65AT
Torque 3.8 Nm= 2.84 ft-#



Advanced Ultra High Speed Motor for Drilling

Axial Design Torque and Power

- 3.0”OD at 10,000rpm, 4” long, 1mm airgap
  Output 4.7Nm=3.51ft-#, 4.7KW= 6.3Hp,
- 3.0” OD at 50rpm, 4” long, 1mm airgap
  Output 3.4Nm= 2.53 ft-#, 0.023Hp
- 1.69”OD (still working on), 10000rpm, 1’ long
  est Output 3.6KW power= 4.8 Hp

Advanced Ultra High Speed Motor for Drilling Remaining “To Do” List

- Heat transfer model/ calculations, flow required to cool
- Method to attach rotors to housing, stators to shaft to transfer torque, maintain fixed stand-off/airgap
- Seals- barrier, bag or labyrinth options, difficult since gas medium needed. ESP models, Weatherbee materials, Kalsi
- Journal Bearings- difficult due to gas environment and narrow placement (shaft up to rotor). Can be used to ensure airgap between discs. Non-magnetic, ad best non-conductant
- Thrust Bearing Options- PDC-PDC, Kalsi
- Identify Motor design consultant to address manufacturing concerns…good design but cannot be made!
- Vibration (balancing) harmonics
- Final Design drawings

Advanced Ultra High Speed Motor for Drilling

Key Dates of Project

- 6Dec04 TerraTek presenttion to DOE on ulra high speed bits
- 14Dec04- Meeting with Dr Fahimi, Dr Dunn-Norman for initial design
- 4Jan05 Shop experiments on rotational drag
- 5Jan05 Fahimi report on 1.69” radial design
- 4Feb05 Fahimi visit to Tulsa
- 28Feb Fahimi report on revised 1.69 design
- 28 April 05 Fahimi report on 3” radial design
- 30April05 status report to Rhonda Jacobs
- 15June 05 Fahimi report on 3.0” axial design
- 22July05 Oglesby visit to UTA lab, review status
- 27July05 presentation to DOE/ Rhonda Jacobs

Conversion Factors

- Torque- Newton Meters to Foot Pounds
  - 1 Nm = 0.73756 ft lbs
- Dimensions- Millimeters to inches
  - 1 mm = 0.03937 inches
- Power- Watts to Horsepower
  - 1 watt = 0.001341 Hp US
  - 1 KW = 1.341 Hp US
  - Horse Power = 0.746 Kilowatts
  - Hp = ft-# torque X rpm /33000

Advanced Ultra High Speed Motor for Drilling

History of Electric Motors for Drilling

- The USSR has performed serious work on electric motor drilling for many decades, although little published work has been found by the author.
- General Electric worked on downhole electric motors for drilling in a DOE funded project, cumulating in a final report in 1977. Several problems were noted, most notably the lack of a high capacity, reliable electrical link to the bottomhole assembly via the jointed drill pipe. No significant problems were reported on the conventional style electric motor, although it still has the conventional limitations.
- The European Drilling Engineers Association (DEA(E)) has a joint industry project headed by XL Technology that is (now-still?) in Phase II- field testing a DC brushless motor. They identified the benefits of an electric motor as-
  - drive power independent of fluid flow,
  - tolerance for energized fluid,
  - high temperature applications,
  - scalable power,
  - real time information,
  - low vibration and
  - reversible direction.

Increasing Power and Torque Options

- Only way to increase torque is
  - Decrease airgap, risk of high velocity collisions in motor
  - Decrease outer housing thickness, limited by strength
  - Decrease shaft thickness (minor compared to housing)
  - Increase current, limited by metal volume and metal type
  - Increase voltage, limited by insulation

Advanced Ultra High Speed Motor for Drilling

DE-FC26-04NT15502

01Oct04 through 31March06

12 September 2005
Project Update

For
Rhonda Jacobs
US Department of Energy
National Energy Technology Lab

By
Ken Oglesby, Impact Technologies LLC
and
Dr Babak Fahimi / Mahesh Krishnamurthy
University of Texas at Arlington

Advanced Ultra High Speed Motor for Drilling
Outline of Discussion

- Contract Requirements
- Summary of Status
- Key Dates of Project
- History of Electric Drilling
- Basic Inverted Motor Configuration and Benefits
- Existing Ultra-high Speed Electrical Motors
- Review of Exiting Ultra-high Speed Cutters/bits, bearings and seals
- Setting HSM IM-Electric Motor Specifications
- Electro-Magnetic-Mechanical Designs
- Bearing / Seal Options

Advanced Ultra High Speed Motor for Drilling
Basic Contracted Tasks to be Performed

- Phase I- identify bit and cutter characteristics for 10,000+ rpm speeds
- Phase II -Prepare CAD drawings for 2 sizes
- Phase III- Construct magnetic model
- Phase IV- FE Modeling for optimization
- Phase V- Final design ready for prototyping

- Note that this is a 10,000+rpm electric IM motor design contract only

Advanced Ultra High Speed Motor for Drilling
Progress Summary

At 12 months into 18 month project

- Accomplished-
  - Phase I- Investigated available bit and cutter technologies
  - Phase I and II- Set motor specifications (dimensions/ voltage/ Hp)- 1.68" and 3.0: OD, 300Volts, 2.5Hp stages, min 4 ft-lbs torque at stall
  - Phase III & IV- Made Electro-Mechanical designs for radial and axial configurations (still performing FEA on 1.69" axial)
  - Phase III-Investigated various bearings and seals for ultra high speed applications- awaiting final EMM design- Kalsi and Dennis Oil Tools
- Remaining-
  - Phase III & IV- Finish EM designs for 1.69inch OD Axial motor
  - Phase III-Mate final EM designs with appropriate thrust / journal bearings and seals
  - Phase IV-Perform heat transfer analysis of final designs
  - Phase V-Perform limited FEA for stress on key components
  - Phase V-Vibration analysis and mitigation methodology
  - Phase V-Ensure manufacturability of design
  - Phase V-Prepare final machine drawings for prototyping

Advanced Ultra High Speed Motor for Drilling

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- 27July05 status report to Rhonda Jacobs/ DOE
- 12Sept05 presentation to DOE

- Final report due 31March06

Advanced Ultra High Speed Motor for Drilling

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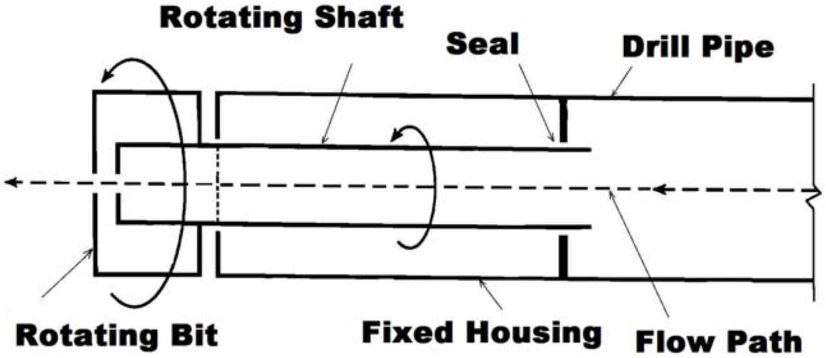
  - drive power independent of fluid flow,
  - tolerance for energized fluid,
  - high temperature applications,
  - scalable power,
  - real time information,
  - low vibration and
  - reversible direction.

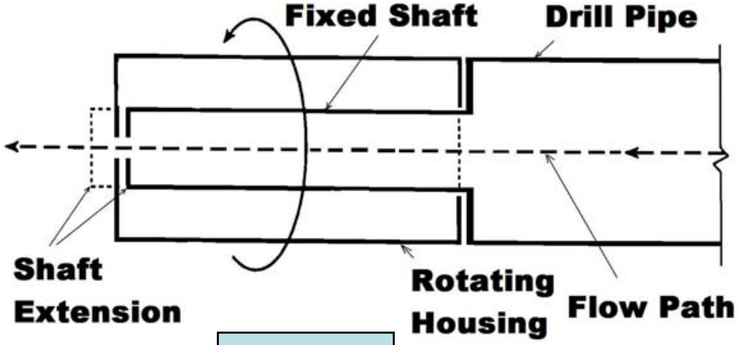
Advanced Ultra High Speed Motor for Drilling
Basic Inverted Motor Configuration

- Basic design
  - Shaft connected to drillstring and not rotating (stator)
  - Housing rotates (rotator) with bit attached
  - Shaft has channels for flow and wires
- Benefits
  - Allows advanced drilling techniques
    - Ultra high pressure / Abrasives / Acids/ bases
  - Directional and Logging (GR, …) tools in/ at bit
  - Multiple motors on BHA/ drillstring
  - Fits into Microhole Project sizes and CT capabilities
  - Ultra short radius turns
- Drawbacks
  - New, not tested
  - Shaft only now holds motor and lower string / tools

Basic Inverted Motor Configuration



Conventional Electric Motor



Inverted Electric Motor

Advanced Ultra High Speed Motor for Drilling

Other types of Inverted Motors

Gerotor Concentric	Gerotor Eccentric
Moineau Concentric	Moineau Eccentric
Roller Vane Concentric	Roller/Wing Concentric
Turbine Concentric	Electric Concentric
Piston Concentric	Others

Advanced Ultra High Speed Motor for Drilling
Channel(s) in Shaft of IM Motor

Fluid/Gas Flow
Ultra High Hydraulic Pressure
Electrical Wires
Optical Wires

for uses in

Hydraulic/Abrasive/Dir Jetting

MWD / LWD
(near-bit or in-bit)

Improved Hole Cleaning

Multiple Motors

Advanced Ultra High Speed Motor for Drilling
Possible IM Benefits

Proven Technology

HP Hydraulic Jetting

Bi-centered/ Hole Enlargement

***Abrasive Jetting** (solids added to HP stream)*

Low Weight on Bit

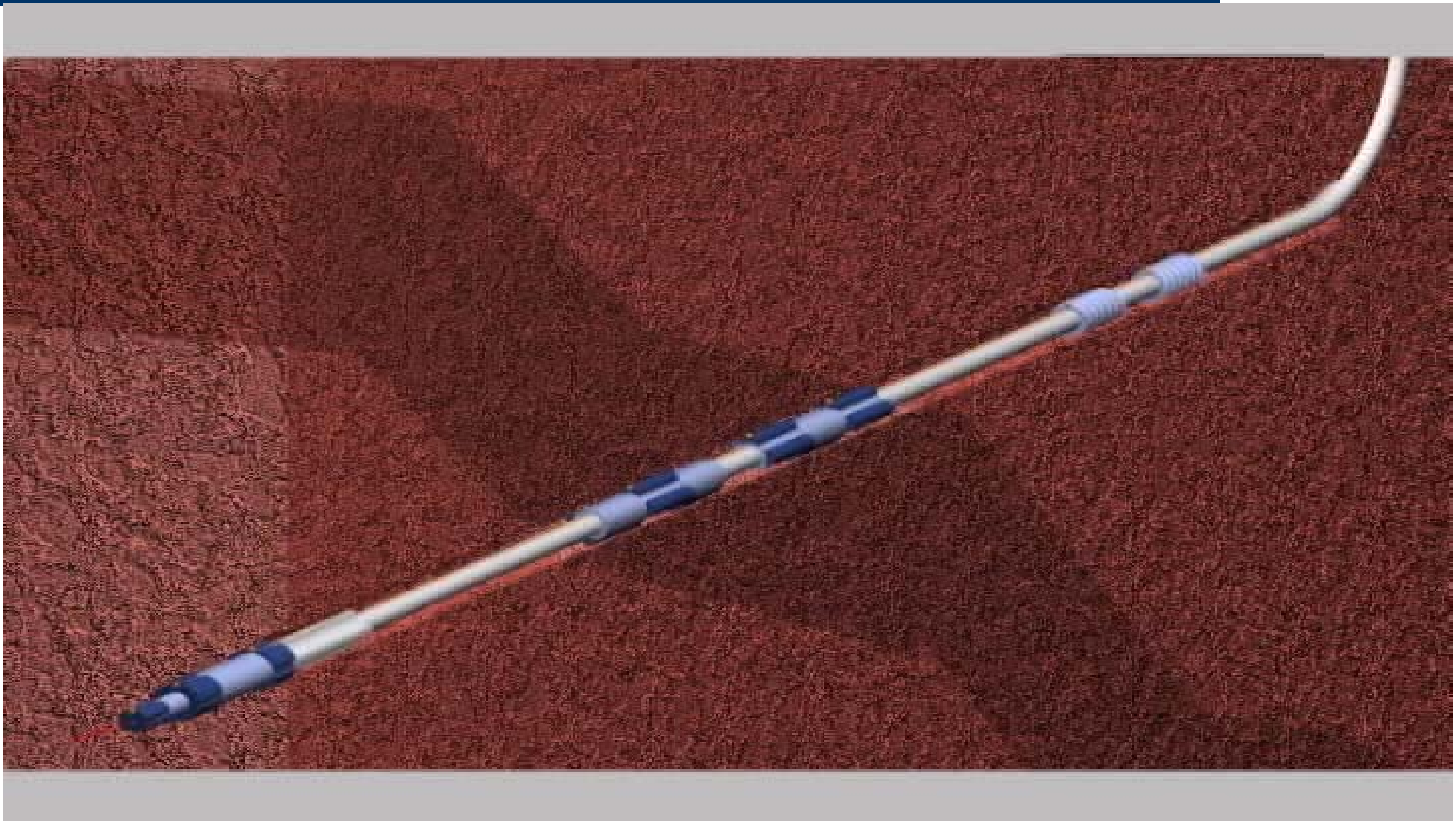
New Technology

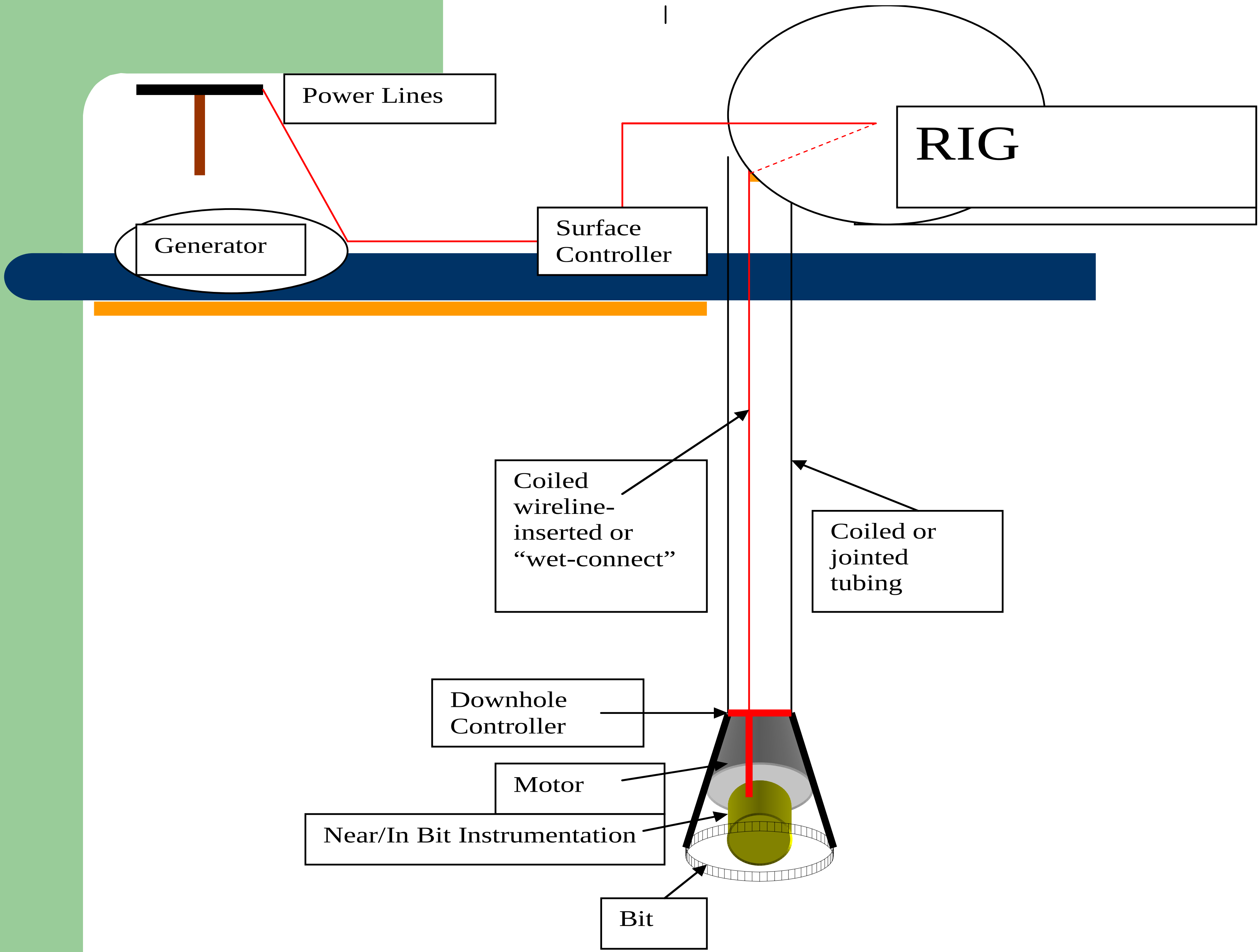
Enhanced Directional Drilling
(Offset Hydraulic / Abrasion Jetting)

Laser/ Plasma Drilling

Clamp-on IM for CTD

Advanced Ultra High Speed Motor for Drilling
IM Drilling System





Power Lines

RIG

Generator

Surface Controller

Coiled wireline-inserted or “wet-connect”

Coiled or jointed tubing

Downhole Controller

Motor

Near/In Bit Instrumentation

Bit

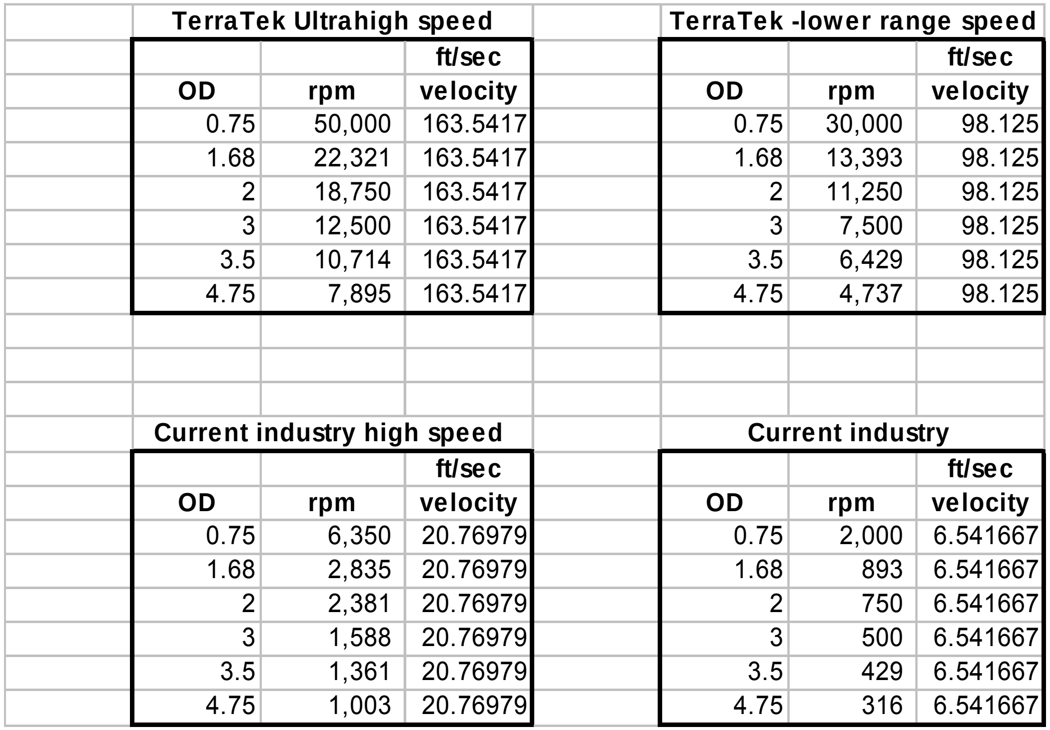
Advanced Ultra High Speed Motor for Drilling
Ultra High Speed Motor Comparison

- General Motors electric car- 16” OD and 13,000rpm
- TerraTek motor specifications (used for Lab testing of high speed cutters) :
  - Koford Hall Effect motor
  - 120VAC at 10 amps
  - Slottless, brushless DC, 2 pole (?) motor
  - 1.6” OD???
  - 51,000rpm no load maximum speed
  - Stall torque 788oz-in==== 4.1 ft-lbs
  - Continuous torque is 80 oz-in=== 0.42ft-lbs
  - Peak output is 7383 watts===9.9 Hp
  - Continuous output 2700 watts===3.6 Hp
  - Maximum current utilized is 9 amps

Advanced Ultra High Speed Motor for Drilling
Motor Specifications-Background

- Literature Review on DC machine fundamentals
  - Electric Machinery Fundamentals by SJ Chapman, ISBN 0-07-246523-9
  - Electrical Motion Devices by PC Krause, ISBN 0-07-035494-4
- Research into ultrahigh speed cutters
  - Ultra high rpms/ velocities generate high temps causing thermal cracking
  - PDCs, diamonds
  - Smith Premium HOT PDC cutters
  - Thermally Stable Polyrystalline Diamond Cutters- Bob Radkte / Technology International/ DOE work
  - TerraTek / Arnis Judzis, Alan Black/ DOE work on testing cutters for ultra high speeds
- Research into ultra high speed bearings
  - Mahlon Dennis/ Dennis Oil Tools- PDC-PDC bearings
  - NASA metal-metal coatings
  - Kalsi
  - Fahimi source
- Research into ultra high speed seals- Kalsi / Weatherbee

Advanced Ultra High Speed Motor for Drilling
Motor Specifications-Background



TerraTek Ultrahigh speed

OD	rpm	ft/sec velocity
0.75	50,000	163.5417
1.68	22,321	163.5417
2	18,750	163.5417
3	12,500	163.5417
3.5	10,714	163.5417
4.75	7,895	163.5417

TerraTek -lower range speed

OD	rpm	ft/sec velocity
0.75	30,000	98.125
1.68	13,393	98.125
2	11,250	98.125
3	7,500	98.125
3.5	6,429	98.125
4.75	4,737	98.125

Current industry high speed

OD	rpm	ft/sec velocity
0.75	6,350	20.76979
1.68	2,835	20.76979
2	2,381	20.76979
3	1,588	20.76979
3.5	1,361	20.76979
4.75	1,003	20.76979

Current industry

OD	rpm	ft/sec velocity
0.75	2,000	6.541667
1.68	893	6.541667
2	750	6.541667
3	500	6.541667
3.5	429	6.541667
4.75	316	6.541667

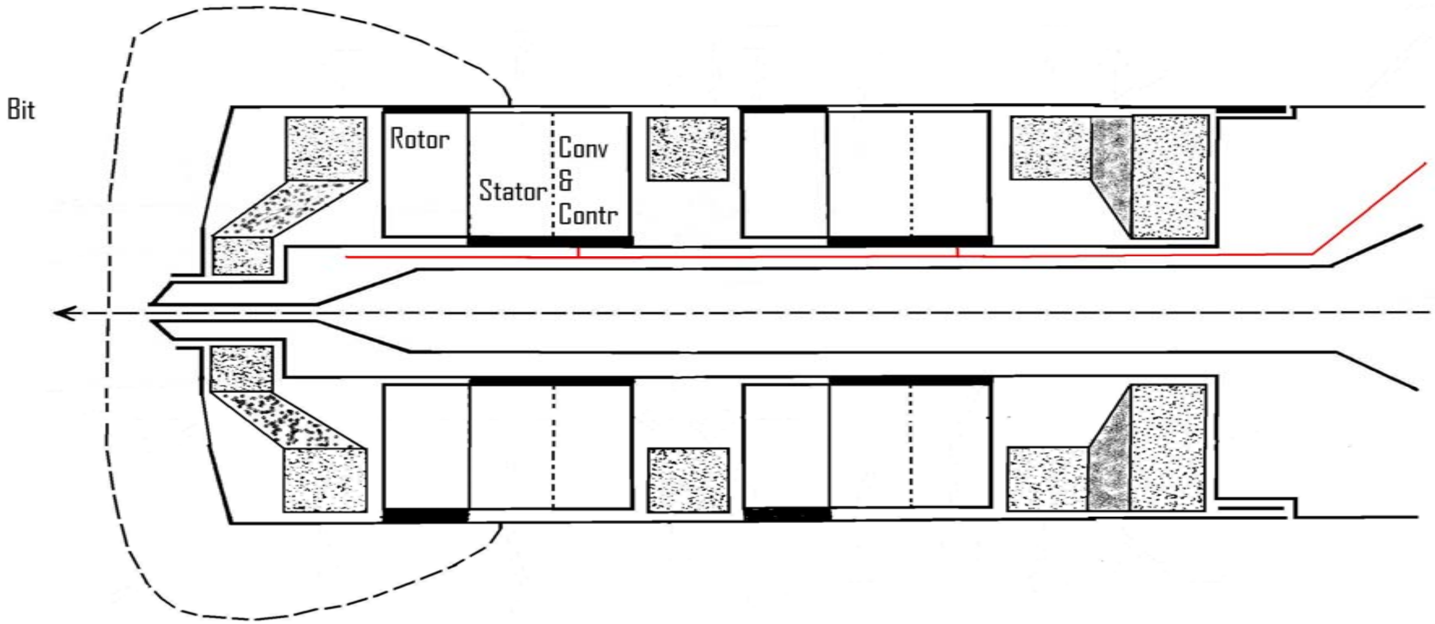
Advanced Ultra High Speed Motor for Drilling
Setting Motor Specifications

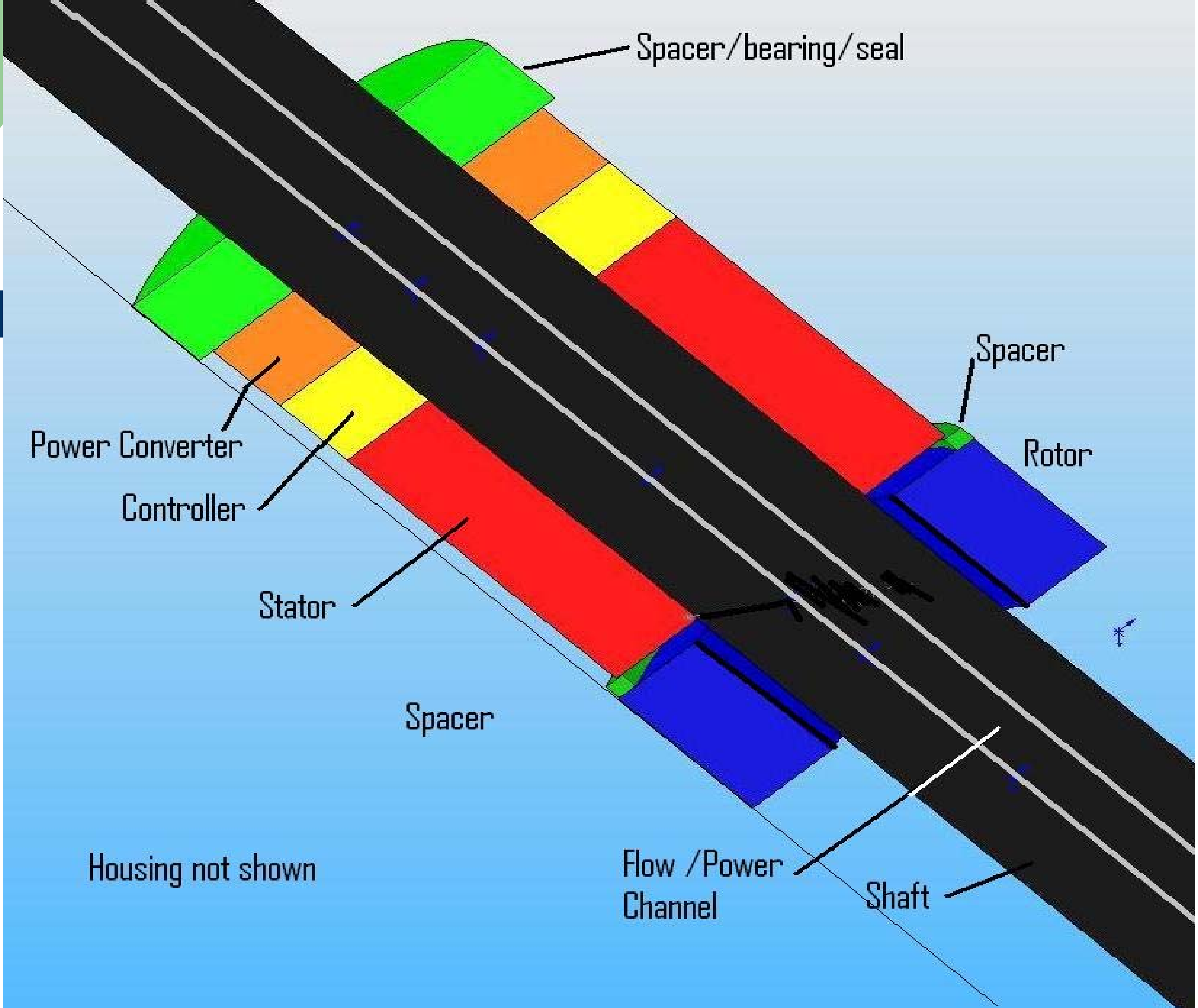
- Set Dimensional specifications
  - DOE Microbore Effort
  - 1.69” OD with 0.5” shaft OD
  - 3.0” OD with 1.0” shaft OD>>>3.125”OD direction
  - Each power section 1 foot long
- Set Voltage and current type- 300 VDC motor with 220VAC 3phase line feed (at motor),
  - AC power Line loss - 8.5 amps 208VAC - 304 watt loss. With AC can embed keys on AC signal for control of motor (versus DC power line loss -10 amp 300VDC 5000’ length - 9.3Volt loss, 279 watt loss)
  - Requires 2 lines for AC power transmission (only 1 if drillstring is used)
  - Higher voltages require special and /or thicker insulation and equipment
- Set Horsepower and Torque-
  - Bench Test Drag study showed 4 ft-lbs drag in horizontal position (without SF)
  - Estimate 2.0 - 10 ft-lbs required for WOB and sizes anticipated from equation:

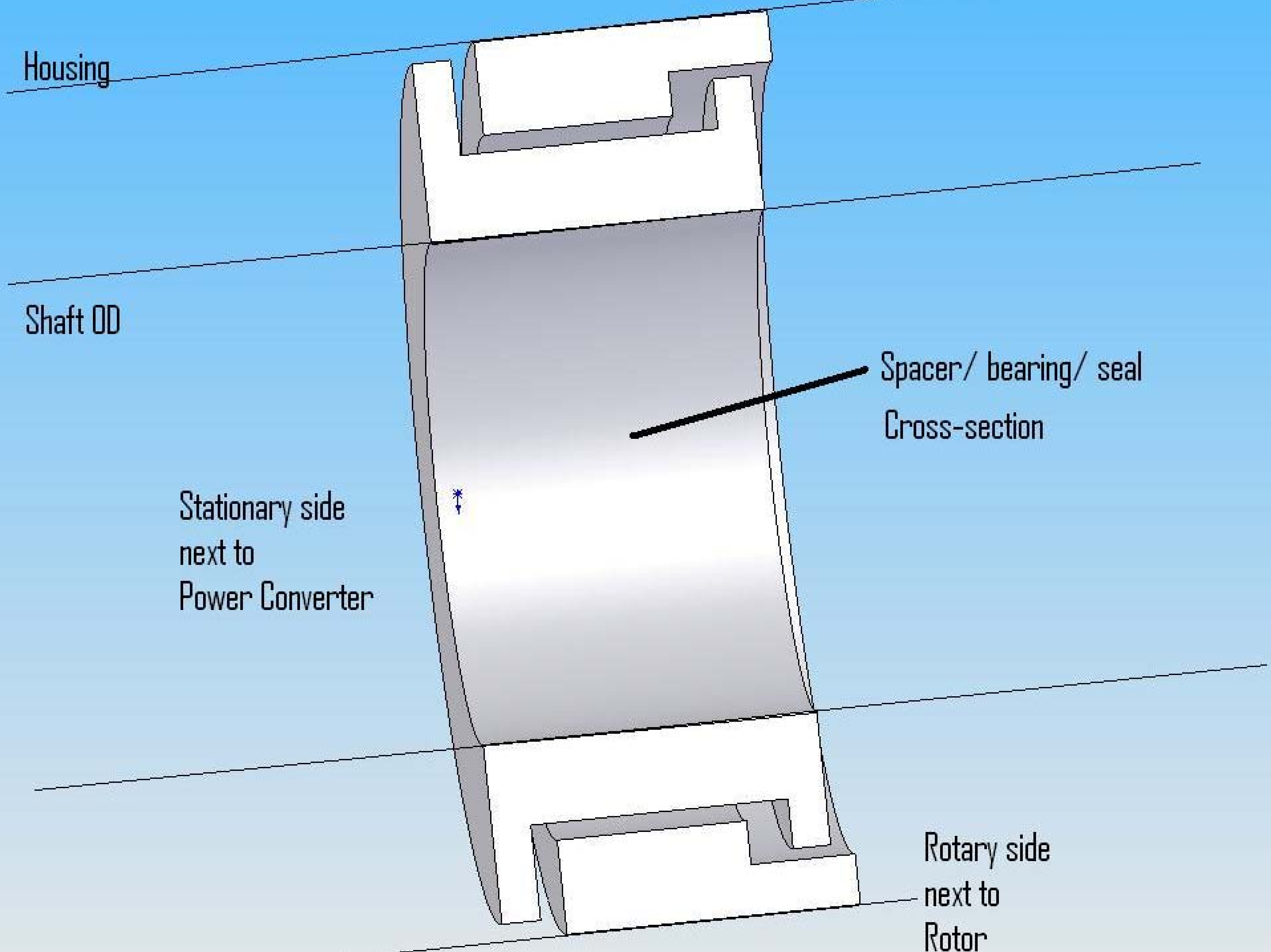
    Torque= 0.5*Bit diameter (inches) * WOB (#) * formation hardness factor (range 0.2-0.4)/ 12
    - Unknown source, estimated at +/- 25% accuracy
  - Target 3Hp stackable motor power stages within housing
  - maximum 1 ft length of motor stage due to bending

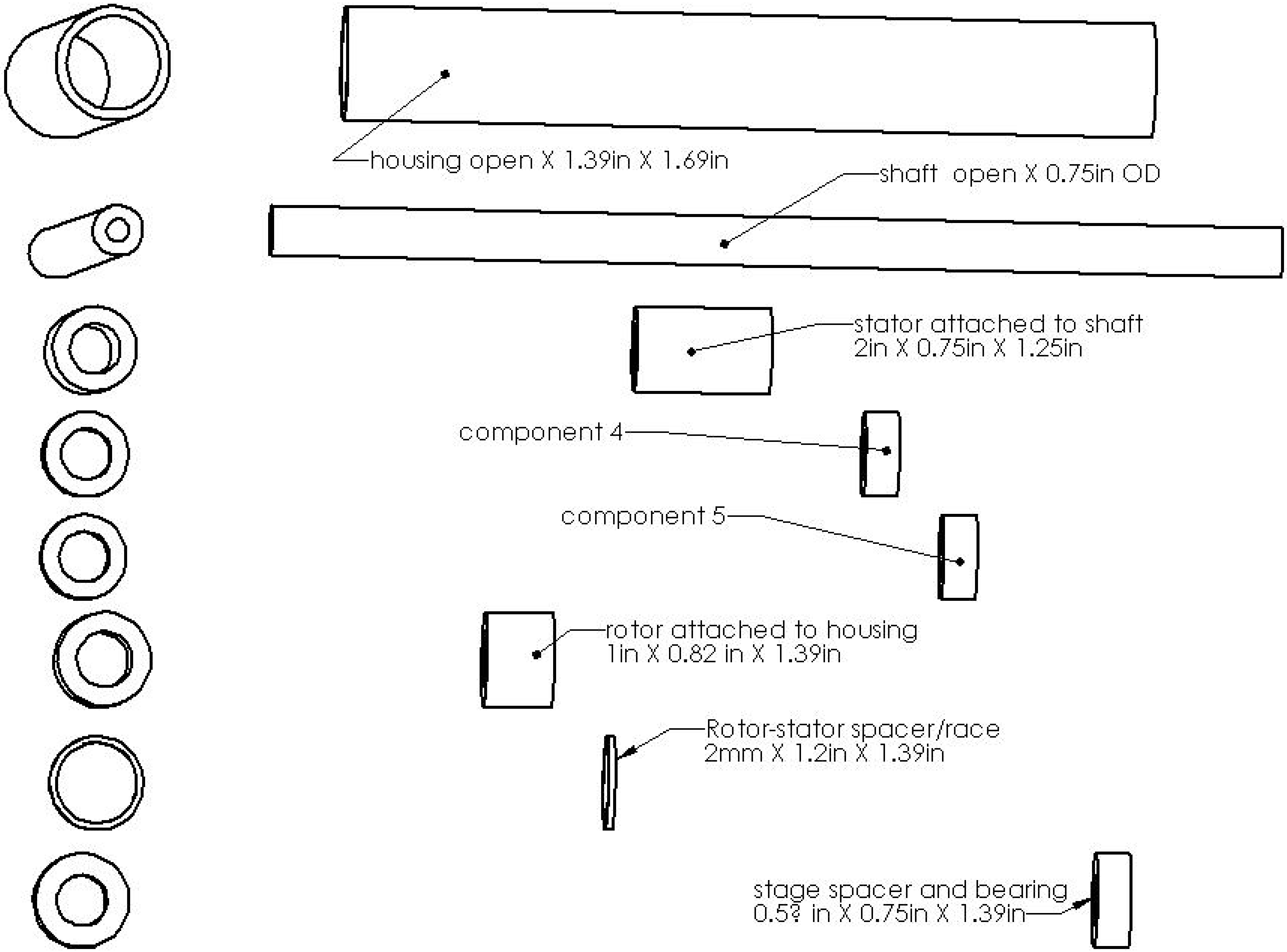
- Set Airgap requirements/ concerns -1mm too small, target 2+mm.
- Flow requirements for cooling due to heat generated by electronics in motor, bearings under loads, cutters in action

Advanced Ultra High Speed Motor for Drilling
Generalized Electric IM Motor Configuration




Spacer/bearing/seal
Spacer
Rotor
Power Converter
Controller
Stator
Spacer
Housing not shown
Flow /Power Channel
Shaft


Housing
Shaft OD
Spacer/ bearing/ seal
Cross-section
Stationary side
next to
Power Converter
Rotary side
next to
Rotor



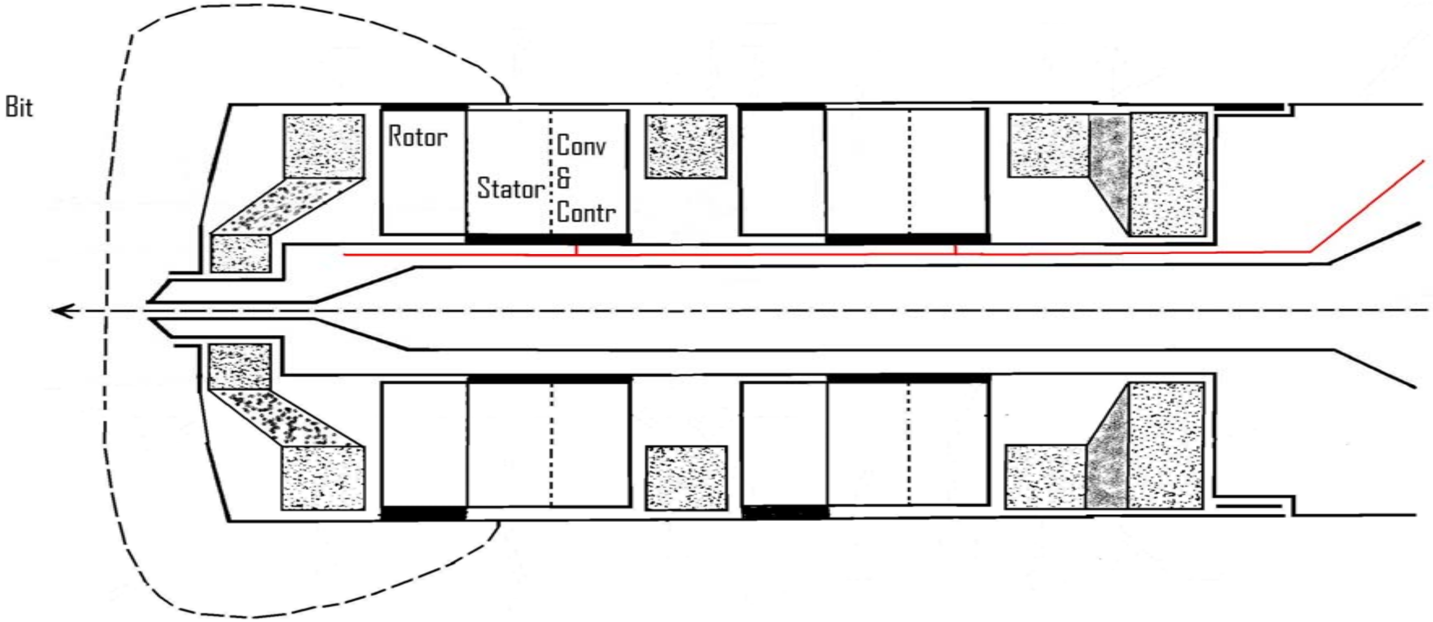
housing open X 1.39in X 1.69in
shaft open X 0.75in OD
stator attached to shaft
2in X 0.75in X 1.25in
component 4
component 5
rotor attached to housing
1in X 0.82 in X 1.39in
Rotor-stator spacer/race
2mm X 1.2in X 1.39in
stage spacer and bearing
0.5? in X 0.75in X 1.39in

Advanced Ultra High Speed Motor for Drilling
Electro-Mechanical Design

Mahesh Krishnamurthy

Doctoral candidate under Dr B. Fahimi
University of Texas at Arlington

Advanced Ultra High Speed Motor for Drilling
Generalized Electric IM Motor Configuration



Advanced Ultra High Speed Motor for Drilling

Remaining “To Do” List

- Finish Axial design for 1.69 inch OD motor
- Heat transfer model/ calculations, flow required to cool
- Method to attach rotors to housing, stators to shaft to transfer torque, maintain fixed stand-off/ airgap
- Seals- barrier, bag or labyrinth options, difficult since gas medium needed. ESP models, Weatherbee materials, Kalsi
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- Identify Motor design consultant to address manufacturing concerns…good design but cannot be made!
- Vibration (balancing) harmonics
- Final EM Designs and drawings

Advanced Ultra High Speed Motor for Drilling

End of Talk

Increasing Power and Torque Options

- Only way to increase torque is
    - Decrease airgap, risk of high velocity collisions in motor
    - Decrease outer housing thickness, limited by strength
    - Decrease shaft thickness (minor compared to housing)
    - Increase current, limited by metal volume and metal type
    - Increase voltage, limited by insulation

Conversion Factors

- Torque- Newton Meters to Foot Pounds
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- Dimensions- Millimeters to inches
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- Power- Watts to Horsepower
  - 1 watt = 0.001341 Hp US
  - 1 KW = 1.341 Hp US
  - Horse Power = 0.746 Kilowatts
  - Hp = ft-# torque X rpm /33000

Advanced Ultra High Speed Motor for Drilling
Electro-Magnetic-Mechanical Design Points

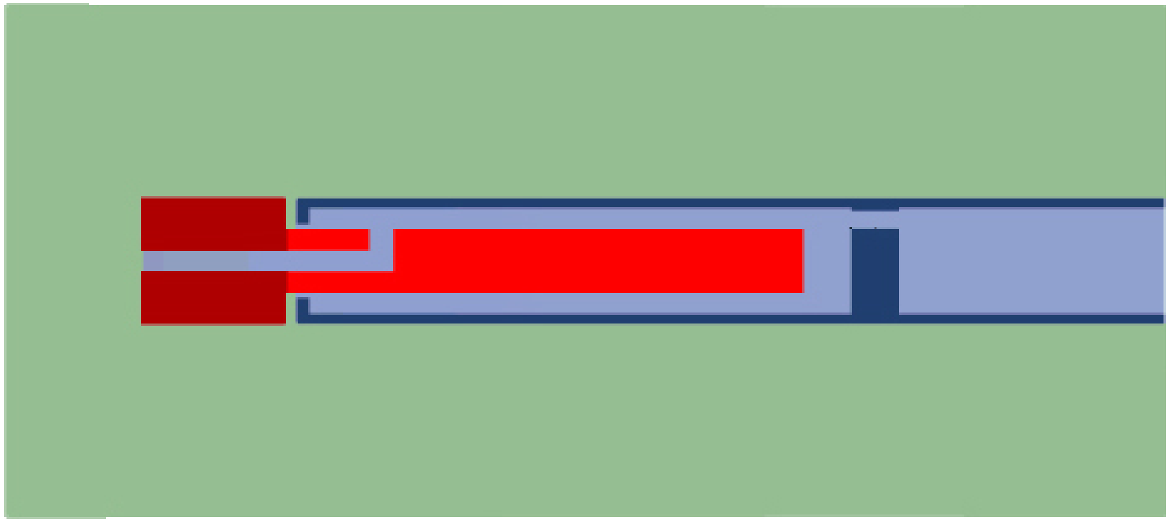
- Permanent Magnet Synchronous Motor, brushless
- Radial or Axial or Modified/ Hybrid
- Fully adjustable for speed and direction by key embedded in AC current
- Current gives power/ torque, but limited by metal type and amount,
- Voltage gives rpm capabilities
- Nonmagnetic materials required for spacers, journal bearings, shaft
- Stackable power sections to meet HP requirements
- 10amps per mmXX2 area is design with 80-90 utilization factor. Can go to 15amps/mm2 for surge of higher power
- Power sections set at maximum 1 ft in length or 3 Hp , whichever is shorter
- Back emf voltage is induced by motion of PMs
- Field weakening is used to keep power up at higher rpms
- Available PM materials are SMCO alloy good for 100C / NDFEBR for 150C
- Cogging is not a problem at high speeds, just low speeds. This is just resistance to motion when PM are much stronger that induced field
- Anything on the outside of the housing will not impact motor performance (cutters,…)

List of Acronyms, Abbreviations, Conversions and Equations

- Power (Horsepower) = $\frac{\text{Torque(lb-ft) * rpm}}{5252}$
- Power (Watts) = $\frac{\text{Torque(lb-ft) * rpm}}{7.04}$
- Foot-Pound Torque =
  Newton-Meters Torque * 0.7376

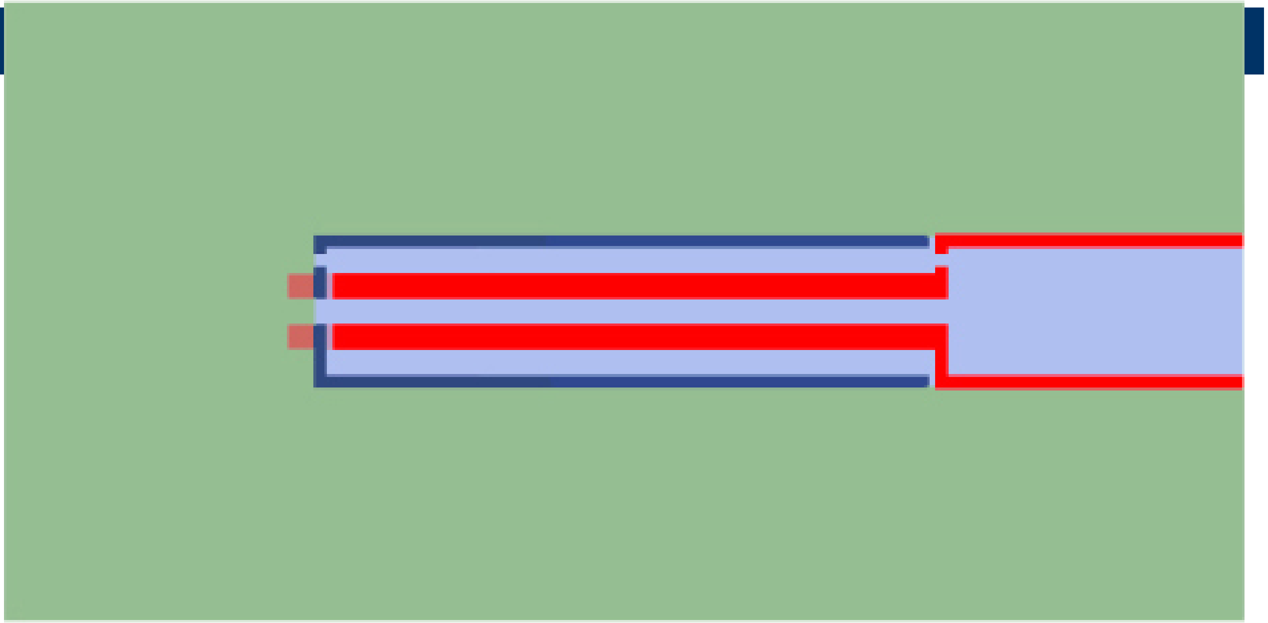
Advanced Ultra High Speed Motor for Drilling

Basic Conventional Motors



Advanced Ultra High Speed Motor for Drilling

Basic Inverted Motor Configuration



Advanced Ultra High Speed Motor for Drilling
Electric IM Drilling System Elements

1. Drill string with connected to motor shaft;
2. Electric (300VAC, 1-2 wire) power cable to surface controller and 3phase AC generator or power lines;
3. Electric wires through shaft and connected to motor’ power converter;
4. Converter disc to convert 3phase AC to DC;
5. Controller disc to monitor the motor position and pulse the proper DC current to the stator coils;
6. Wired coils embedded in a stator (axial- disc, radial disc) and attached/wired to the non-rotating shaft;
7. Shaft (non magnetic) with flow and electrical wire channels,
8. Permanent magnets attached to outer housing (axial-disc, radial- inner lining);
9. Journal Bearings (non magnetic) between Shaft – Rotors and Stator- Rotors;
10. Thrust bearings on both ends of housing;
11. Keepers on both ends of housing; and
12. Bit connected to Housing

Advanced Ultra High Speed Motor for Drilling

Other IM Benefits

Multiple Motor Types & Designs
Multiple Liquids/Gases/Solids
HP / HT Applications
Hydraulic/Abrasive/ Dir Jetting
Multiple Motors
MWD/LWD thru Motor(s)
Balanced Force Motor Designs
Bi-centered Style Movement
Hole Enlargement
Compact Motor Designs
Ultra-short Turning Radii
Enhanced Hole Cleaning

- **AC Loss estimation (5000 ft.):**
- Wire gauge used: AWG #1
- Effective Inductive Reactance ≈ 0 Ω
- DC Resistance = 0.62 Ω
- Cumulative drop in voltage = 9.3 V
- Power loss = 139.5 W
- **DC Loss estimation (5000 ft.):**
- DC Resistance = 0.62 Ω
- Inductive Reactance = 0.7318 Ω
- Total resistance = 1.3518 Ω
- Cumulative drop in voltage = 20.28 V
- Power loss = 304.16W

- **Though voltage drop across the cable in dc transmission is lower, ac transmission is suggested. Reasons:**
  - DC transmission would require converter to be placed underground with the machine. This reduces accessibility and impedes corrective measures.
  - Signal wires need to be sent in with the dc transmission which would be subject to attenuation. Such an arrangement is not advisable since these wires need to be kept short to avoid introduction of noise and faulty trigger.
- **However drawbacks of this system are:**
  - Three ac cables would mean extra cumulative losses in the cables due to inductive reactances.
  - Shielding of cables needs to be much better than that required for dc.

Design of 3-phase Permanent Magnet Synchronous Machine for Drilling Application

12 September 2005
Project Update

For
Rhonda Jacobs
US Department of Energy

By
Ken Oglesby
IMPACT TECHNOLOGIES LLC
&
Mahesh Krishnamurthy
Dr. Babak Fahimi
University of Texas at Arlington

Outline

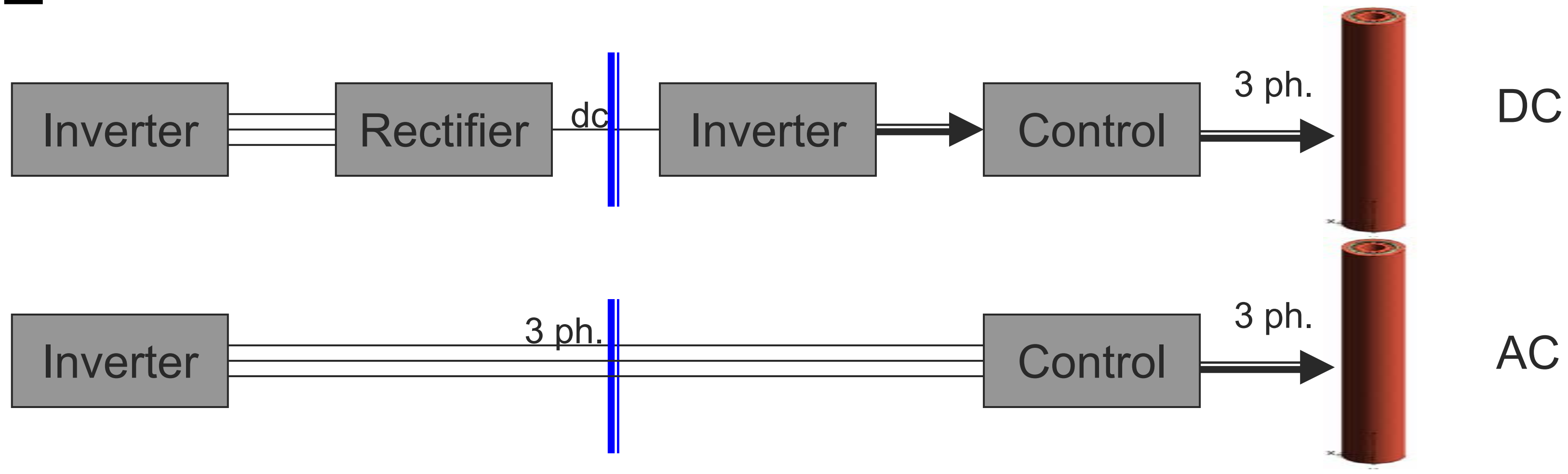
- Objectives
- Selection of Transmission Method
- Radial Vs. Axial Flux Design
- Design Summary
- Material Selection
- Modeling Approach
- Summary of Models
- Simulation Results
  - 2 Radial Designs
  - 2 Axial Designs
- Results

Advanced Ultra High Speed Motor for Drilling: Objectives

- Optimizing parameters:
  - Outer diameter
  - Stack length
  - Air-gap
  - Generated Torque

- Requirements:
  - Inverted rotor (Exterior rotor) configuration
  - Torque = 2.1 Nm at standstill
  - Power = 3 hp @ 10,000 rpm
  - Nominal speed: 10,000 rpm
  - Maximum stack length allowed = 12”
  - Number of phases: 3
  - Design geometry:
    - Radial
    - Axial

Selection of Transmission Method



Inverter

Rectifier

dc

Inverter

Control

3 ph.

DC

Inverter

3 ph.

Control

3 ph.

AC

AC Transmission

DC Transmission

Loss estimation (5000 ft.):

Wire gauge used: AWG #1

Effective Inductive Reactance ≈ 0 Ω

DC Resistance = 0.62 Ω

Cumulative drop in voltage = 9.3 V

Power loss = 139.5 W

Loss estimation (5000 ft.):

DC Resistance = 0.62 Ω

Inductive Reactance = 0.7318 Ω

Total resistance = 1.3518 Ω

Cumulative drop in voltage = 20.28 V

Power loss = 304.16W

Selection of Transmission Method

- **Though voltage drop across the cable in dc transmission is lower, ac transmission is suggested. Reasons:**
  - DC transmission would require converter to be placed underground with the machine. This reduces accessibility and impedes corrective measures.
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- **However drawbacks of this system are:**
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  - Shielding of cables needs to be much better than that required for dc.

Radial PMSM Vs Axial PMSM

Radial PMSM	Axial PMSM
■ Useful when the motor has a long shaft. ■ As the number of poles increases, torque density decreases after a slight increase. ■ Manufacturability is easier	■ Delivers high torque densities for short axial lengths. ■ As number of poles increases, torque density increases since motor active weight (copper and iron weight required by magnetic circuit) reduces faster than decrease in electromagnetic torque. ■ Best suited in applications with limited space and for rapid acceleration and deceleration.

Material Selection (1 of 2)

- Motor lamination: Hiperco 50A alloy

Carbon	0.00 %	Manganese	0.05 %
Silicon	0.05 %	Cobalt	48.75 %
Vanadium	2.00 %	Iron	Balance

Reason for selection:

- High knee point in BH characteristics (allows high flux densities)
- High D.C. maximum permeability
- Low D.C. coercive force
- Low A.C. core loss
- Higher strength

Typical application: Aircraft generators and motors.

Material Selection (2 of 2)

- Permanent Magnet: N40SH (Sintered NdFeB)

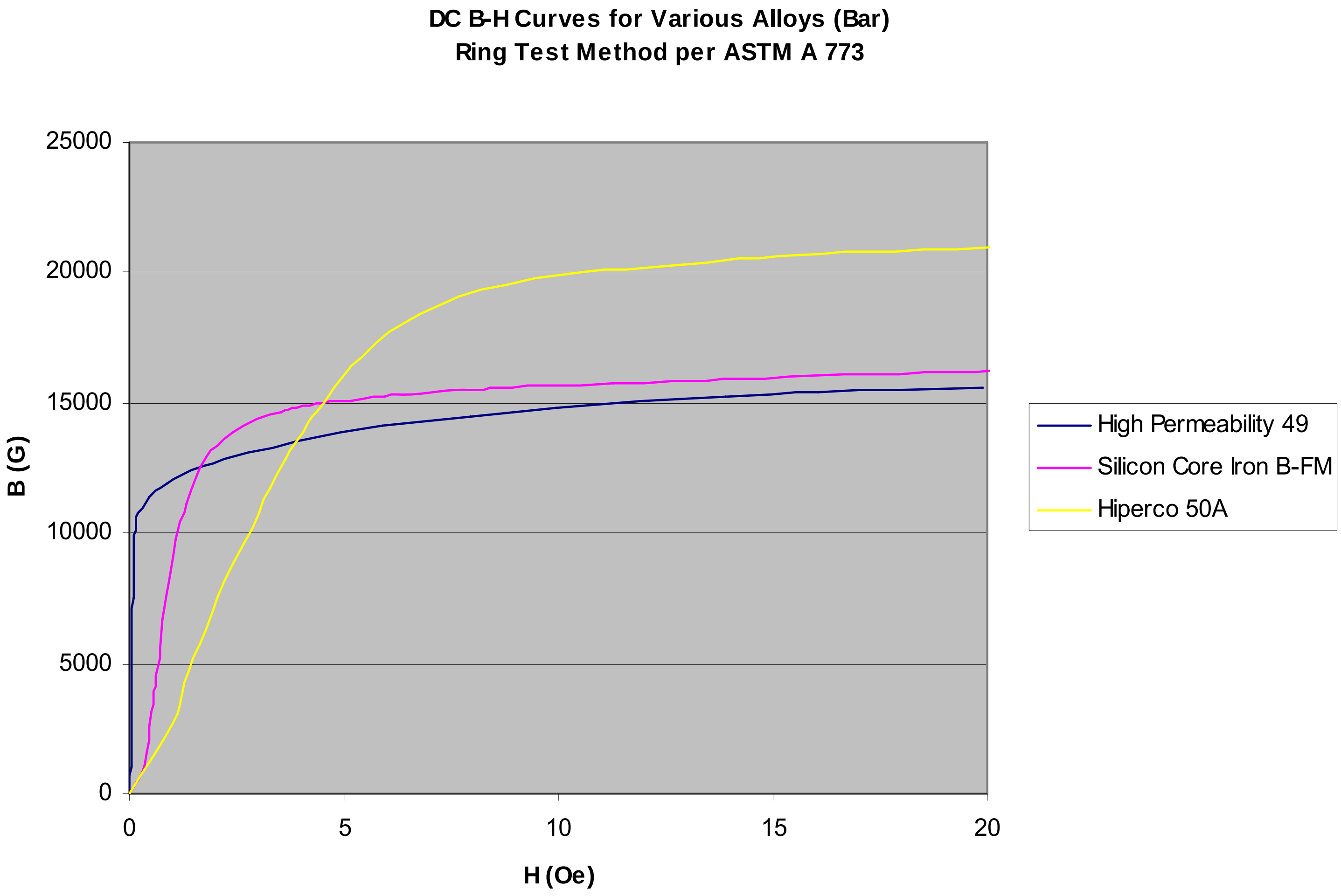
Br (kiloGauss)	12.4 -12.8	BH_{max} (MGOe)	38 - 41
Hc (kiloOersted)	>11.8	Curie Temp. (°C)	340
Hc_i (kiloOersted)	>20	Max Op. Temp (°C)	150

Characteristic features of conventional NdFeB:

- High Maximum Energy product (BH_{max}).
- Temperature stability unaffected up to 180 °C, ideal for temperature < 80 °C.
- Lower corrosion and oxidation than SmCo.

Sintered NdFeB is formed by powder metallurgical process. They can be die-pressed or isostatically pressed. Magnetic domains are aligned during pressing by application of a magnetic field to optimize magnetic performance to suit requirement.

BH Curve for Hiperco 50A Alloy Vs. Alternate Choices



Modeling Approach

- Modeling of machine geometry based on application requirement.
- Generation of back EMF profile of the machine under no-load condition.
- Development of excitation sequence for the machine.
- Calculation of torque using equation for conservation of power as given below:

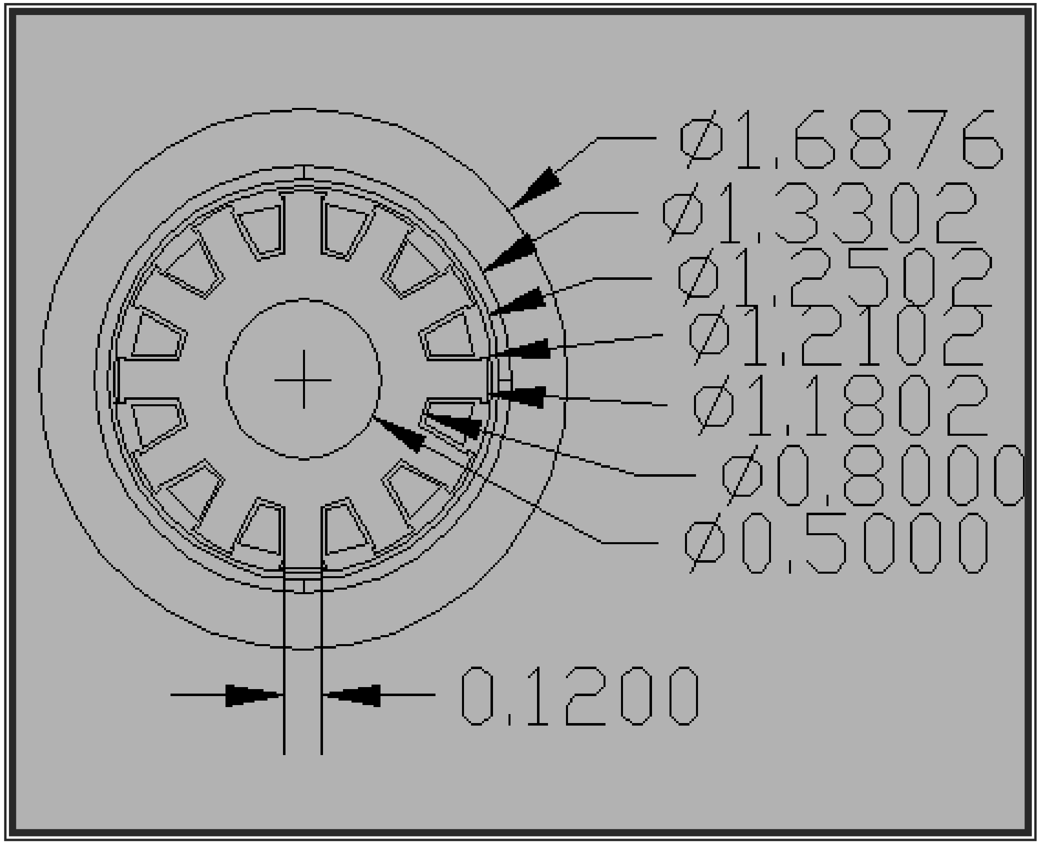
$$T.\omega = E_a I_a + E_b I_b + E_c I_c$$

$$where\ E_i,\ I_i = back\ \ emf\ \ \&\ \ current\ \ of\ \ i^{th}\ \ phase\ \ respectively.$$

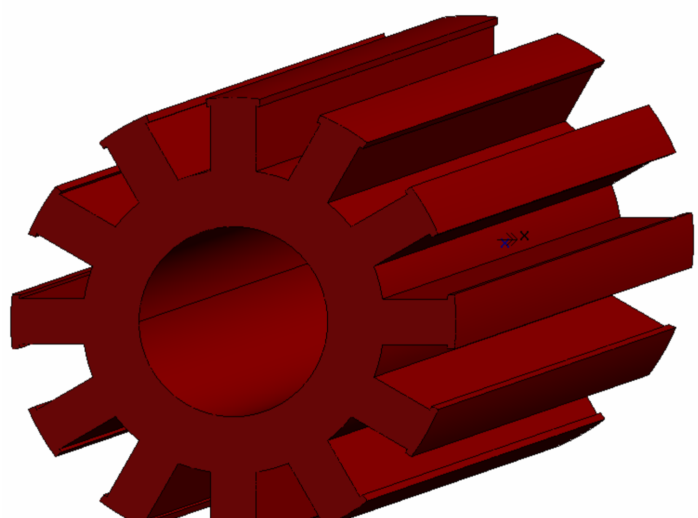
$$\omega = speed\ \ of\ \ operation$$

Radial Design-1 Geometry

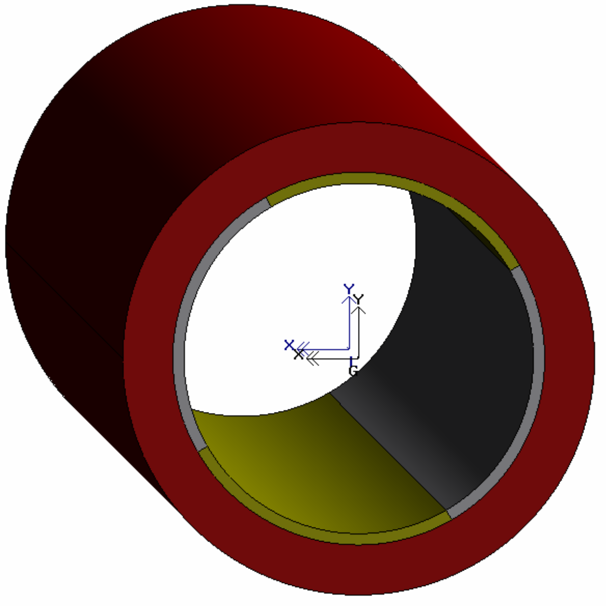
- **Rotor OD = 1 11/16”**
- **Stator OD = 1.1802”**
- **Shaft OD = 0.5”**
- **Air gap length = 1 mm**
- **Phases = 3**
- **Stack length = 12”**
- **No. of turns = 65**
- **Current = 2A**



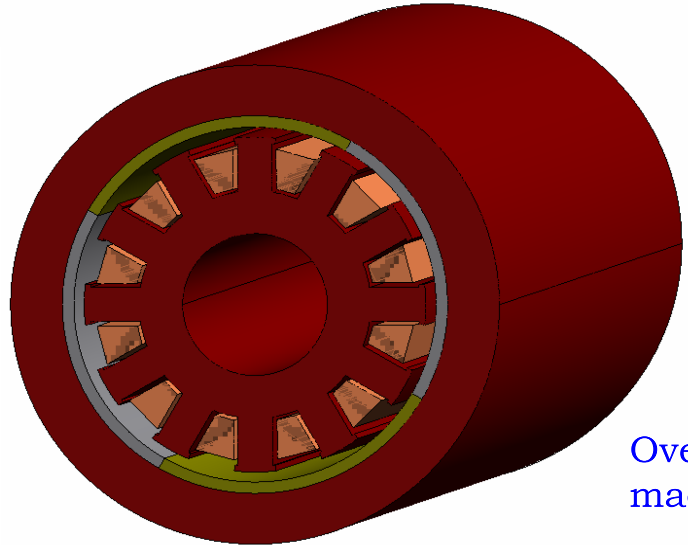
2D Finite Element Model (1.69” OD)



Stator geometry (12 poles)

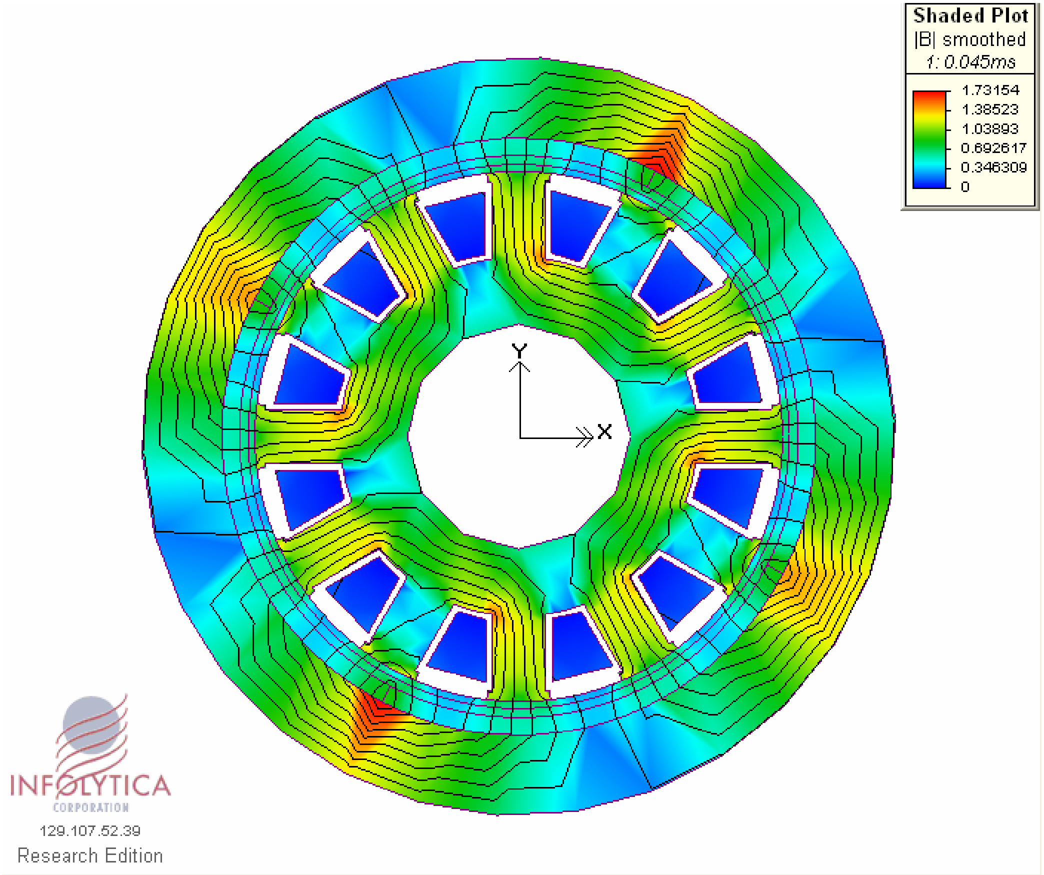


Magnet placement on external rotor

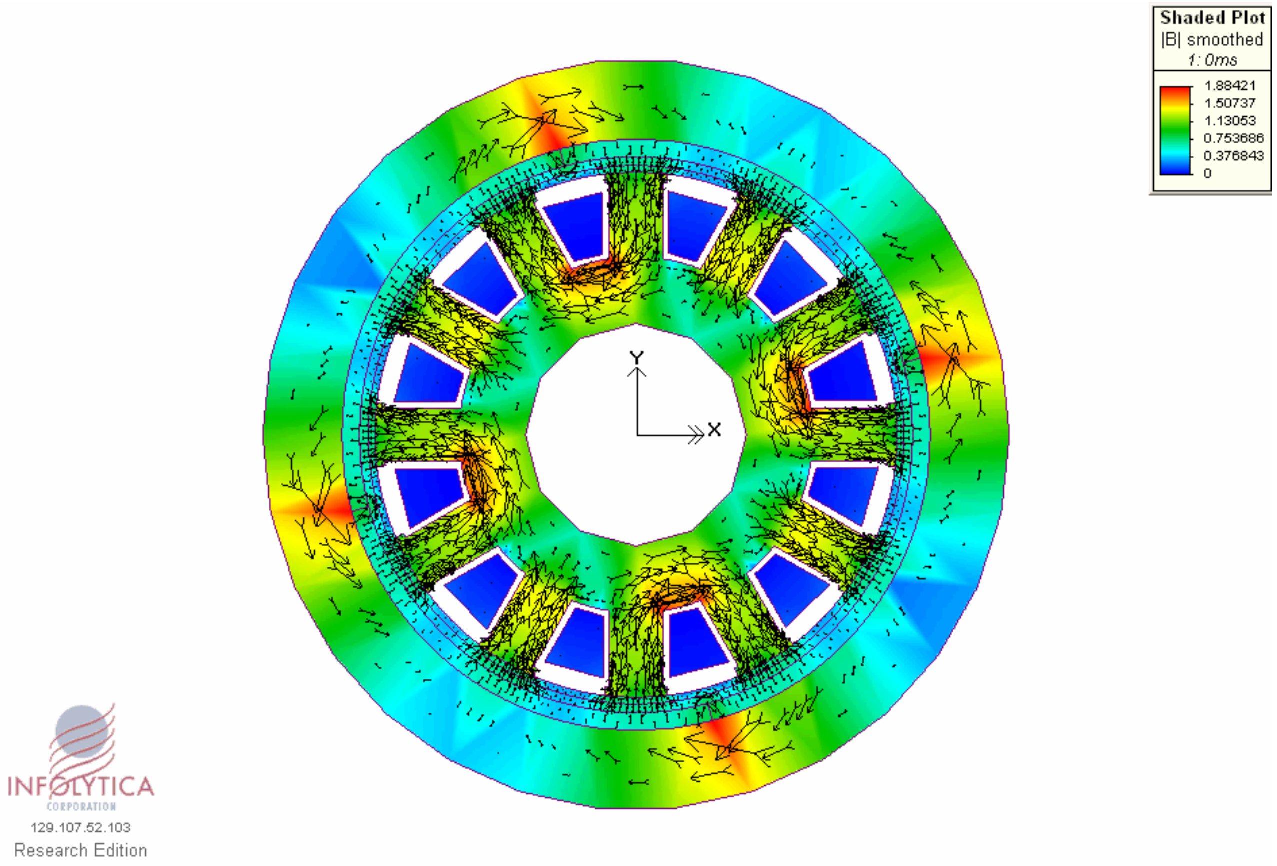


Overall radial machine geometry

Magnetic Flux Density Distribution (1.69” OD)

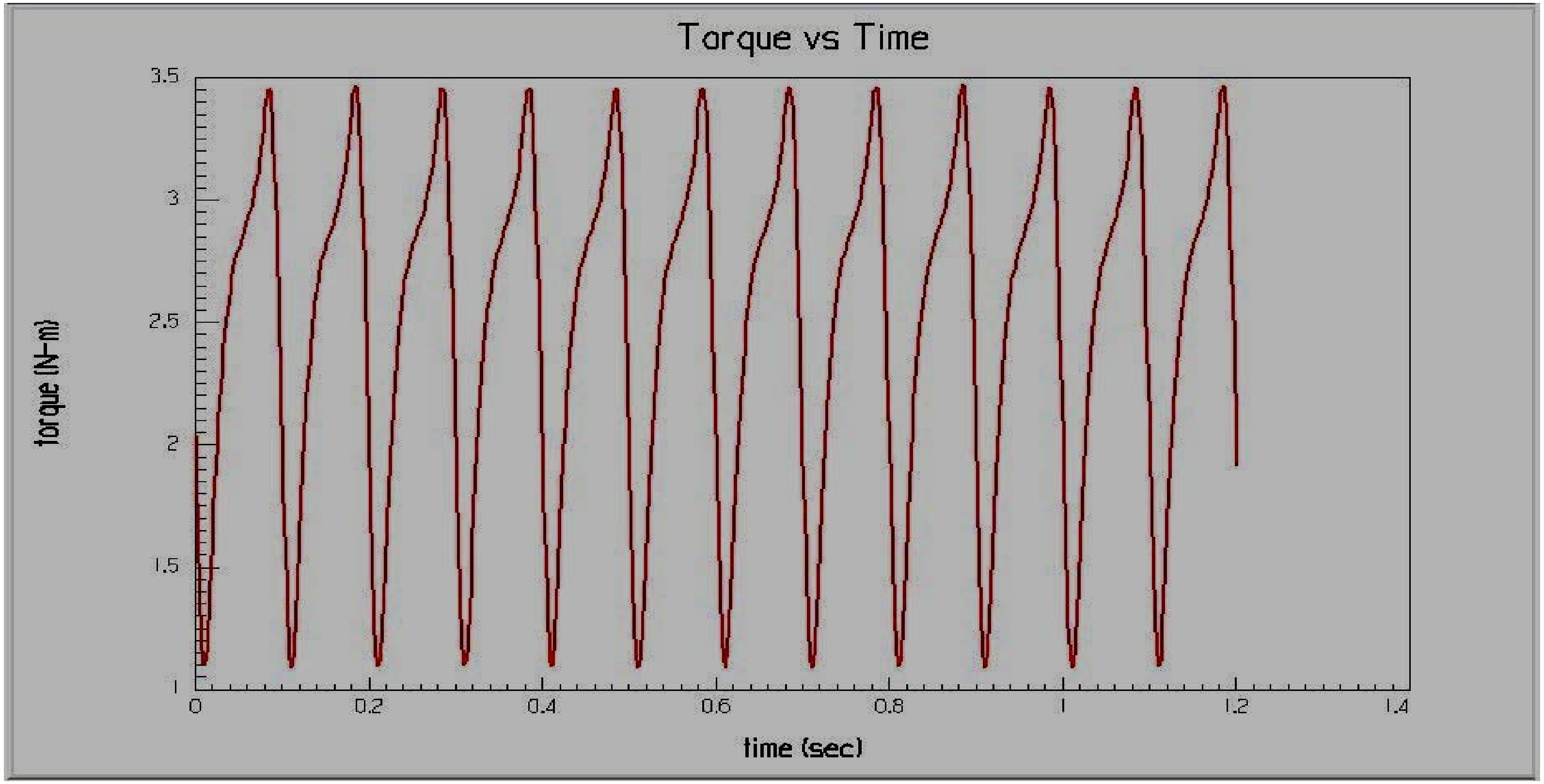


Operation of Radial PMSM



Advanced Ultra High Speed Motor for Drilling

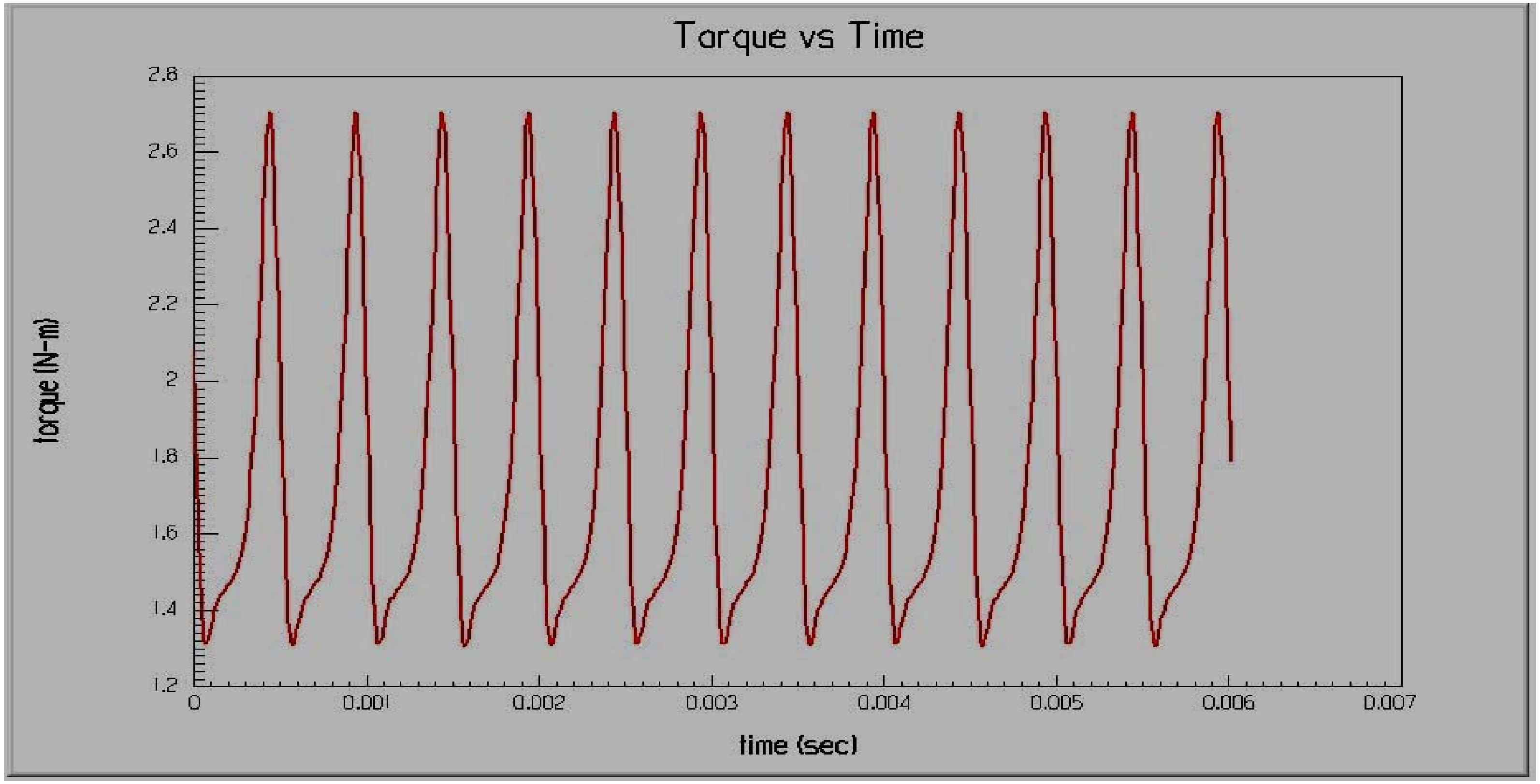
Finite Element Modeling of Radial Design, 1.69"OD



Torque profile at 50 rpm - 2Nm=1.48ft# , 0.013 Hp

Advanced Ultra High Speed Motor for Drilling

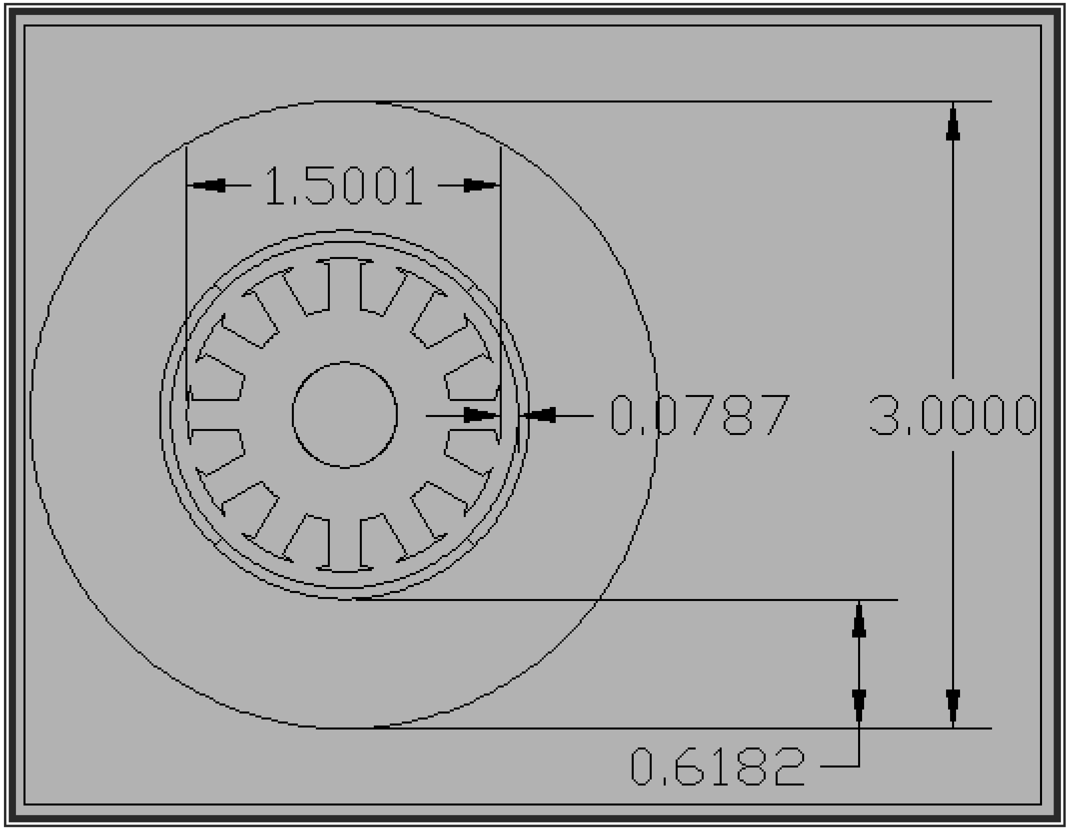
Finite Element Modeling of Radial Design, 1.69”OD



Torque profile at 10000 rpm - 2 Nm =1.48ft-#, 2.68 Hp

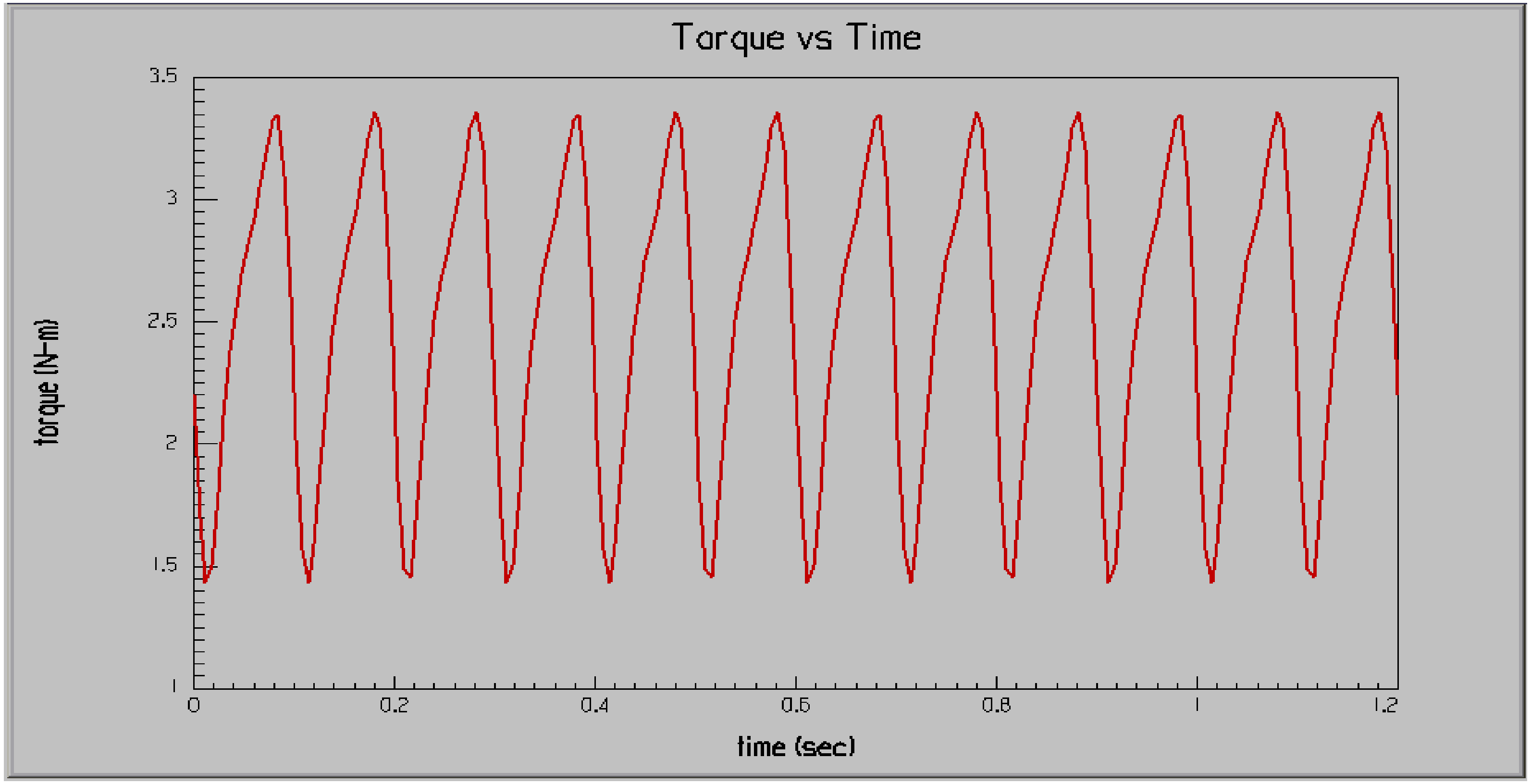
Radial Design-2

- Rotor OD = 3”
- Stator OD = 1.5”
- Shaft OD = 0.5”
- Phases = 3
- Stack length = 12”
- No. of turns = 65
- Current = 2A



Advanced Ultra High Speed Motor for Drilling

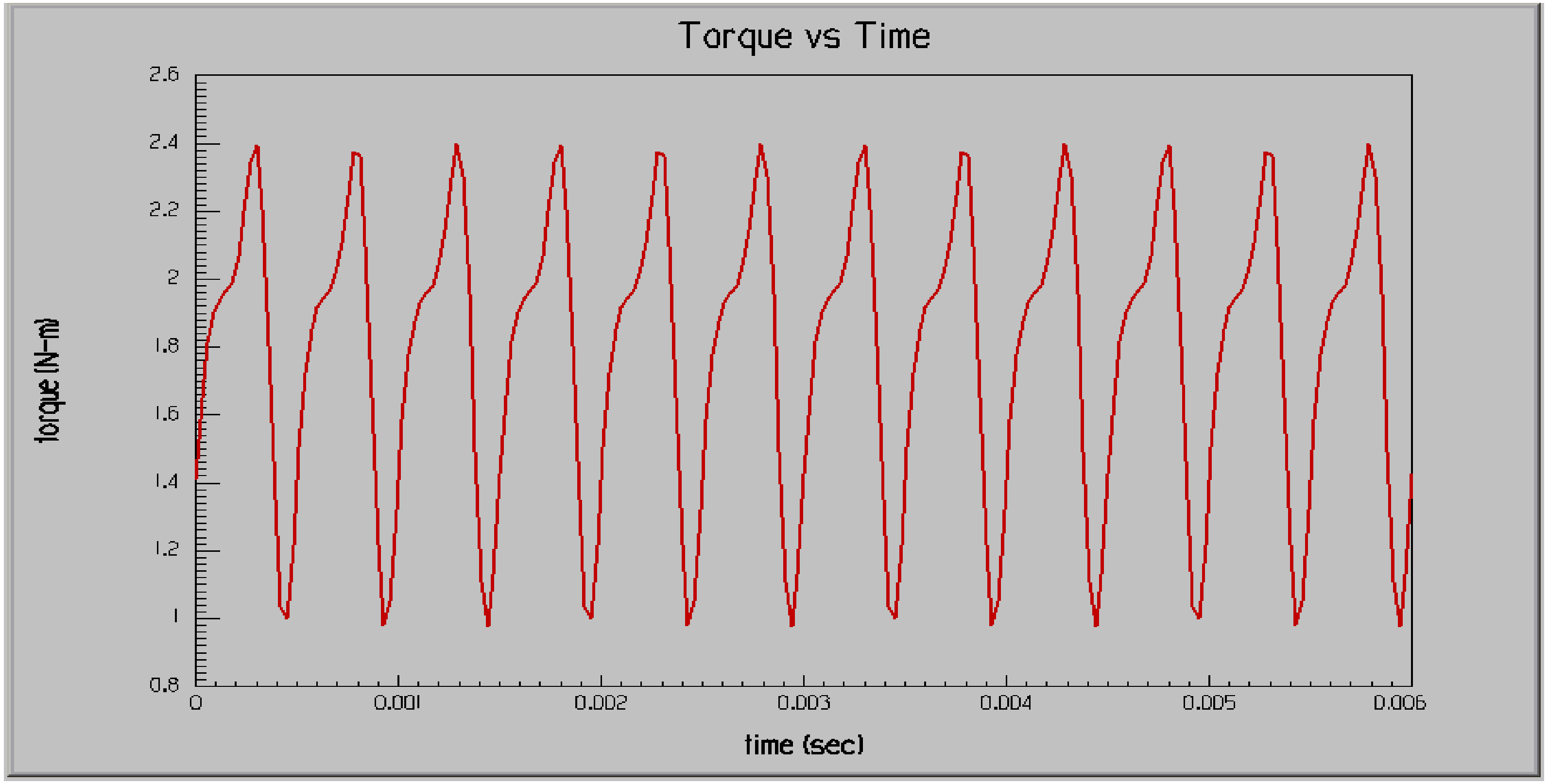
Finite Element Modeling of Radial Design, 3"OD



Torque profile at 50 rpm - 2 Nm =1.48ft-#, 2.68 Hp

Advanced Ultra High Speed Motor for Drilling

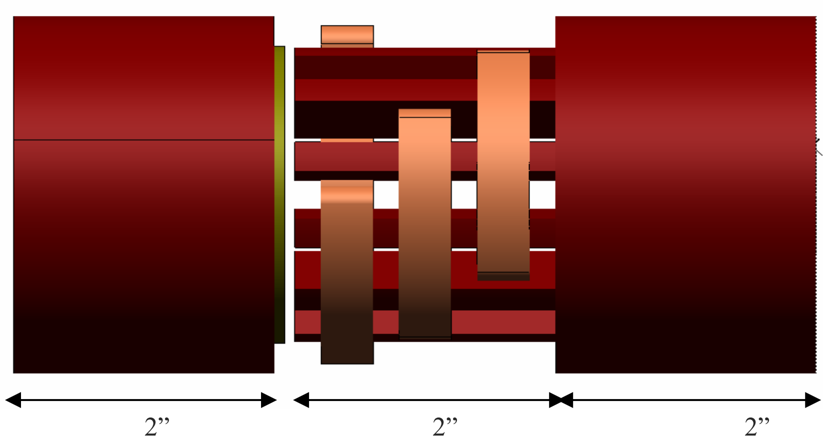
Finite Element Modeling of Radial Design, 3”OD

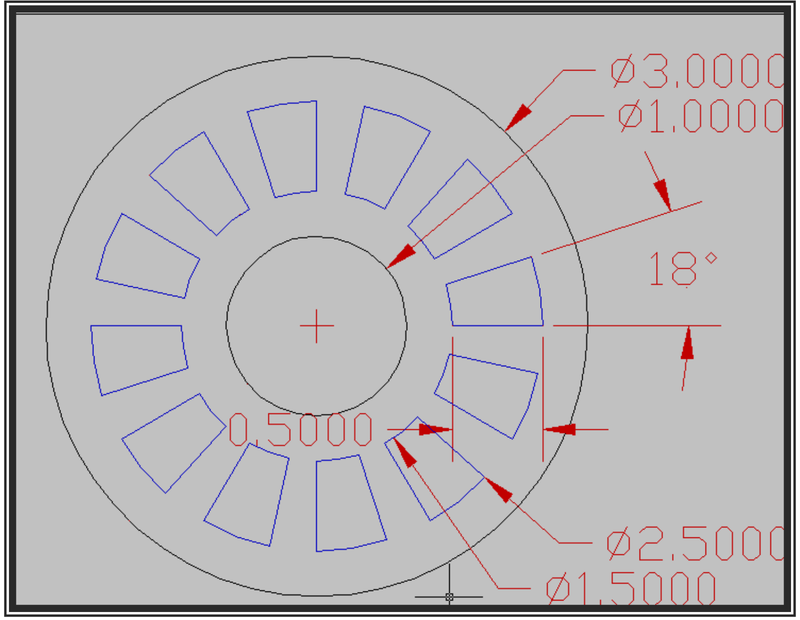


Torque profile at 10,000 rpm - 2 Nm =1.48ft-#, 2.68 Hp

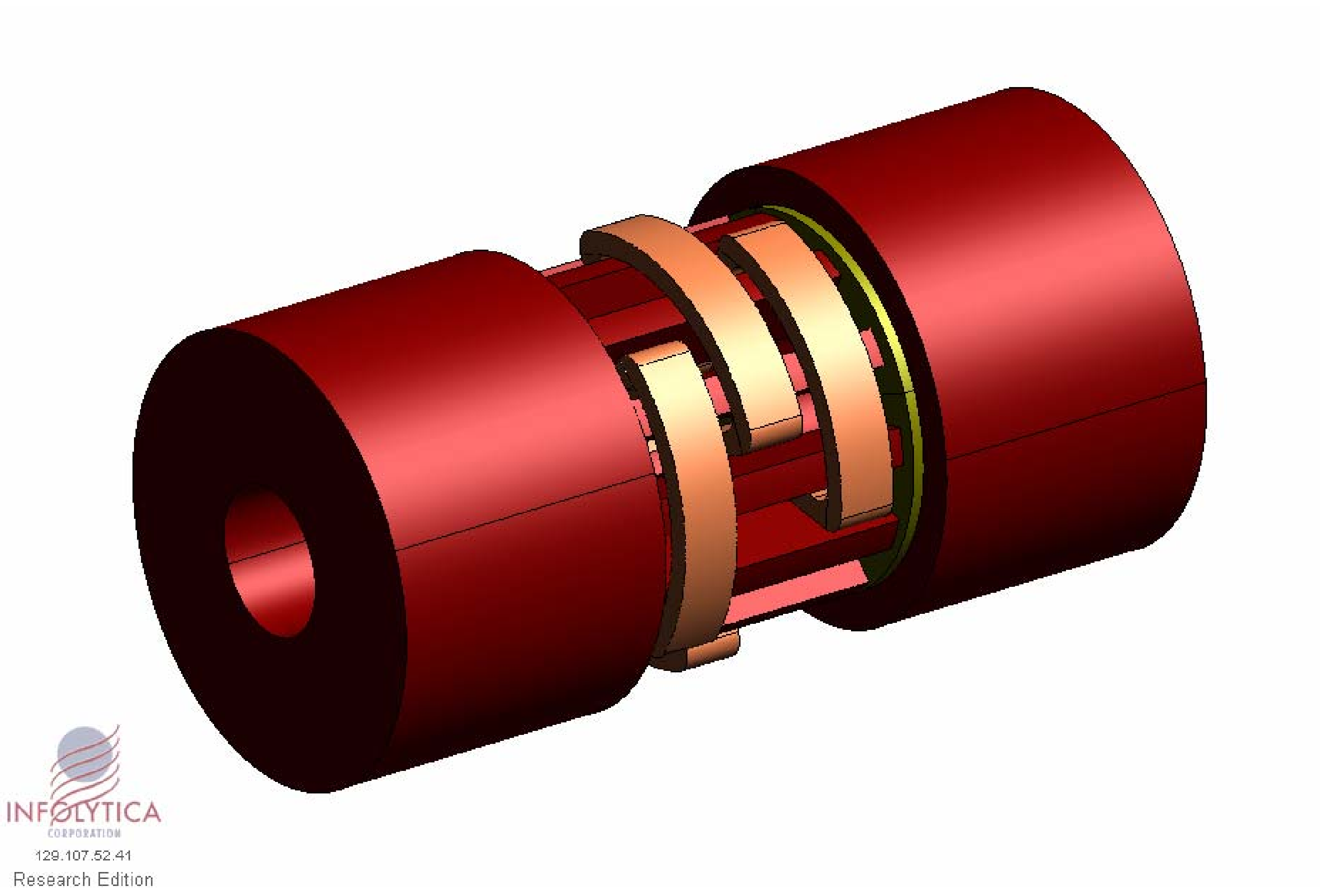
Axial Design-1 Geometry

- Outer Diameter = 3”
- Number of phases = 3
- Speed = 10,000 rpm
- Air gap length = 2 mm
- Stack length = 6 inches
- Magnet thickness = 2 mm
- Number of turns = 65
- Current = 2A



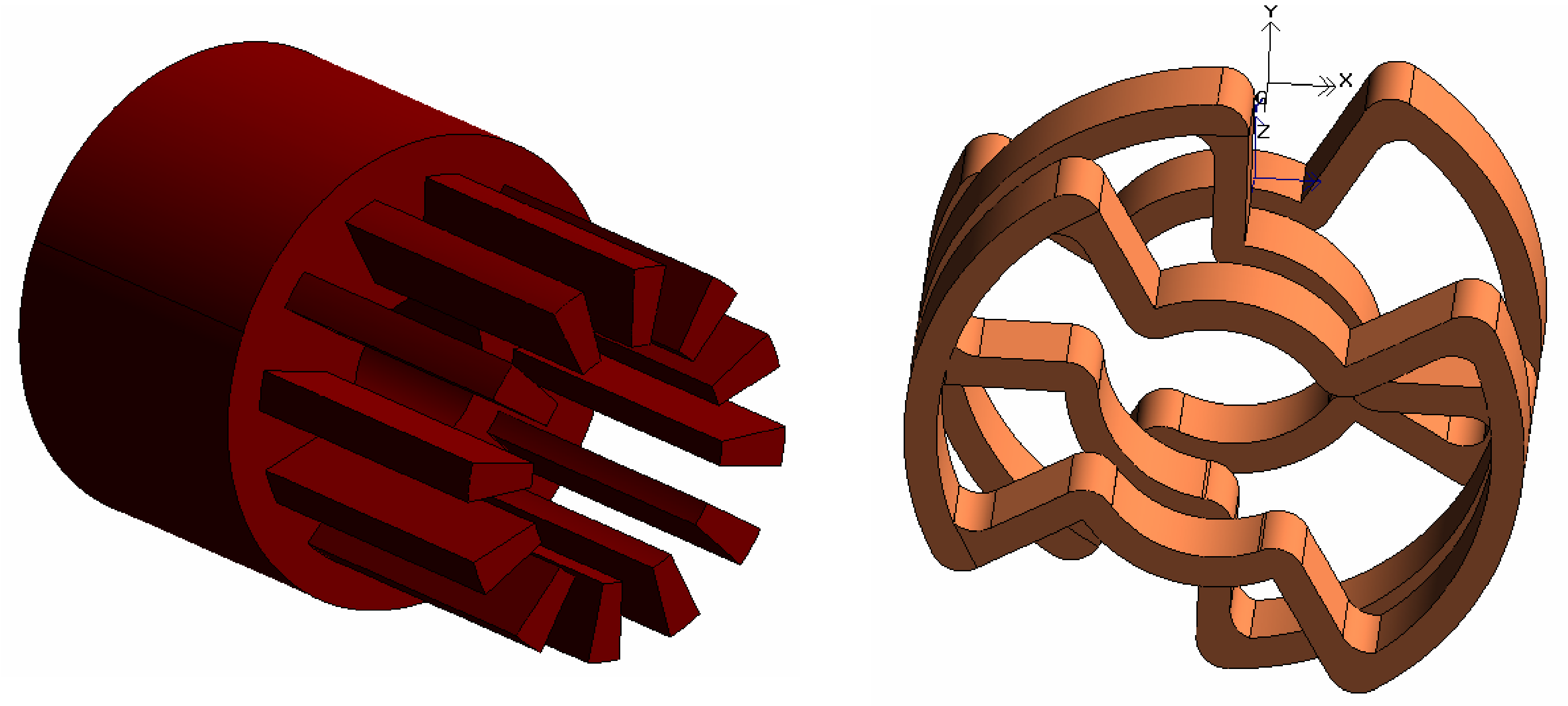


Advanced Ultra High Speed Axial Motor for Drilling



3D Finite Element Model (6” Stack Length)

Advanced Ultra High Speed Axial Motor for Drilling

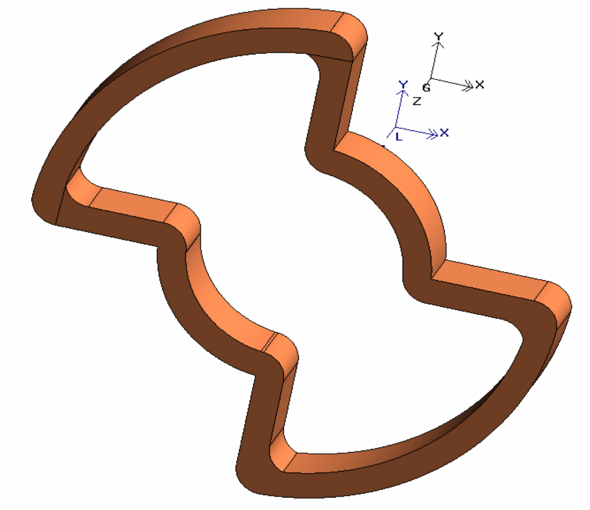


Stator back iron + teeth

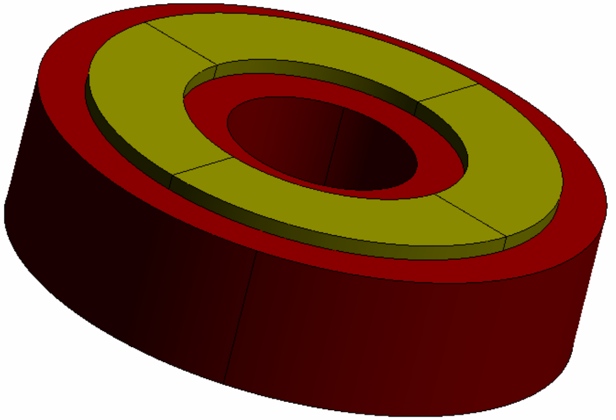
3D Coil Geometry

Finite Element Stator & Coil Geometry

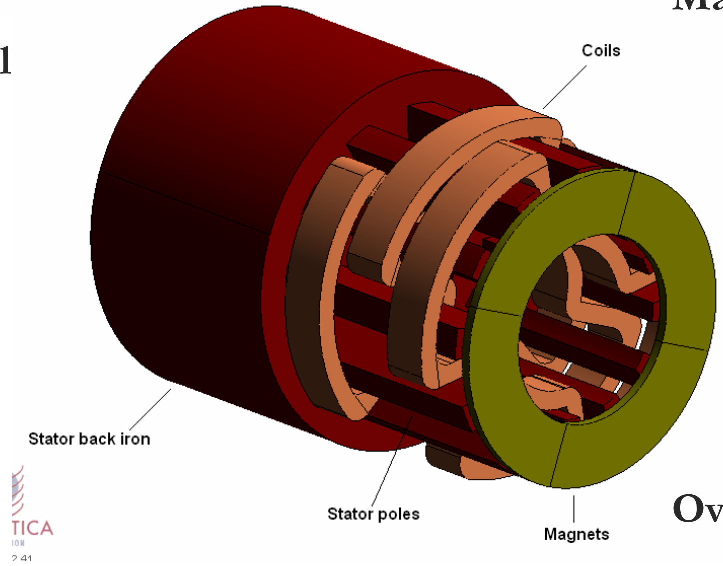
Advanced Ultra High Speed Axial Motor for Drilling



3D model of stator coil



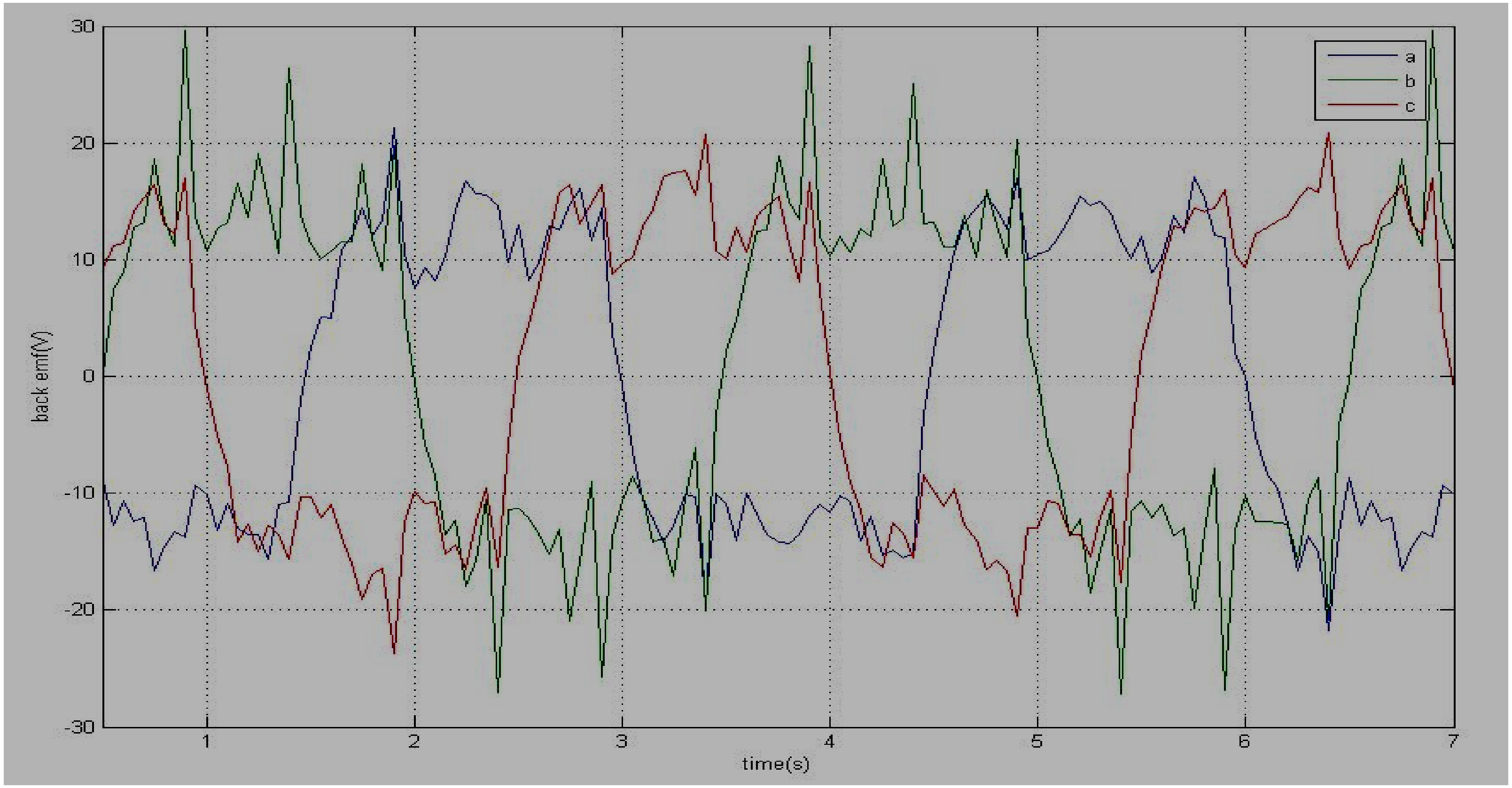
Magnet arrangement on rotor



Overall stator model + Magnets

Advanced Ultra High Speed Axial Motor for Drilling

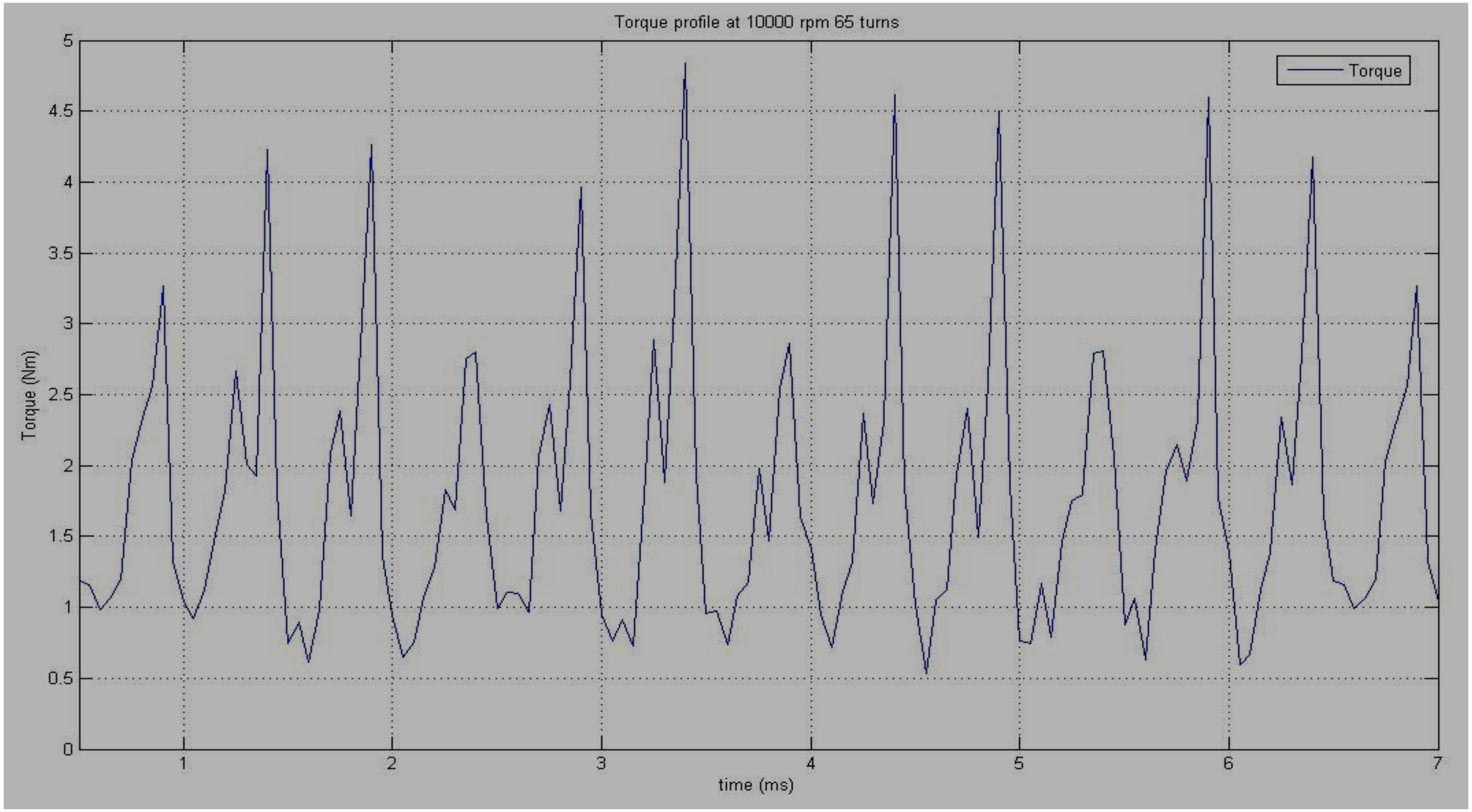
Finite Element Modeling of Axial Design, 3.0"OD



Back EMF plot at 10000 rpm

Advanced Ultra High Speed Axial Motor for Drilling

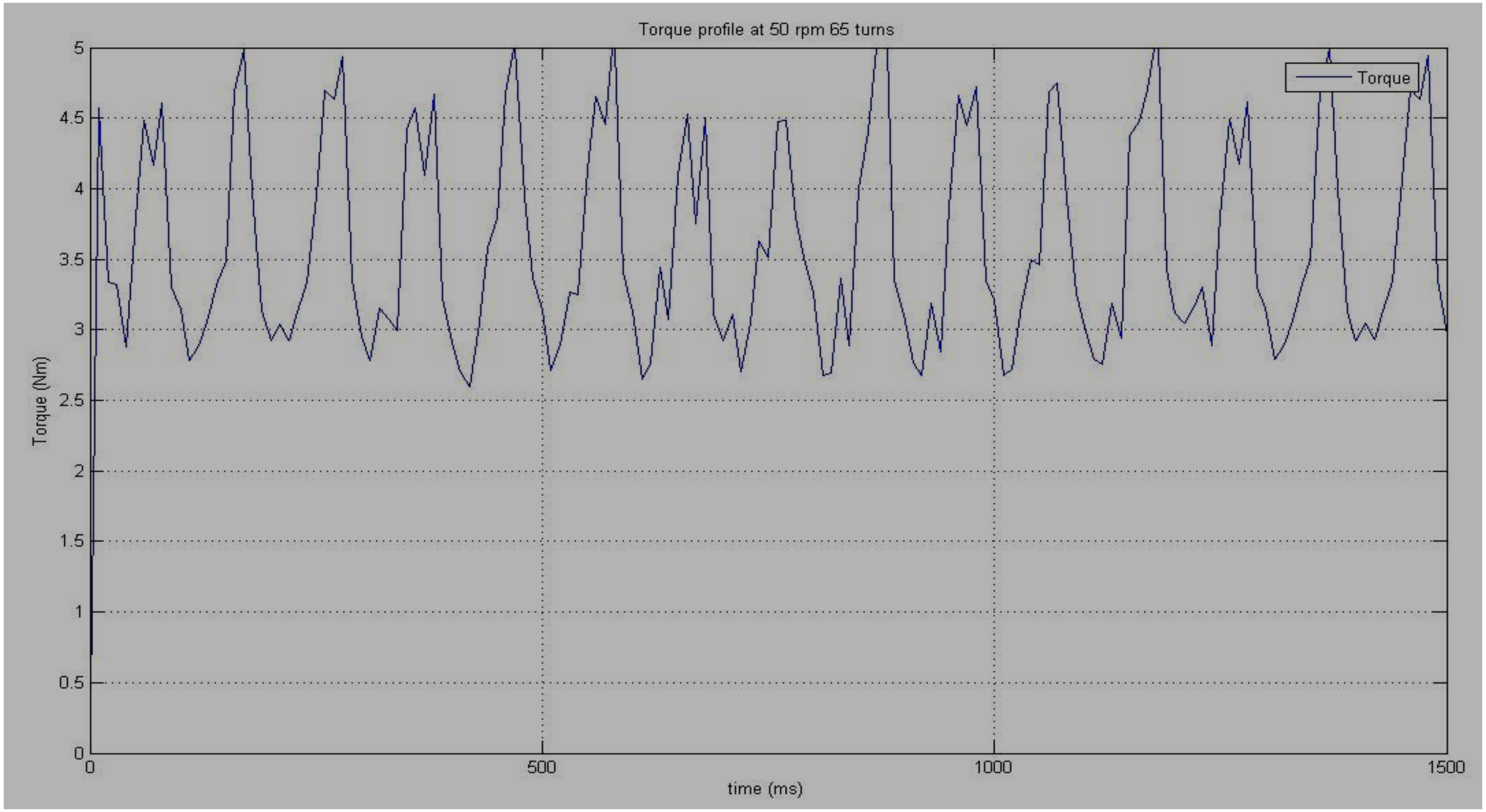
Finite Element Modeling of Radial Design, 3.0”OD



Torque profile at 10000 rpm

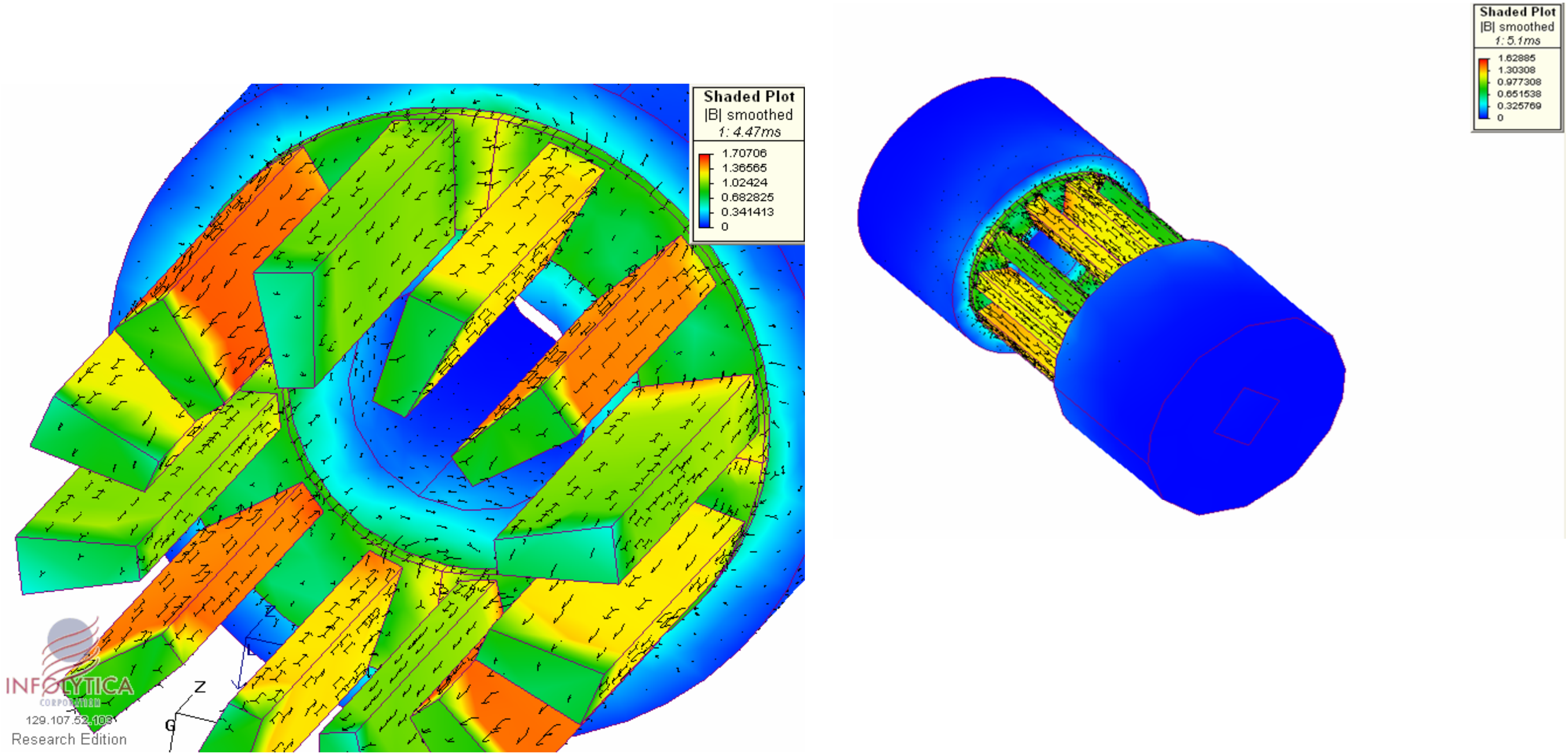
Advanced Ultra High Speed Axial Motor for Drilling

Finite Element Modeling of Radial Design, 3.0"OD



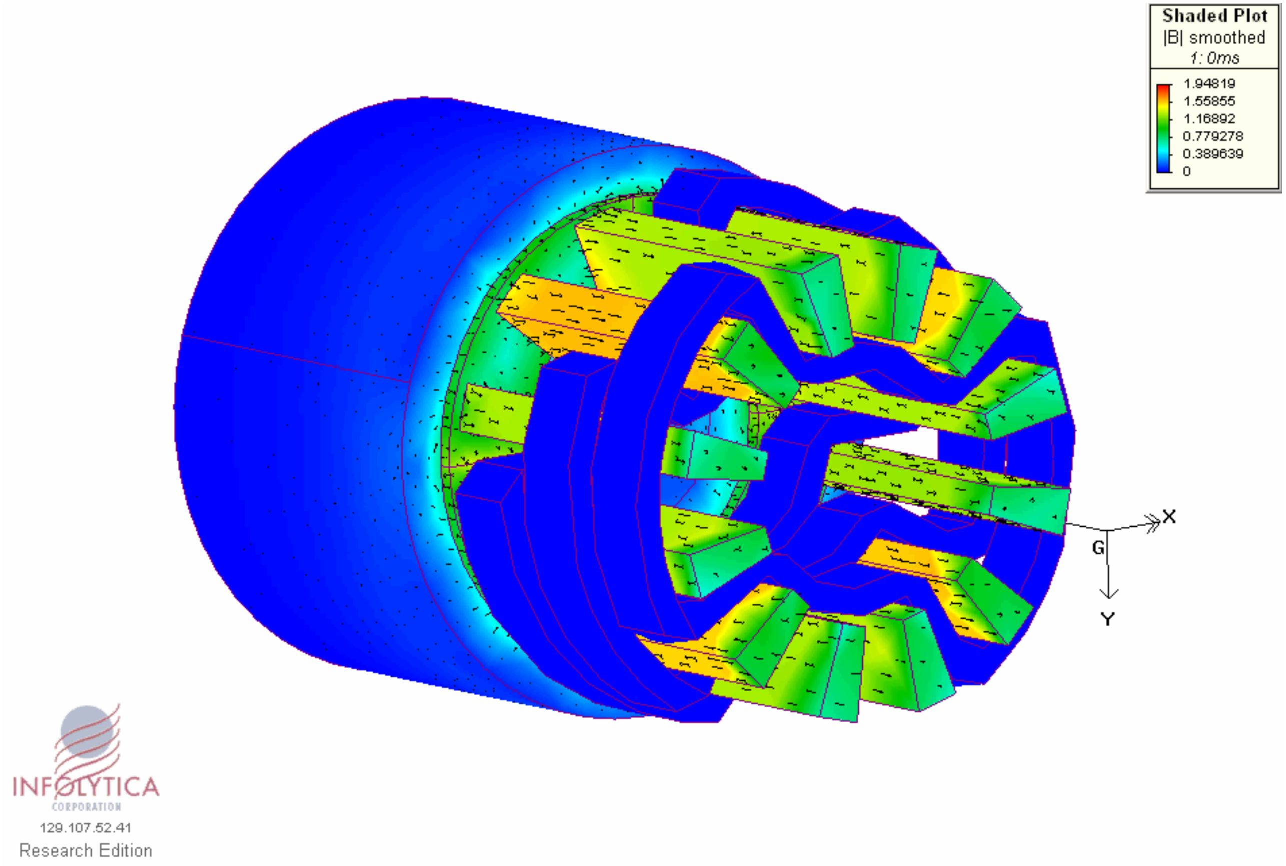
Torque profile at 50 rpm

Advanced Ultra High Speed Axial Motor for Drilling



Magnetic Flux Density (B) Distribution in the Machine

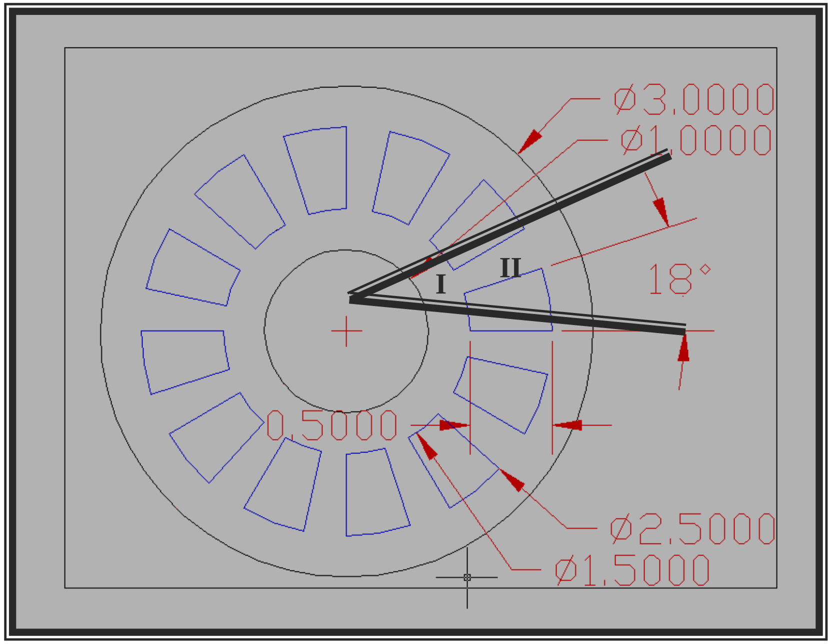
Advanced Ultra High Speed Axial Motor for Drilling



Operation of Axial Design-1

Loss Calculation for Axial 6" Stack @ 10,000 rpm

- Assumption:
  - Rotor is considered free of iron losses.
- Approach:
  - Division of stator geometry into twelve symmetrical sectors.
  - Segmentation of each sector into two parts for analysis, namely back-iron and stator tooth.
  - Loss Calculation of each segment of the stator.
  - Overall calculation of Iron losses in the PM Machine



$$f(t_n) = \frac{1}{2}A_0 + \sum_{p=1}^{N}[A_p \cos(\omega_p t) + B_p \sin(\omega_p t)]$$

Loss Calculation for Axial 6” Stack @ 10,000 rpm

Table I: Mass distribution in the stator

Region	**Cross section area (mm^2)**	**Volume (mm^3)**	**Mass (kg)**
I	101.60	5161.28	0.1429
II	337.81	17160.0	0.4750
Total (12 sections)	439.41 x 12	22321.28 x 12	0.6179 x 12 = 7.42

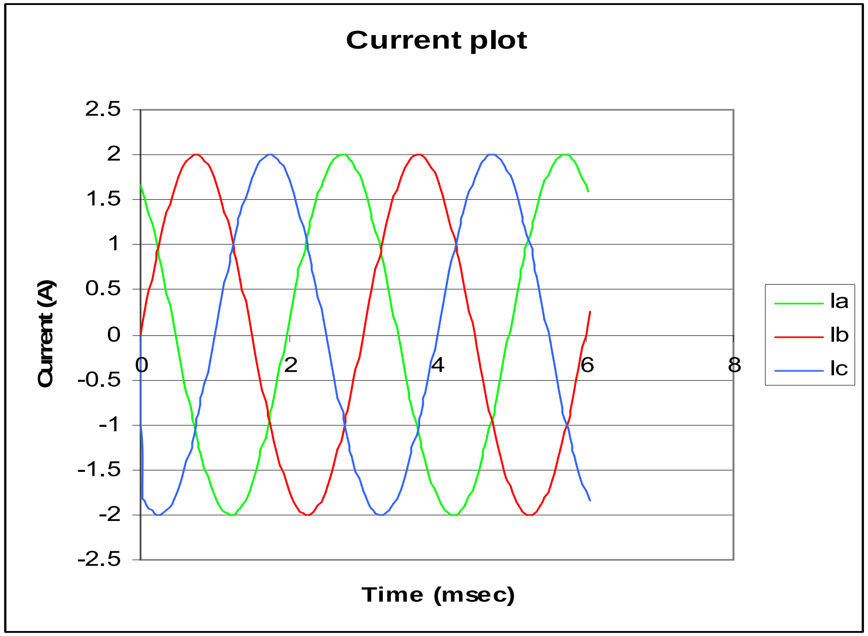
Density of chosen grade of steel (ρ) = 000027.68 kg/mm^3]

Table II: Harmonic components in different sections of stator

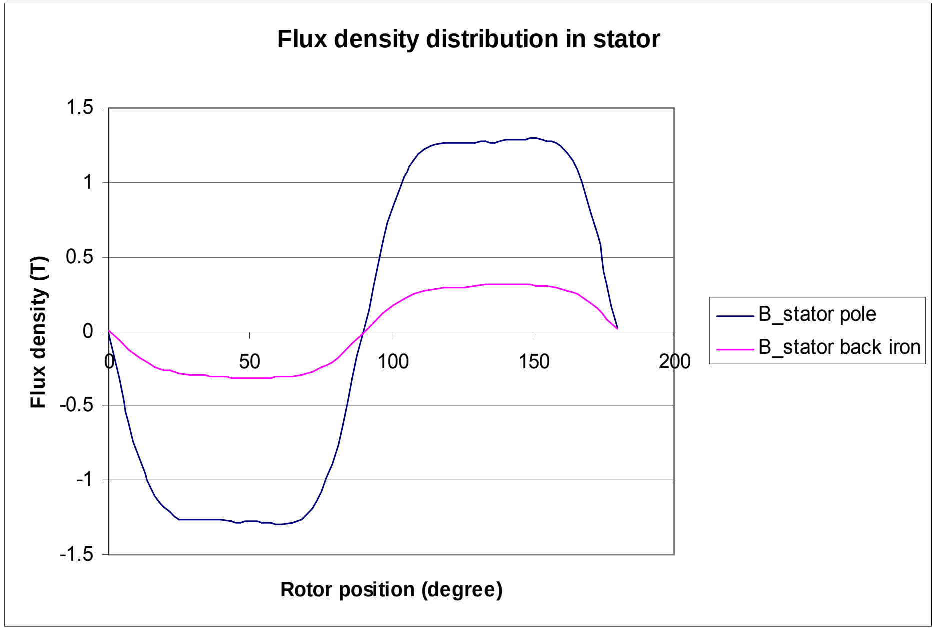
Quantity	**1st Harmonic**	**3rd Harmonic**	**5th Harmonic**
B1	1.4972	0.2389	0.0041
B2	0.3507	0.0424	0.0002

Fundamental frequency of excitation: 333.33 Hz

Loss Calculation for Axial 6” Stack @ 10,000 rpm



Excitation current as applied to the stator windings



Comparative distribution of flux densities in various sections of the stator regions

Loss Calculation for Axial 6” Stack @ 10,000 rpm

Table III: Loss density distribution in the stator

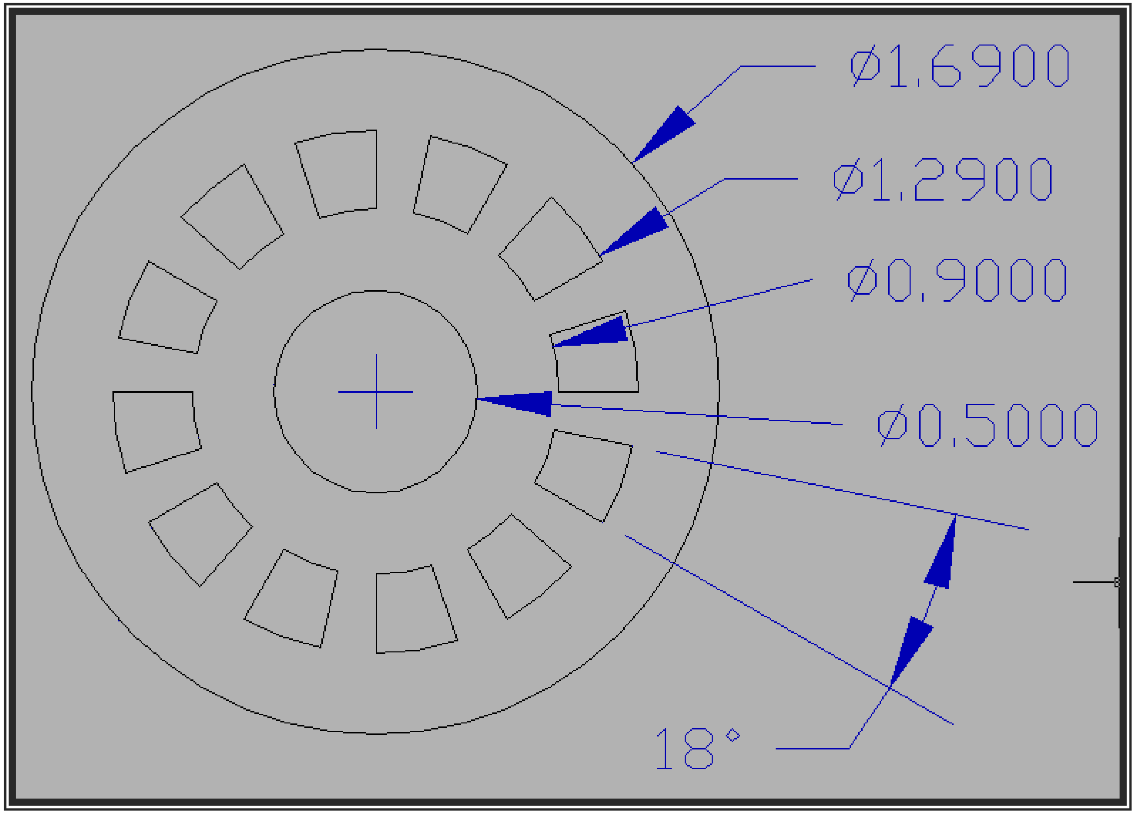
	Region 1	**Region 2**
1st harmonic	6	2
3rd harmonic	0.03	0.02
5th harmonic	0.001	0
Total	6.03	2.02

Table IV: Loss distribution in the stator

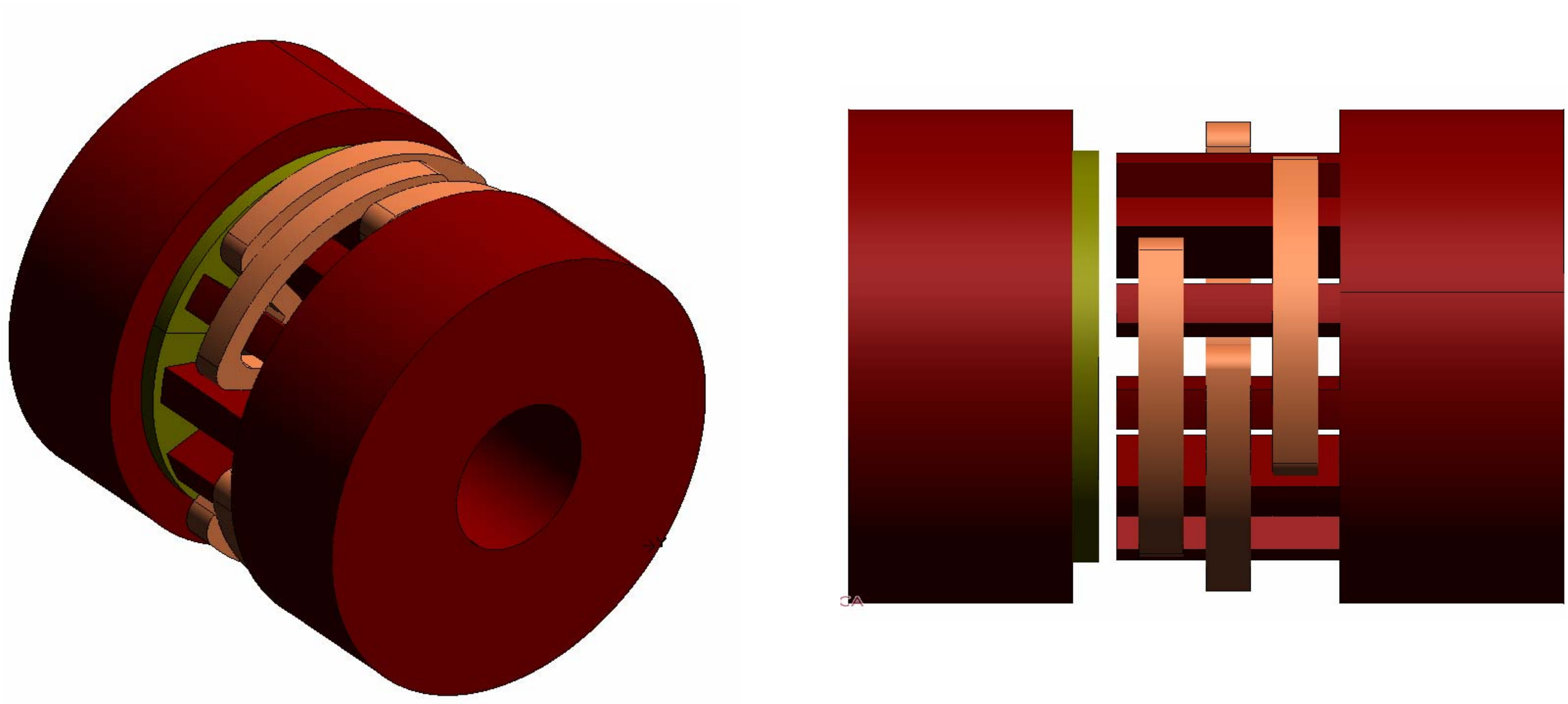
Region	**Mass (kg)**	**Mass (lbs)**	**Iron loss (W)**
I	1.72	3.79	22.74
II	2.85	6.28	12.69
Total	4.57	10.07	**35.43**

Axial design 2 (In progress)

- Outer Diameter = 1.69”
- Number of phases = 3
- Speed = 10,000 rpm
- Air gap length = 2 mm
- Stack length = 3 inches
- Number of turns = 65
- Current = 2A



Advanced Ultra High Speed Axial Motor for Drilling

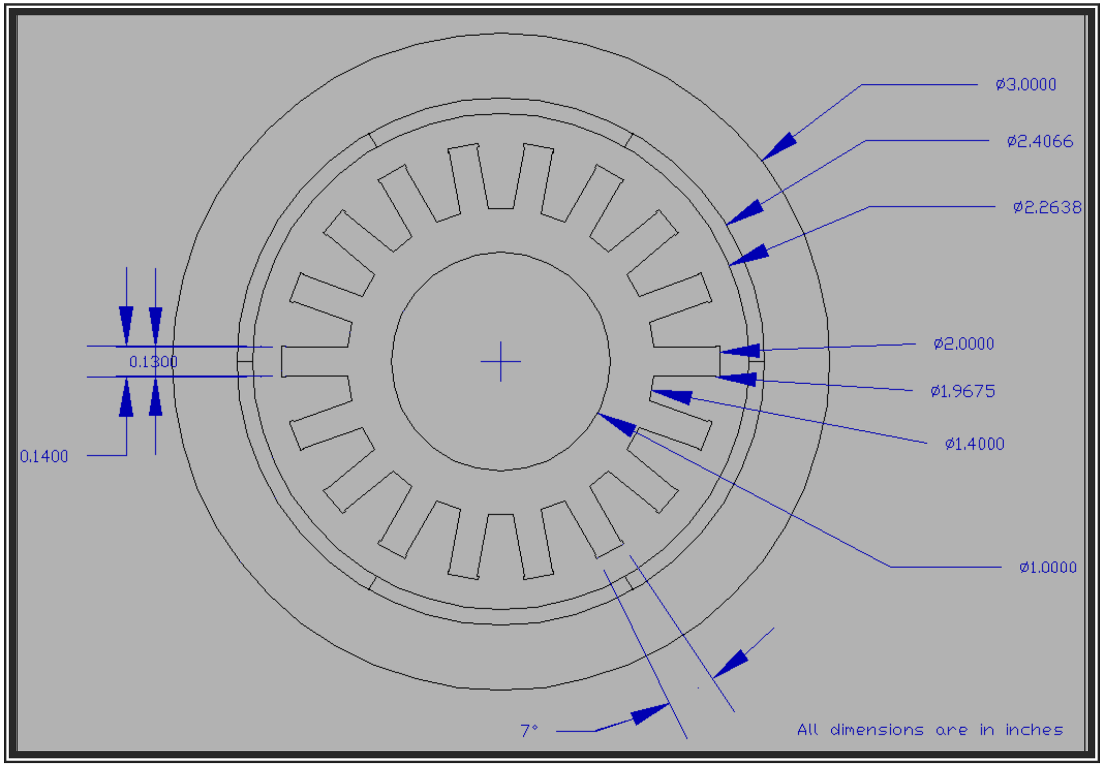


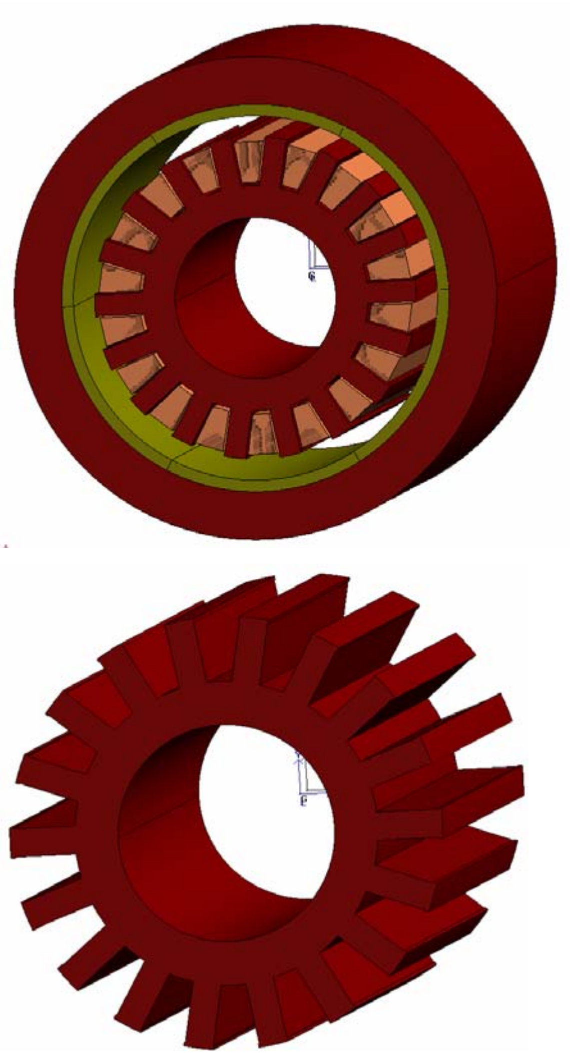
3D-model of Axial Design 2

Design Summary

- Radial 3:
  - OD = 3”, stack length = 12”, phases = 3, poles = 6
- Radial 4:
  - OD = 3”, stack length = 12”, phases = 3, poles = 8
- Axial 3 :
  - OD = 3”, stack length = 6”, phases = 3, poles = 6

Advanced Low Speed Radial Motor for Drilling

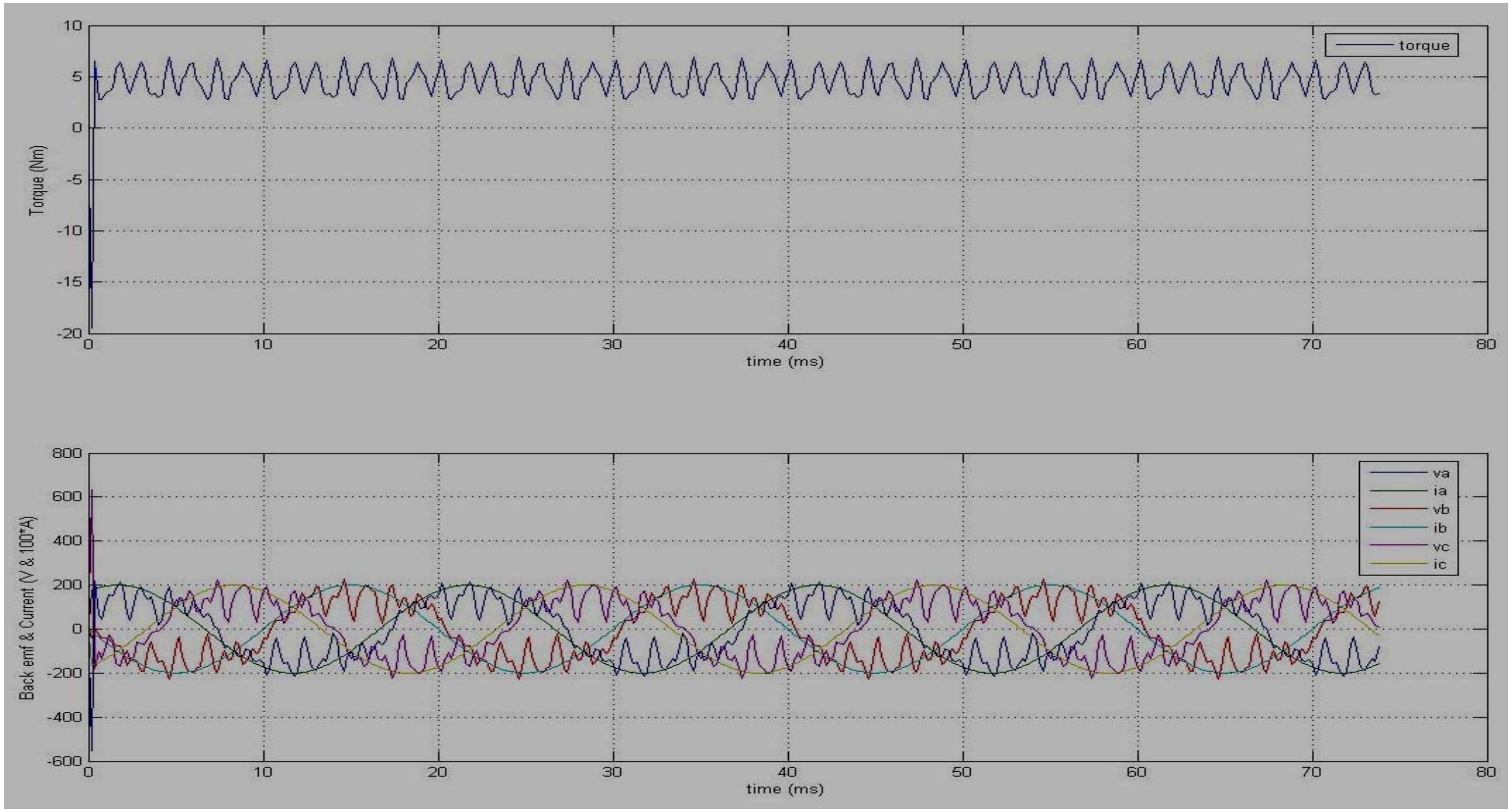




Finite Element Modeling of 6-pole Radial Design

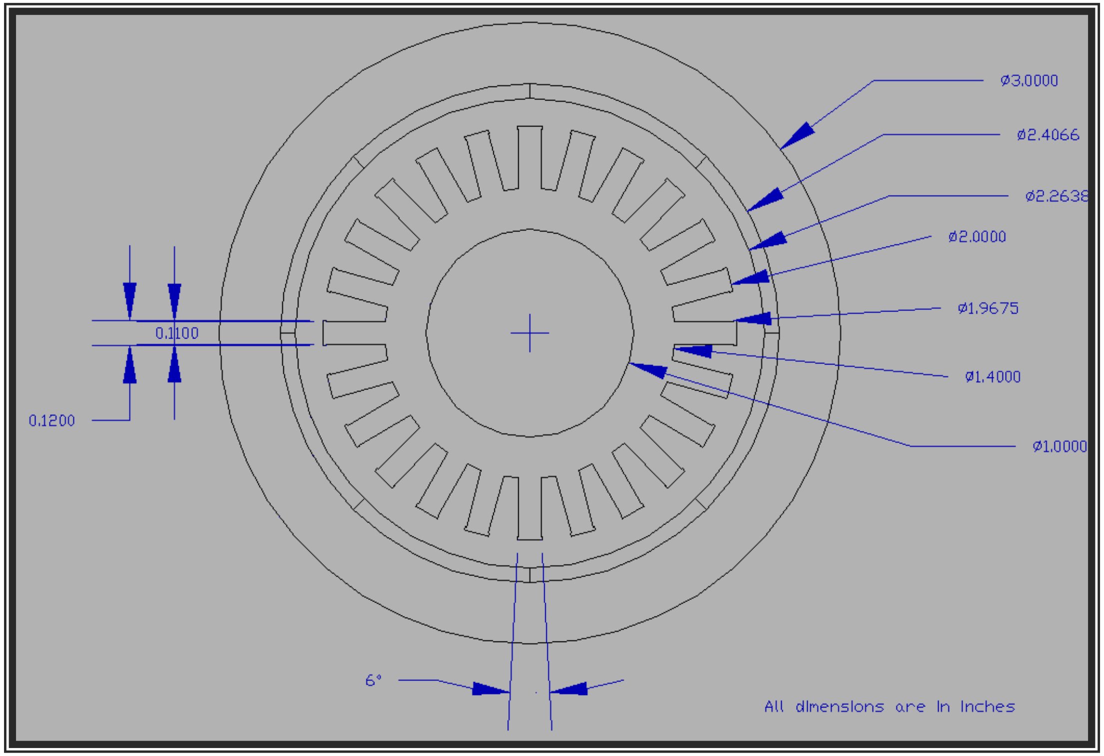
Advanced Low Speed Radial Motor for Drilling

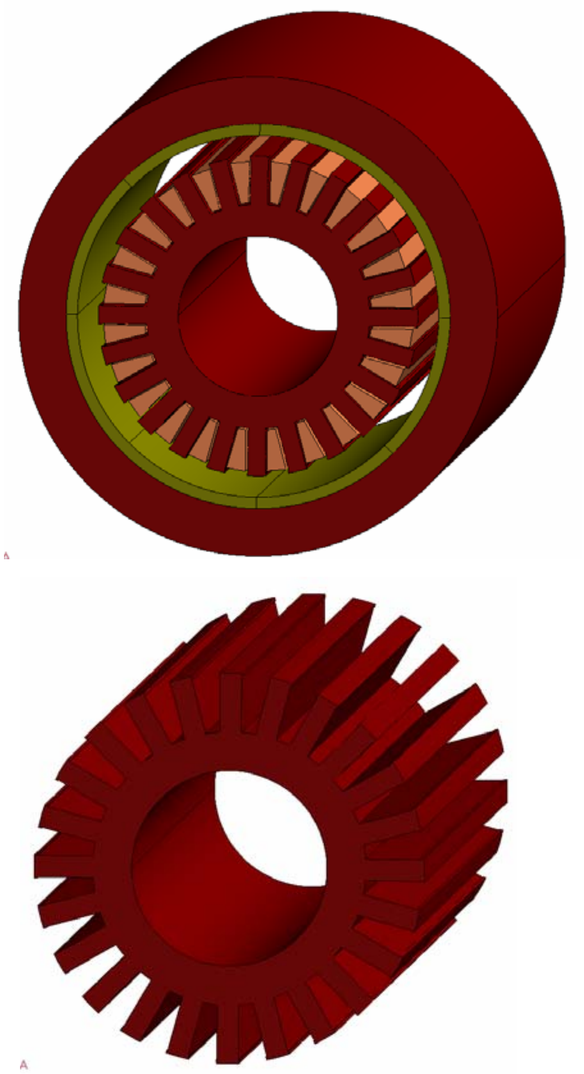
Finite Element Modeling of 6-pole Radial Design, 3.0"OD



Torque profile at 1000 rpm

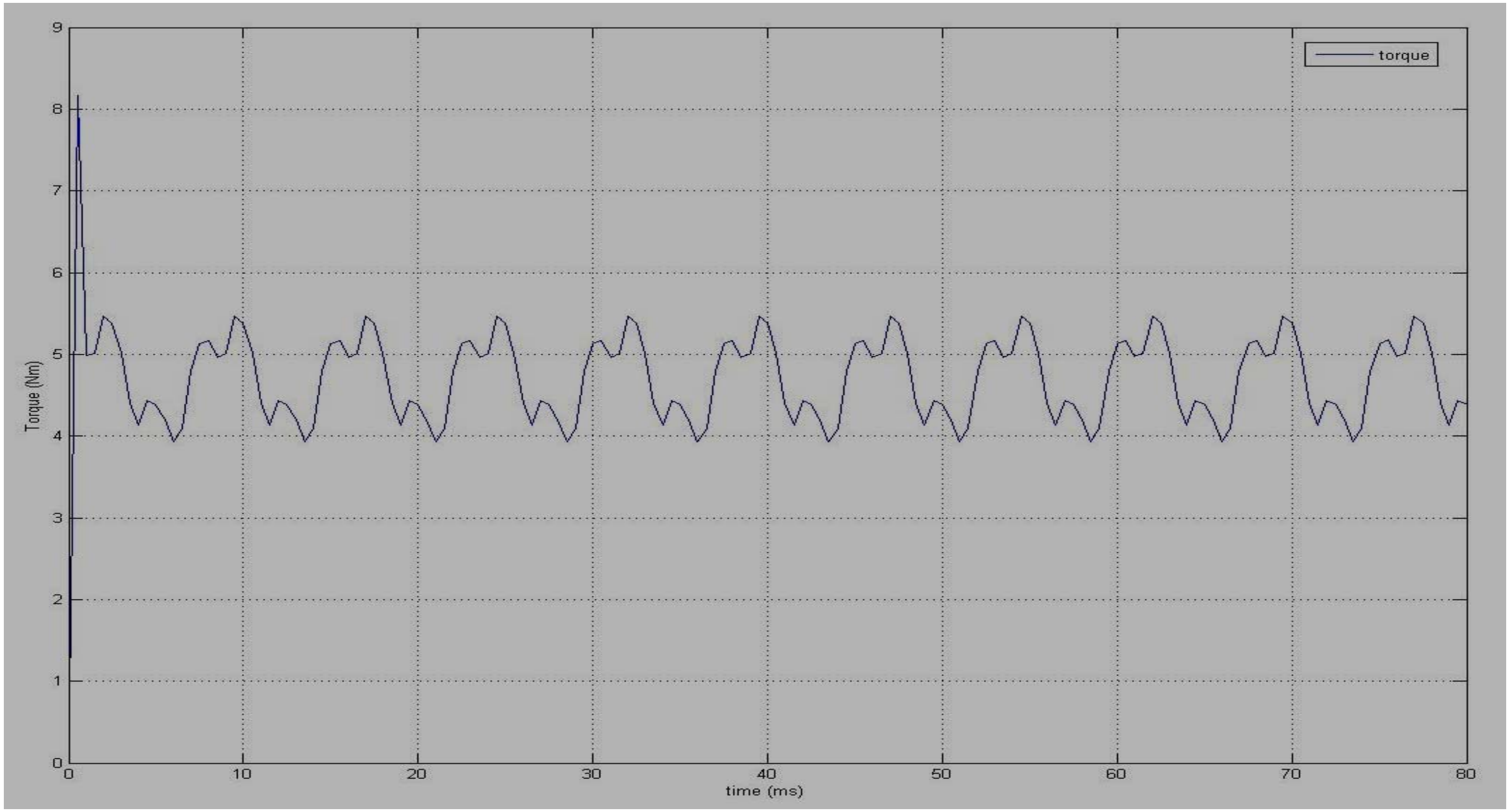
Advanced Low Speed Radial Motor for Drilling





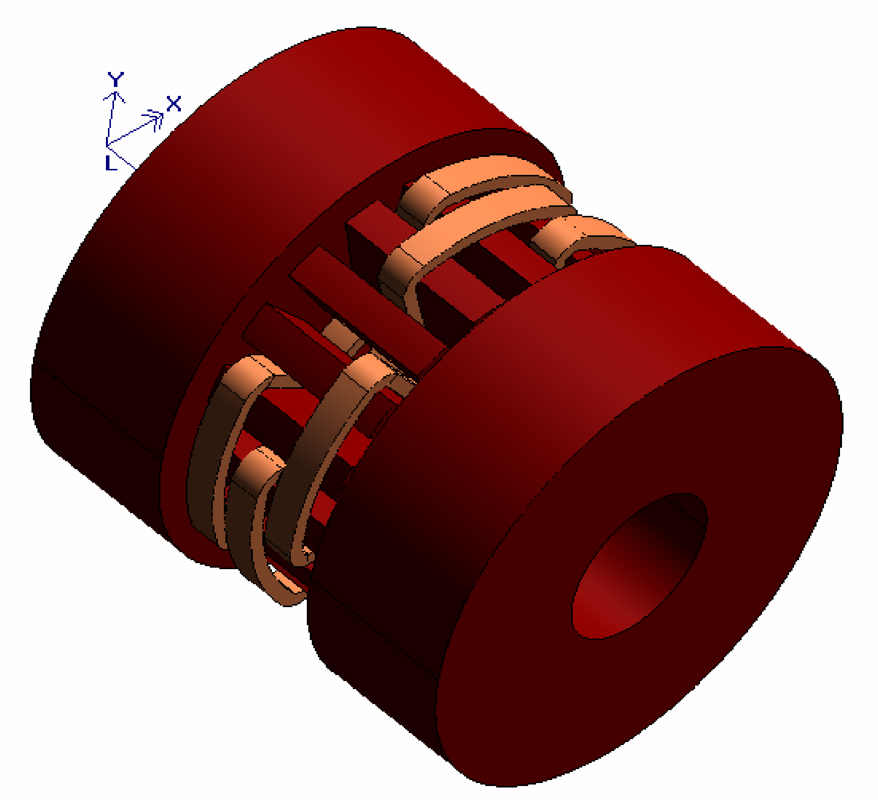
Advanced Low Speed Radial Motor for Drilling

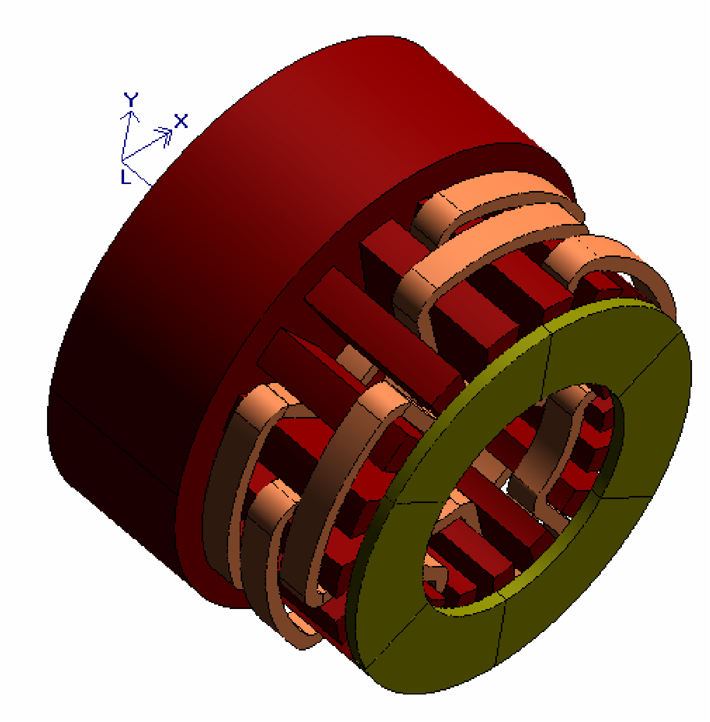
Finite Element Modeling of 6-pole Radial Design, 3.0”OD



Torque profile at 1000 rpm

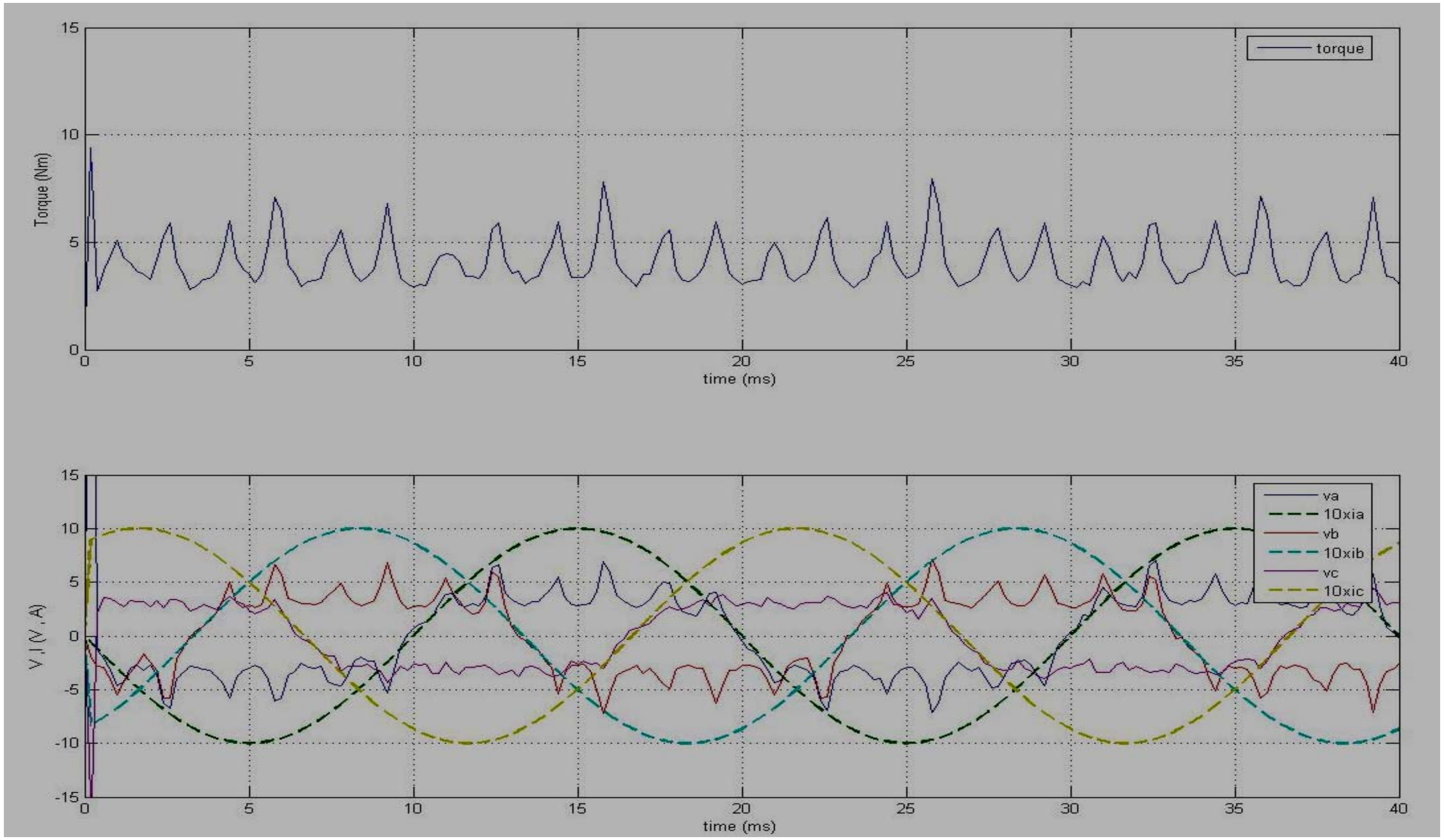
Advanced Low Speed Axial Motor for Drilling





Advanced Low Speed Axial Motor for Drilling

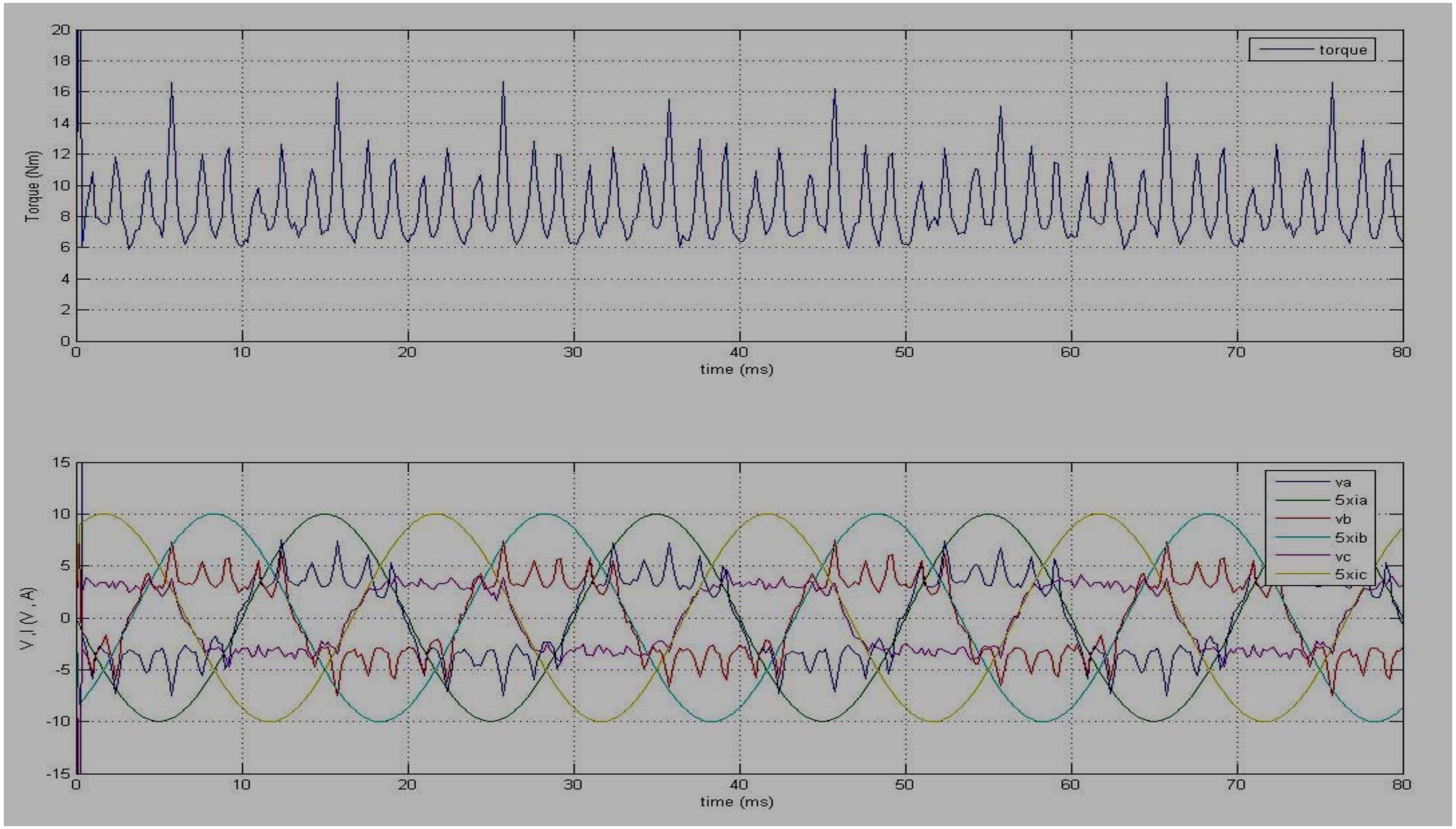
Finite Element Modeling of Axial Design, 3.0"OD



Torque profile at 1000 rpm

Advanced Low Speed Axial Motor for Drilling

Finite Element Modeling of Axial Design, 3.0”OD



Torque profile at 1000 rpm

Inverted Motors for Drilling

16September 2005

For
University of Tulsa
Graduate Seminar

By
Ken Oglesby, Impact Technologies LLC

Additional Recognition

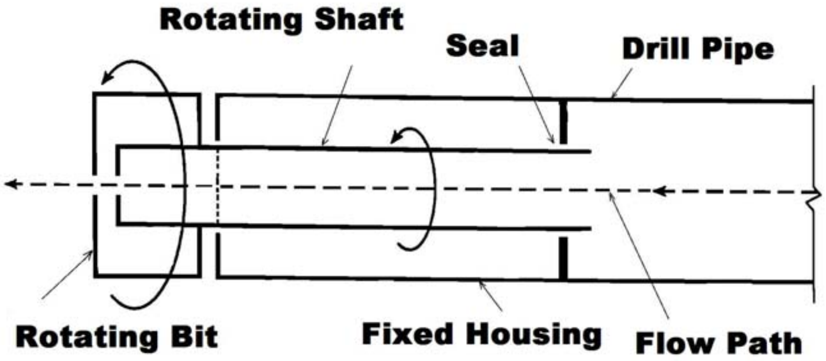
Rhonda Jacobs
US Department of Energy, NETL

Babak Fahimi , PhD
Mahesh Krishnamurthy
University of Texas at Arlington

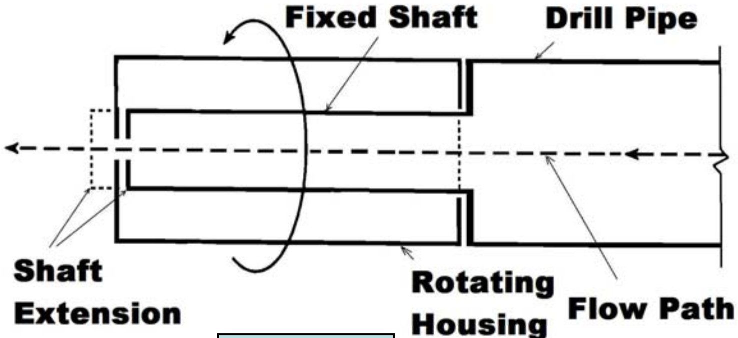
Inverted Motors for Drilling
Outline of Discussion

- Introductions and Recognition
- Basic Inverted Motor Configuration
- Inverted Motor Design Benefits
- History of Electric Drilling
- DOE Ultra-High Speed Inverted Electric Motor
- Low Speed Inverted Electric Motor
- Electro-Magnetic-Mechanical Designs
- Bearing / Seal Options
- Hydraulic and Pneumatic Inverted Motor Design

Basic Inverted Motor Configuration

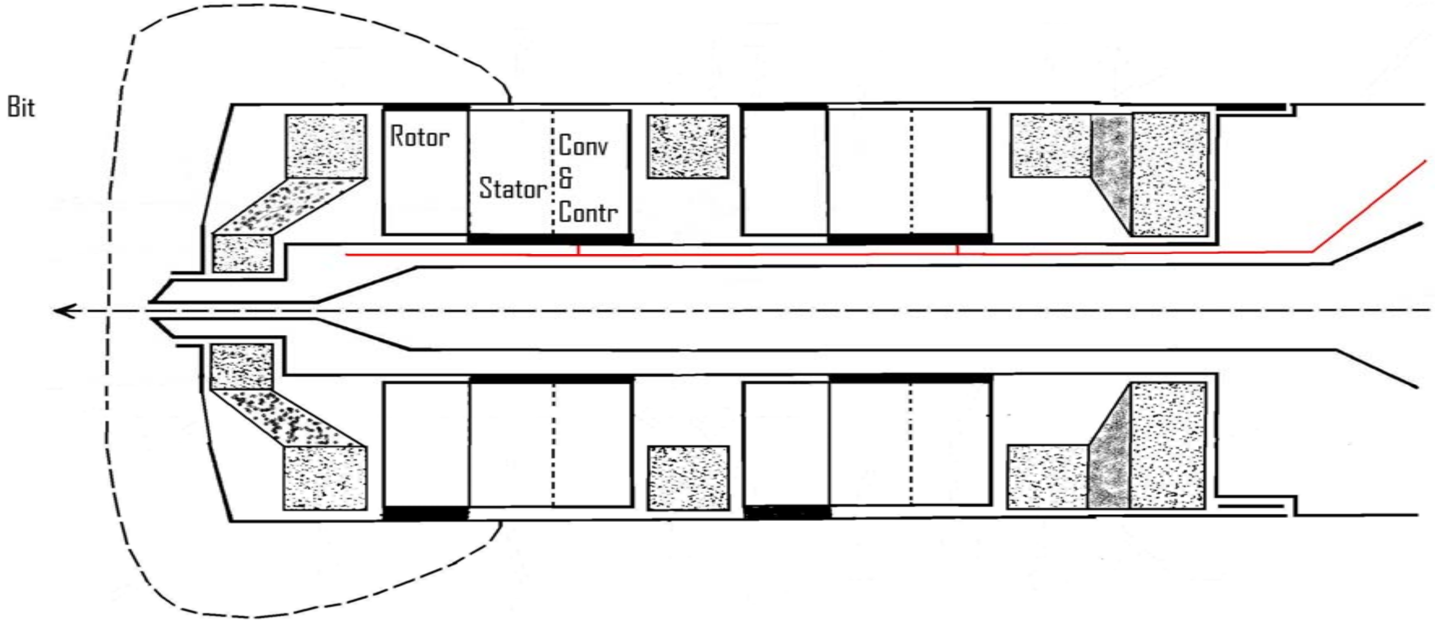


Conventional Electric Motor



Inverted Electric Motor

Inverted Motors for Drilling
Generalized IM Motor Configuration



Inverted Motors for Drilling
Basic Inverted Motor Configuration

- Basic design
  - Shaft connected to drillstring and not rotating (stator)
  - Housing rotates (rotator) with bit attached
  - Shaft has channels for flow and wires
- Benefits
  - Allows advanced drilling techniques
    - Ultra high pressure / Abrasives / Acids/ bases
  - Directional and Logging (GR, …) tools in/ at bit
  - Multiple motors on BHA/ drillstring
  - Ultra short radius turns
  - Initial designs fit into DOE Microhole Project sizes and CT capabilities
- Drawbacks
  - New, not tested
  - Shaft only now holds motor and lower string / tools

Inverted Motors for Drilling

Other types of Inverted Motors

Gerotor
Concentric

Moineau
Concentric

Roller Vane
Concentric

Turbine
Concentric

Piston
Concentric

Gerotor
Eccentric

Moineau
Eccentric

Roller/Wing
Concentric

Electric
Concentric

Others

Inverted Motors for Drilling

- Concentric Movement

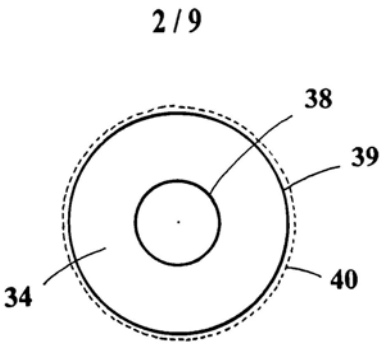


Fig. 3

- Eccentric Movement

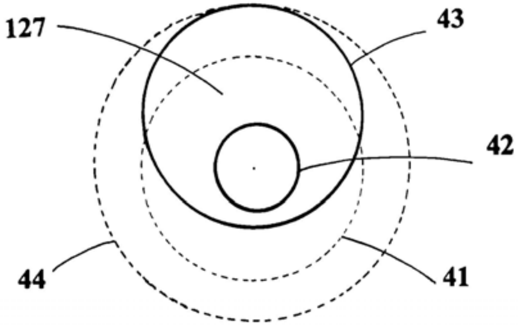


Fig. 4

Inverted Motors for Drilling

Channel(s) in Shaft of IM Motor

Fluid/Gas Flow
Ultra High Hydraulic Pressure
Electrical Wires
Optical Wires

for uses in

Hydraulic/Abrasive/Dir Jetting

MWD / LWD
(near-bit or in-bit)

Improved Hole Cleaning

Multiple Motors

Inverted Motors for Drilling
Possible IM Benefits

The Evolutionary Next Step in Advanced Drilling Technology

Proven Technology

HP Hydraulic Jetting
Bi-centered/ Hole Enlargement
***Abrasive Jetting** (solids added to HP stream)*
Low Weight on Bit

New Technology

Enhanced Directional Drilling
(Offset Hydraulic / Abrasion Jetting)
Laser/ Plasma Drilling
Clamp-on IM for CTD

Inverted Motors for Drilling

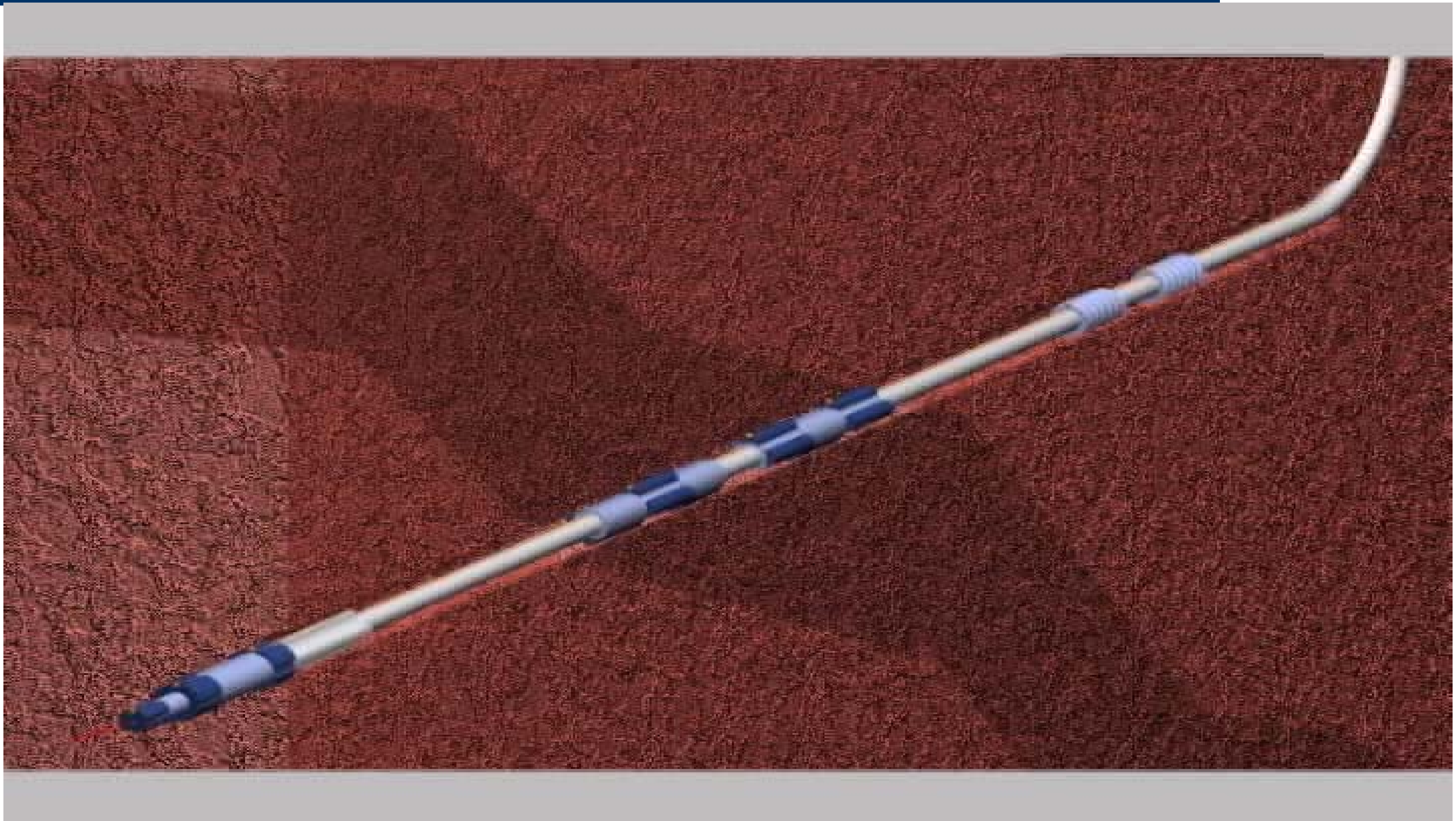
Independent motors in Series or Parallel

Bi-centered style Movement or Concentric Drilling/Reaming

Balanced Radial Forces (Torque)
clockwise /counter clockwise rotation
low net torque to drill string

Balanced Axial Forces
opposing motor stages in parallel flow
HP utilization, smaller bearings&seals

Inverted Motors for Drilling
IM Drilling System



Inverted Electric Motors for Drilling

- US Department of Energy
  - Advanced Ultra-High Speed Motor for Drilling

- University of Texas
  - Low Speed Inverted Motor for Drilling

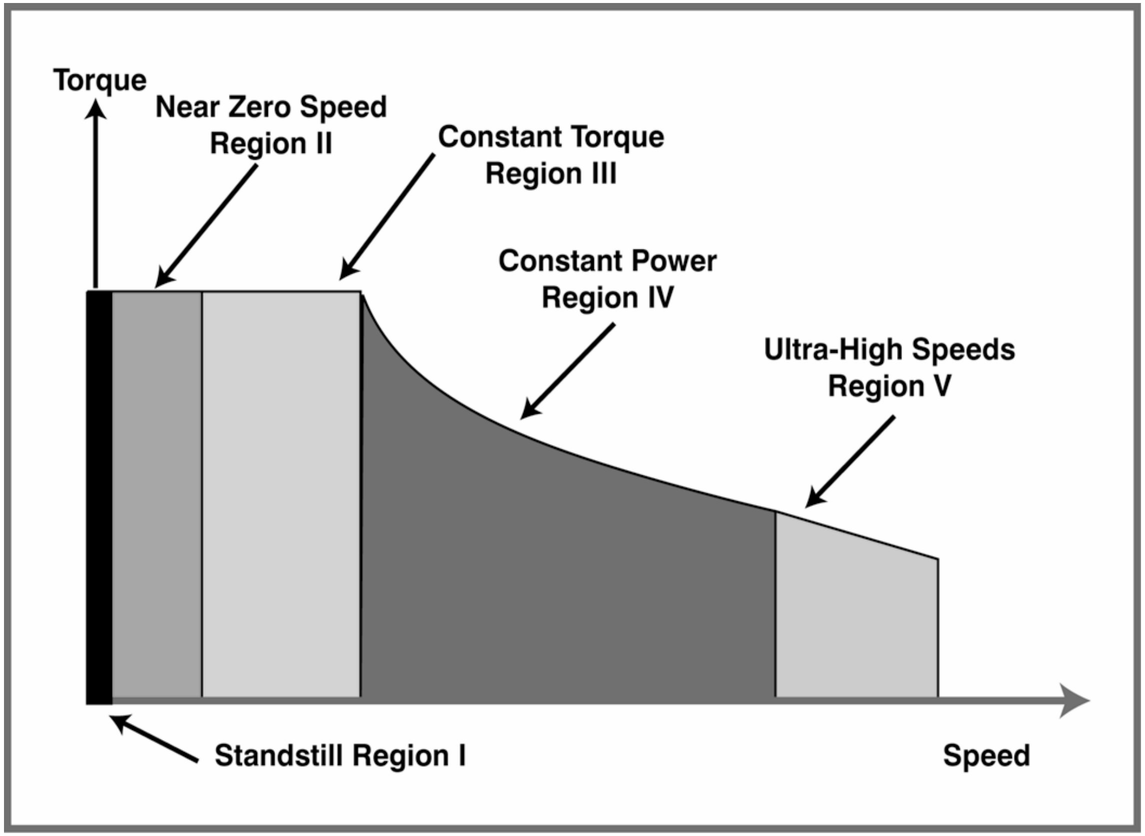
History of Drilling with (Conventional) Electric Motors

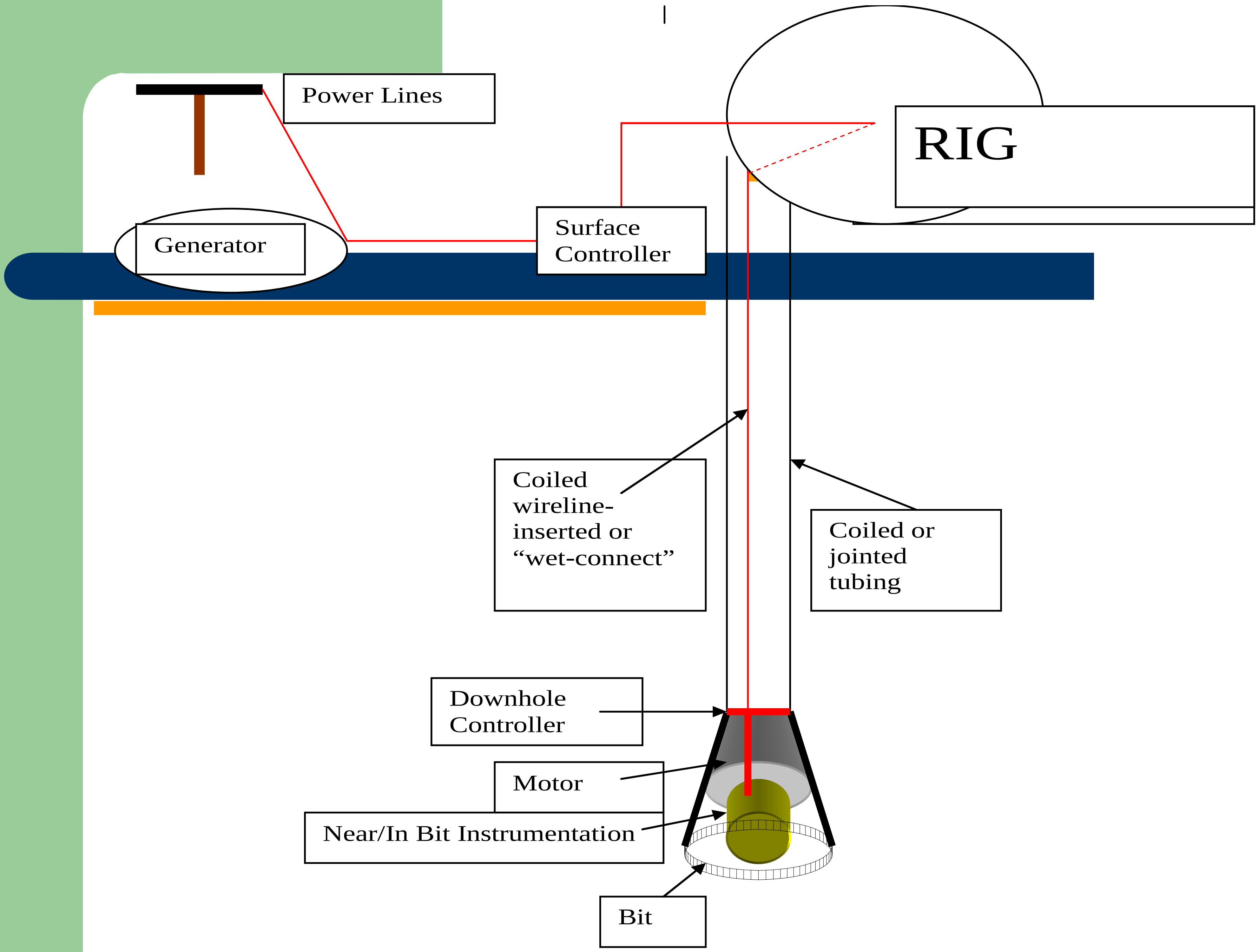
- The USSR performed serious work and field tested on electric motor drilling for many decades, although little published work has been found by the author.

- General Electric worked on downhole electric motors for drilling in a FERC/ pre-DOE funded project, cumulating in a final report in 1977. Key and fatal problem was the lack of a high capacity, reliable electrical link to the bottomhole assembly via the jointed drill pipe. No significant problems were reported on the conventional style electric motor.

- The European Drilling Engineers Association (DEA(E)) has a joint industry project headed by XL Technology that is (now-still?) in Phase II- field testing a DC brushless motor. They identified the benefits of an electric motor as-
  - drive power independent of fluid flow,
  - tolerance for energized fluid,
  - high temperature applications,
  - scalable power,
  - real time information,
  - low vibration and
  - reversible direction.

Inverted Electric Motor for Drilling





Power Lines

RIG

Generator

Surface Controller

Coiled wireline-inserted or “wet-connect”

Coiled or jointed tubing

Downhole Controller

Motor

Near/In Bit Instrumentation

Bit

Advanced Ultra High Speed Motor for Drilling
Motor Specifications-Background

- Literature Review on DC machine fundamentals
  - Electric Machinery Fundamentals by SJ Chapman, ISBN 0-07-246523-9
  - Electrical Motion Devices by PC Krause, ISBN 0-07-035494-4
- Research into ultrahigh speed cutters
  - Ultra high rpms/ velocities generate high temps causing thermal cracking
  - PDCs, diamonds
  - Smith Premium HOT PDC cutters
  - Thermally Stable Polyrystalline Diamond Cutters- Bob Radkte / Technology International/ DOE work
  - TerraTek / Arnis Judzis, Alan Black/ DOE work on testing cutters for ultra high speeds
- Research into ultra high speed bearings
  - Mahlon Dennis/ Dennis Oil Tools- PDC-PDC bearings
  - NASA metal-metal coatings
  - Kalsi
  - Fahimi source
- Research into ultra high speed seals- Kalsi / Weatherbee

Advanced Ultra High Speed Motor for Drilling
Motor Specifications-Background

TerraTek Ultrahigh speed

OD	rpm	ft/sec velocity
0.75	50,000	163.5417
1.68	22,321	163.5417
2	18,750	163.5417
3	12,500	163.5417
3.5	10,714	163.5417
4.75	7,895	163.5417

TerraTek -lower range speed

OD	rpm	ft/sec velocity
0.75	30,000	98.125
1.68	13,393	98.125
2	11,250	98.125
3	7,500	98.125
3.5	6,429	98.125
4.75	4,737	98.125

Current industry high speed

OD	rpm	ft/sec velocity
0.75	6,350	20.76979
1.68	2,835	20.76979
2	2,381	20.76979
3	1,588	20.76979
3.5	1,361	20.76979
4.75	1,003	20.76979

Current industry

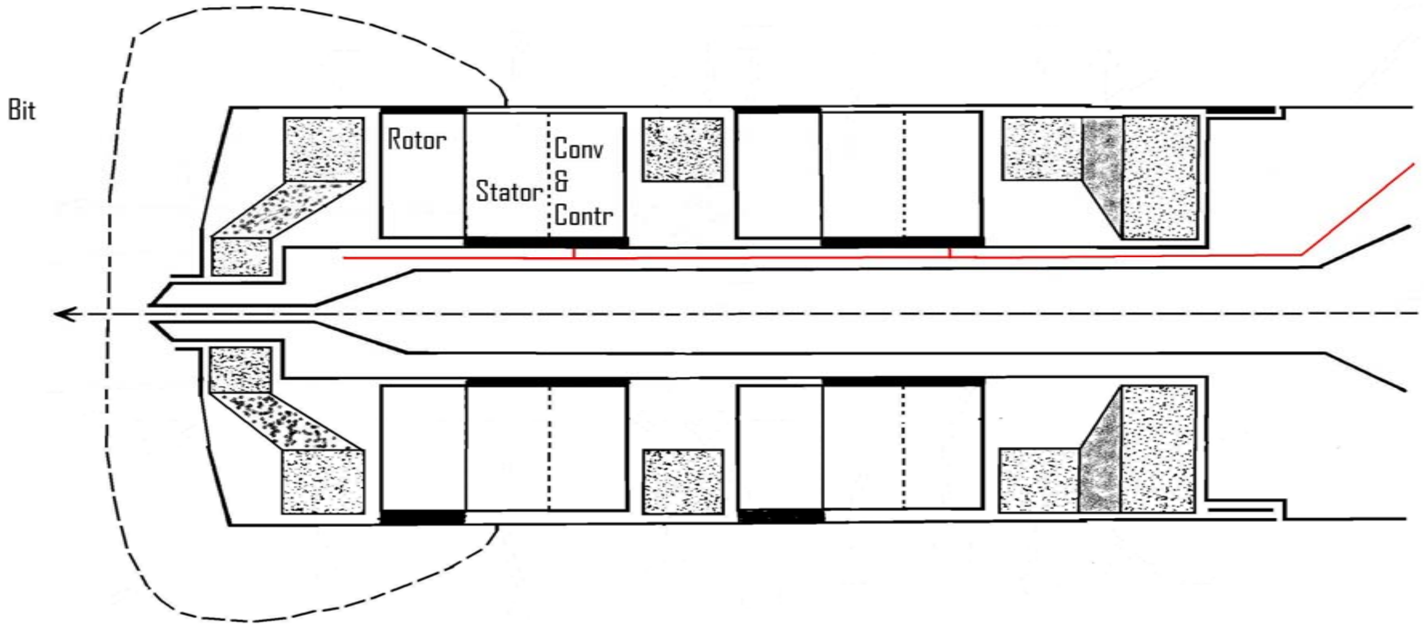
OD	rpm	ft/sec velocity
0.75	2,000	6.541667
1.68	893	6.541667
2	750	6.541667
3	500	6.541667
3.5	429	6.541667
4.75	316	6.541667

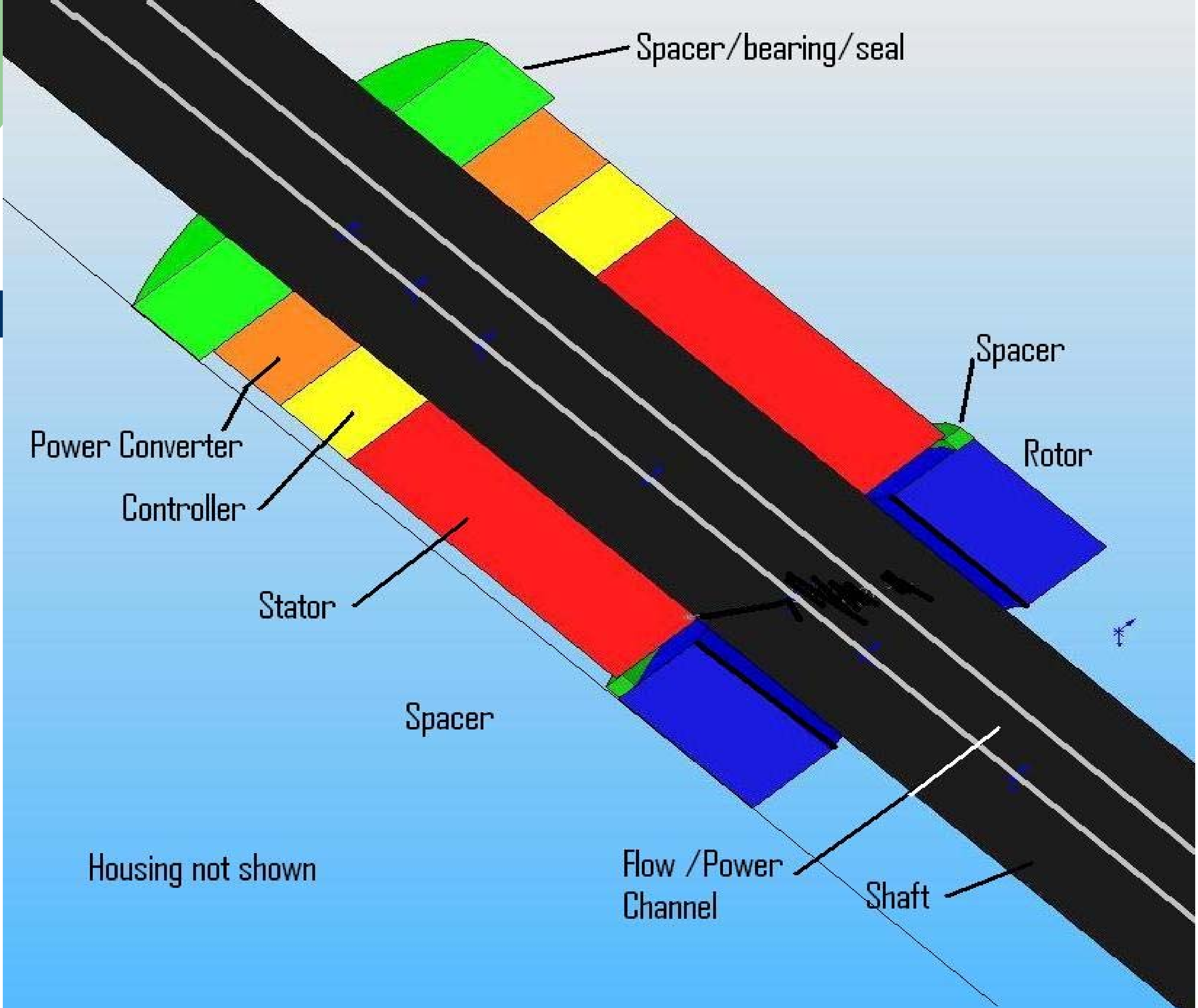
Advanced Ultra High Speed Motor for Drilling
Setting Motor Specifications

- Set Dimensional specifications
  - DOE Microbore Effort
  - 1.69” OD with 0.5” shaft OD
  - 3.0” OD with 1.0” shaft OD>>>3.125”OD direction
  - Each power section 1 foot long
- Set Voltage and current type- 300 VDC motor with 220VAC 3phase line feed (at motor),
  - AC power Line loss - 8.5 amps 208VAC - 304 watt loss. With AC can embed keys on AC signal for control of motor (versus DC power line loss -10 amp 300VDC 5000’ length - 9.3Volt loss, 279 watt loss)
  - Requires 2 lines for AC power transmission (only 1 if drillstring is used)
  - Higher voltages require special and /or thicker insulation and equipment
- Set Horsepower and Torque-
  - Bench Test Drag study showed 4 ft-lbs drag in horizontal position (without SF)
  - Estimate 2.0 - 10 ft-lbs required for WOB and sizes anticipated from equation:
    Torque= 0.5*Bit diameter (inches) * WOB (#) * formation hardness factor (range 0.2-0.4)/ 12
    - Unknown source, estimated at +/- 25% accuracy
  - Target 3Hp stackable motor power stages within housing
  - maximum 1 ft length of motor stage due to bending

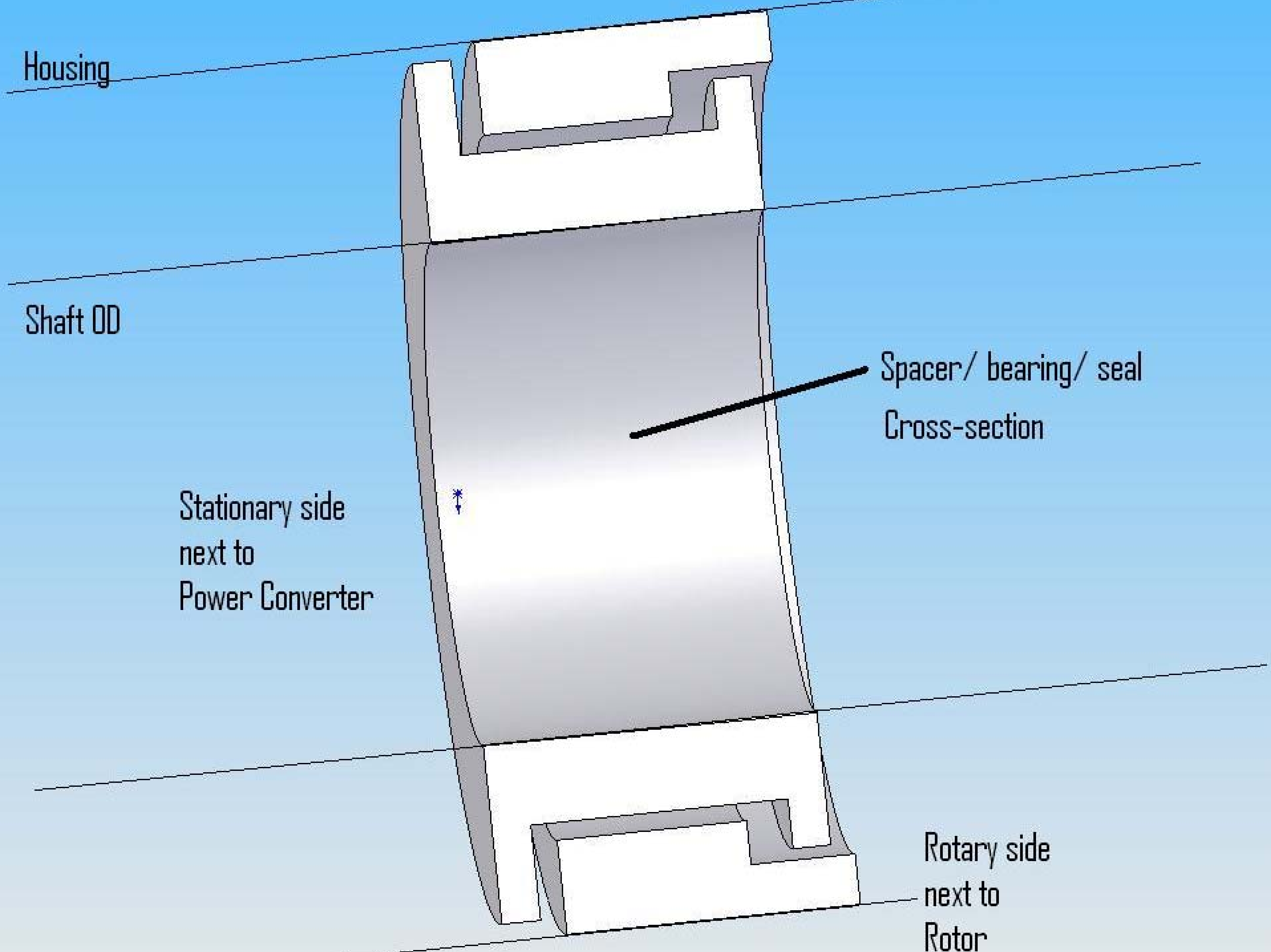
- Set Airgap requirements/ concerns -1mm too small, target 2+mm.
- Flow requirements for cooling due to heat generated by electronics in motor, bearings under loads, cutters in action

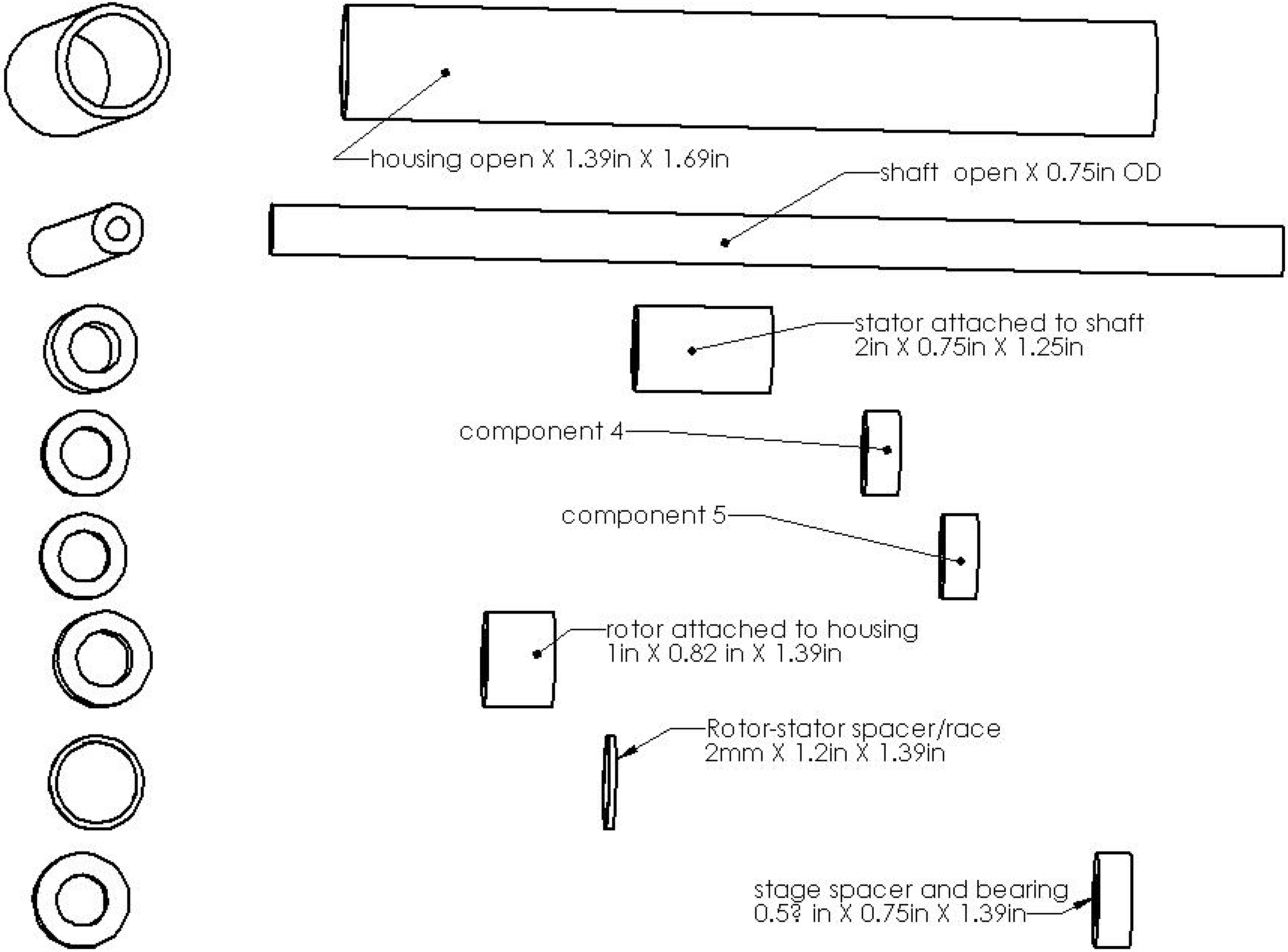
Advanced Ultra High Speed Motor for Drilling
Generalized Staged Inverted Electric Motor





Housing not shown


Housing
Shaft OD
Spacer/ bearing/ seal
Cross-section
Stationary side
next to
Power Converter
Rotary side
next to
Rotor


housing open X 1.39in X 1.69in
shaft open X 0.75in OD
stator attached to shaft
2in X 0.75in X 1.25in
component 4
component 5
rotor attached to housing
1in X 0.82 in X 1.39in
Rotor-stator spacer/race
2mm X 1.2in X 1.39in
stage spacer and bearing
0.5? in X 0.75in X 1.39in

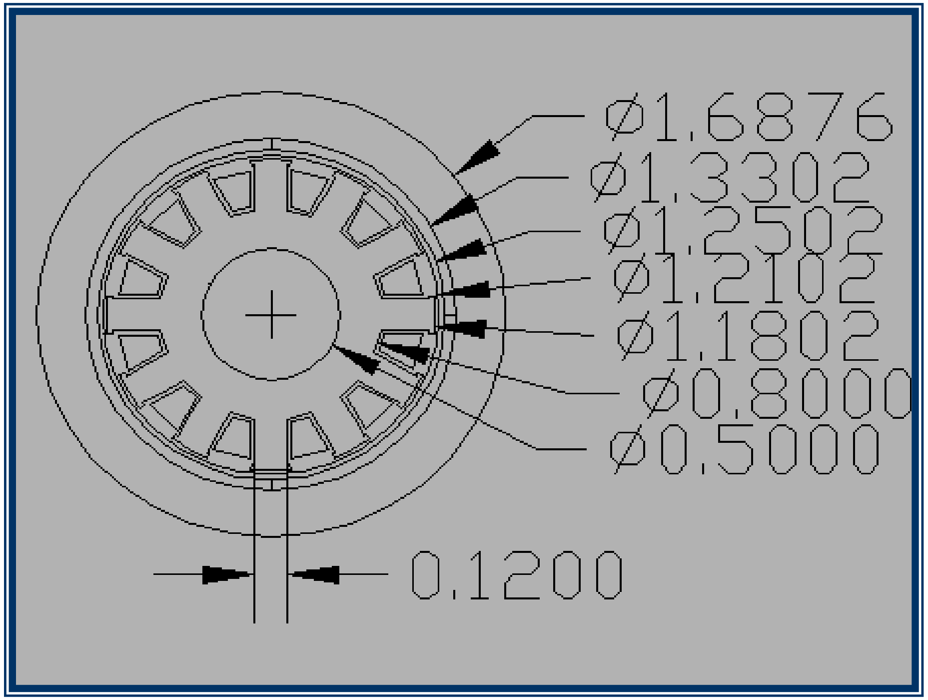
Advanced Ultra High Speed Motor for Drilling
Electro-Mechanical Radial Design-1

Rotor OD	**= 1 11/16”**
Stator OD	**= 1.1802”**
Shaft OD	**= 0.5”**
Air gap length	**= 1 mm**

Phases = 3

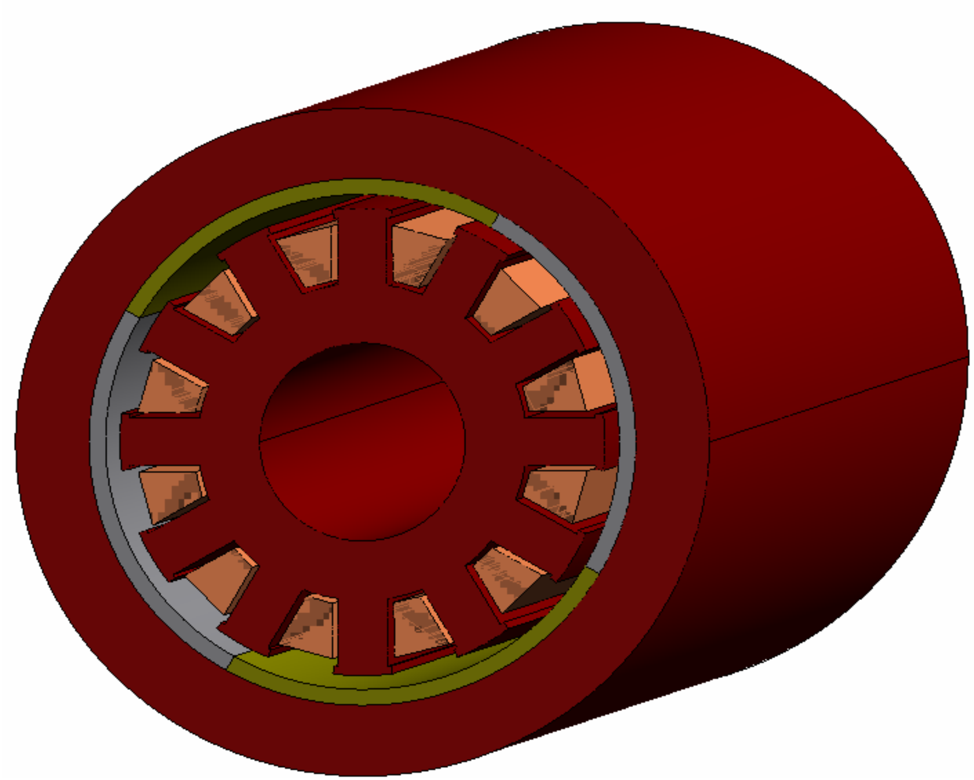
Stack length	**= 12”**
No. of turns	**= 65**

Current = 2A

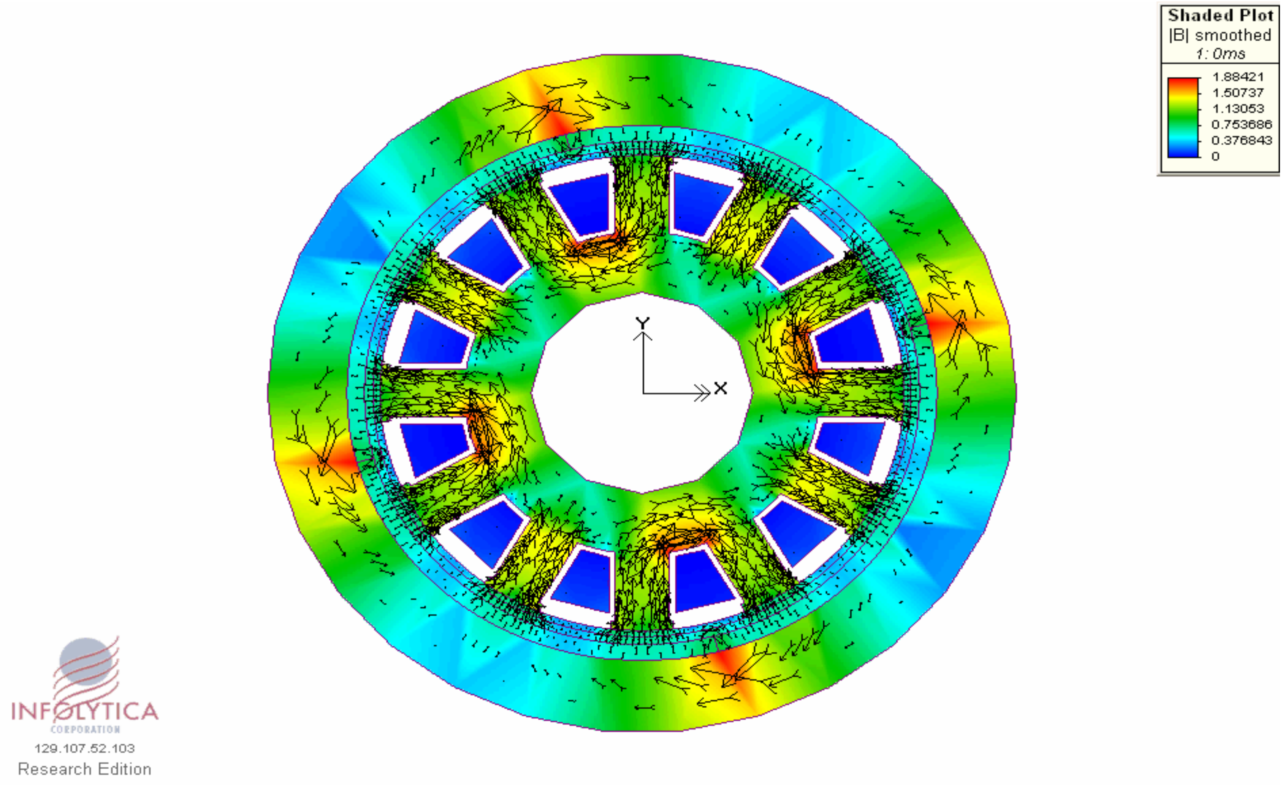


Advanced Ultra High Speed Motor for Drilling

Electro-Mechanical Radial Design-1

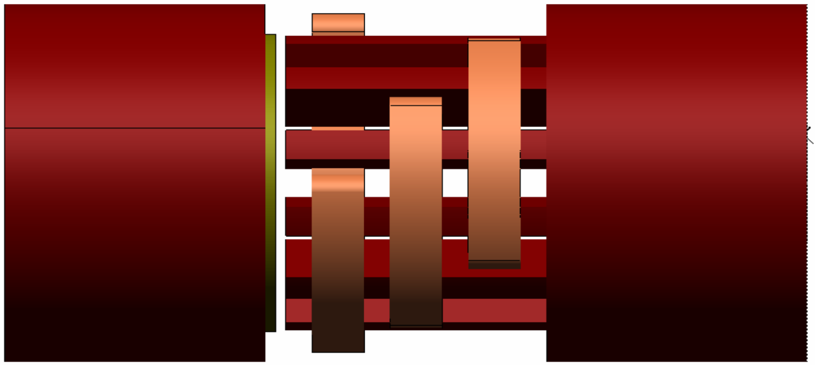


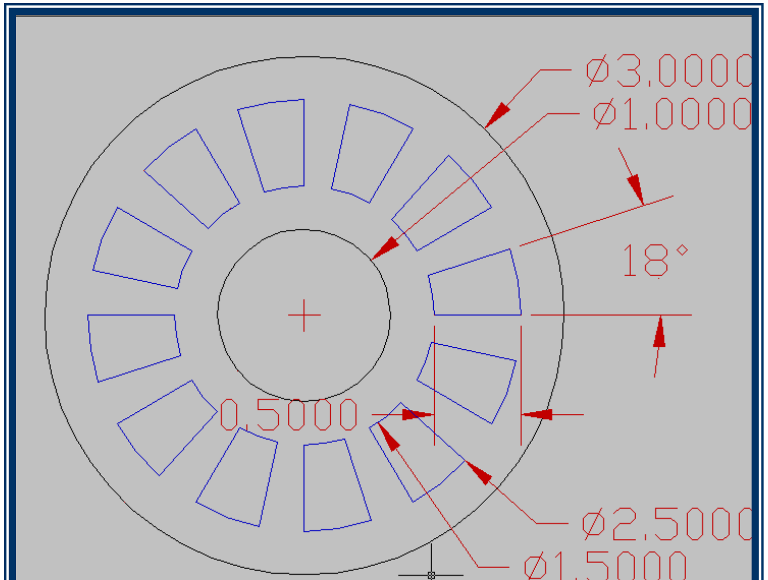
Operation of Radial PMSM-Design 1



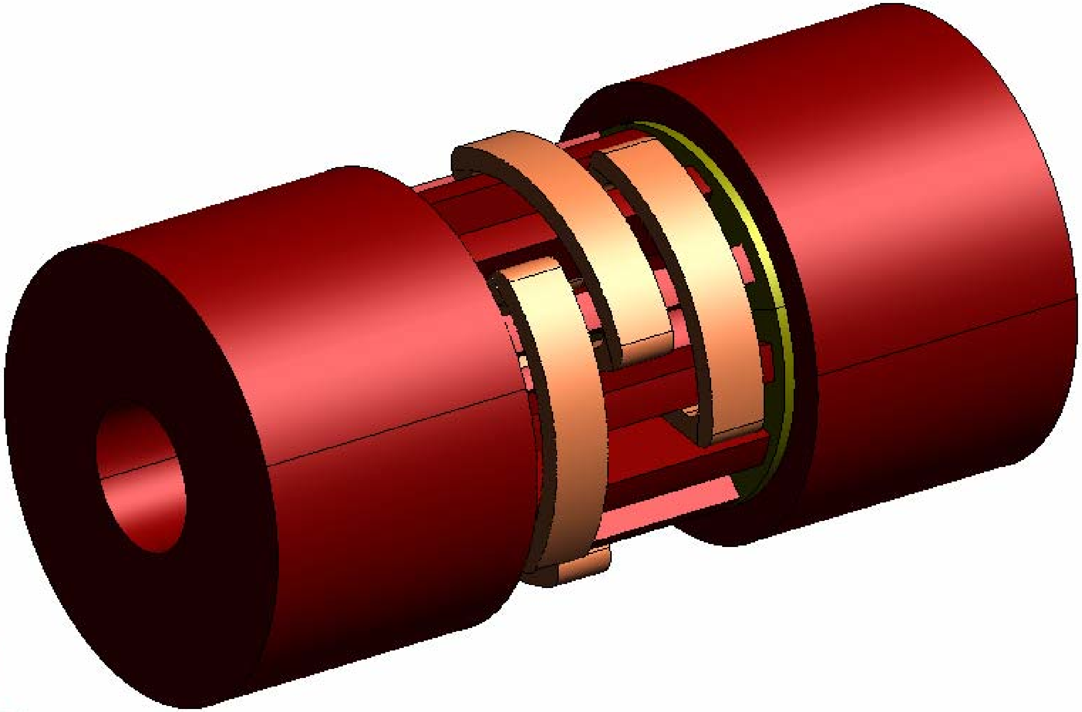
Operation of Axial PMSM-Design 3

Outer Diameter = 3”
Number of phases = 3
Speed = 10,000 rpm
Air gap length = 2 mm
Stack length = 6 inches
Magnet thickness = 2 mm
Number of turns = 65
Current = 2A

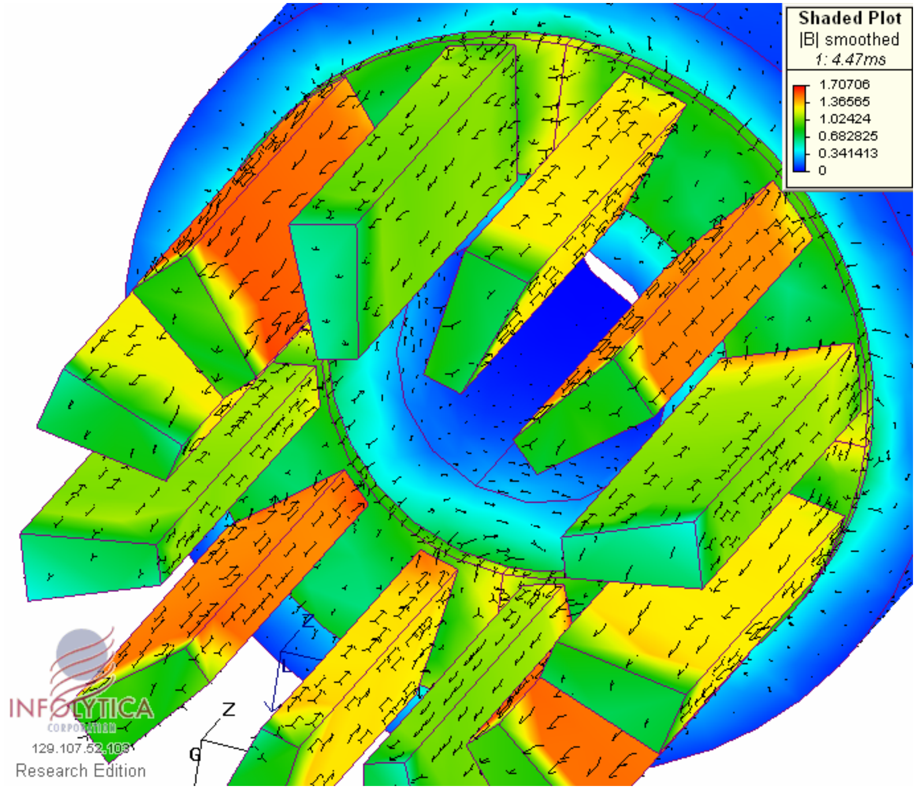


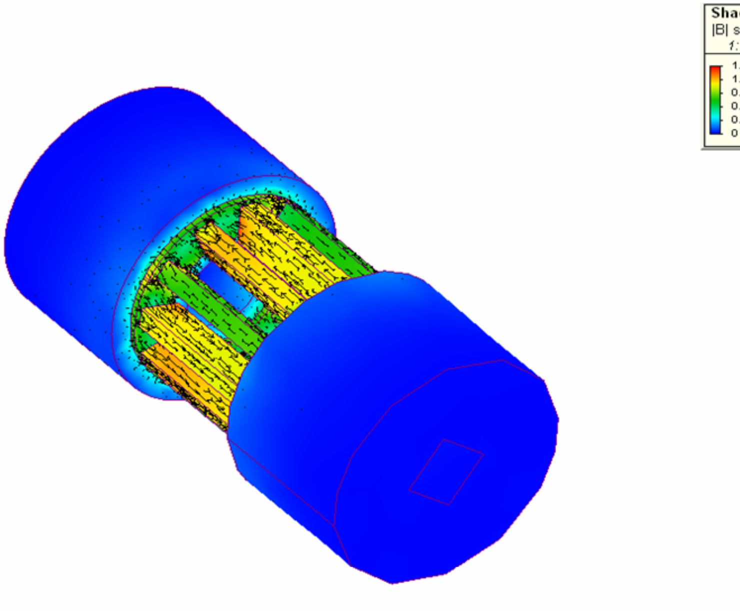


Advanced Ultra High Speed Motor for Drilling
Electro-Mechanical Design 3



Advanced Ultra High Speed Motor for Drilling
Electro-Mechanical Axial Design 3

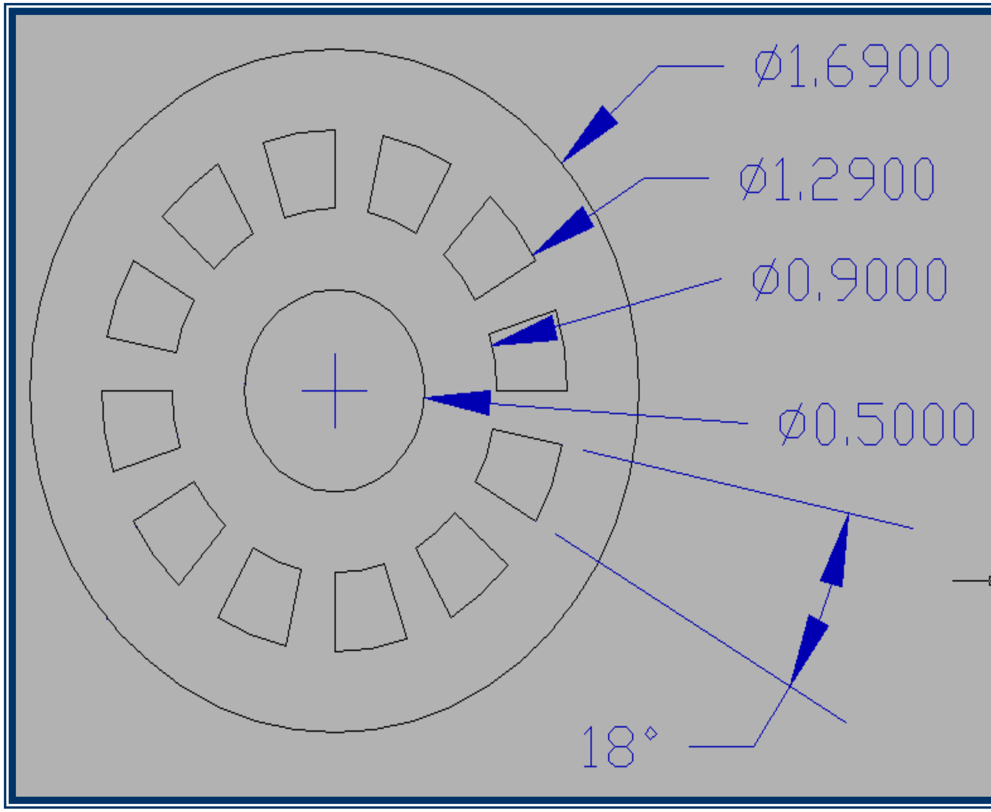




Advanced Ultra High Speed Motor for Drilling

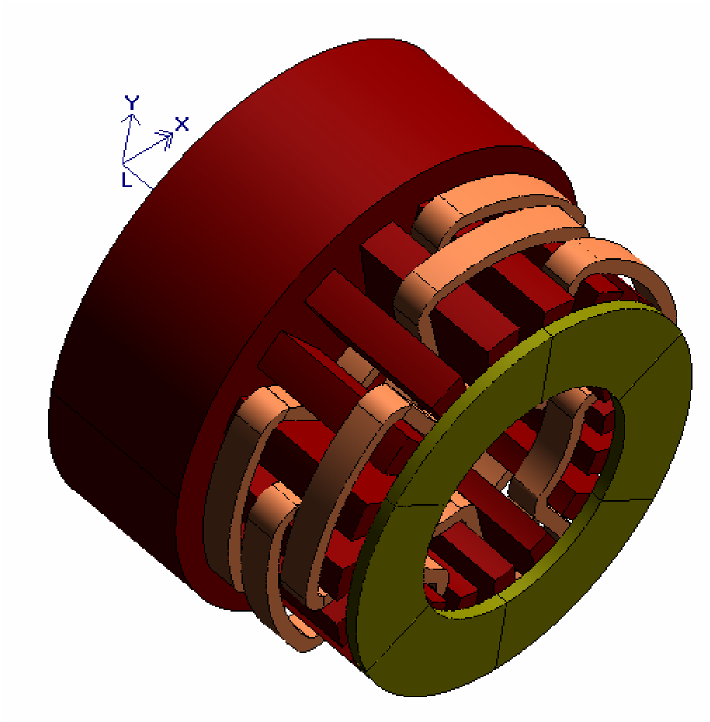
Electro-Mechanical Axial Design 4

Outer Diameter = 1.69”
Number of phases = 3
Speed = 10,000 rpm
Air gap length = 2 mm
Stack length = 3 inches
Number of turns = 65
Current = 2A



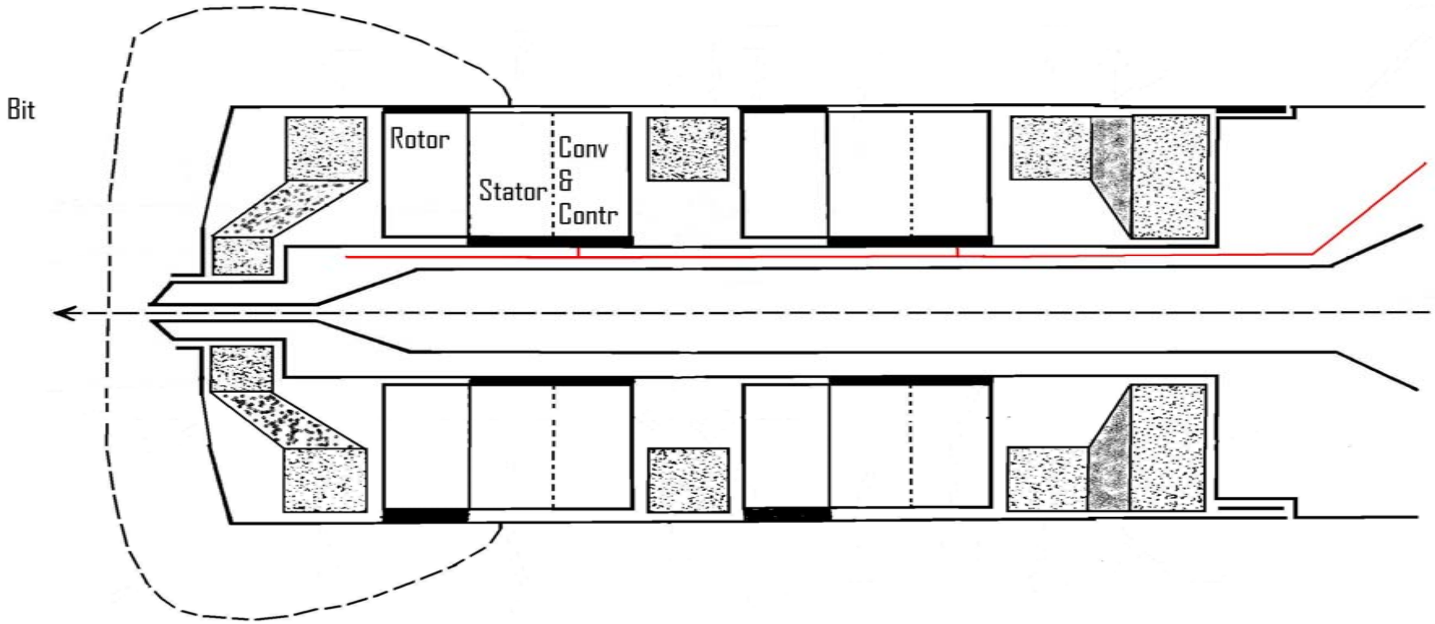
Advanced Low Speed Motor for Drilling

Electro-Mechanical Design 5

- 

Inverted Motors for Drilling

Generalized Electric IM Motor Configuration



Inverted Motors for Drilling
Remaining “To Do” List

- Finish Axial design for 1.69 inch OD motor
- Heat transfer model/ calculations, flow required to cool
- Method to attach rotors to housing, stators to shaft to transfer torque, maintain fixed stand-off/ airgap
- Seals- barrier, bag or labyrinth options, difficult since gas medium needed. ESP models, Weatherbee materials, Kalsi
- Journal Bearings- difficult due to gas environment and narrow placement (shaft up to rotor). Can be used to ensure airgap between discs. Non-magnetic, and best electrical insulator
- Thrust Bearing Options- PDC-PDC, Kalsi
- Identify Motor design consultant to address manufacturing concerns…good design but cannot be made!
- Vibration (balancing) harmonics
- Final EM Designs and drawings

Inverted Motors for Drilling

End of Talk

Increasing Power and Torque Options

- Only way to increase torque is
    - Decrease airgap, risk of high velocity collisions in motor
    - Decrease outer housing thickness, limited by strength
    - Decrease shaft thickness (minor compared to housing)
    - Increase current, limited by metal volume and metal type
    - Increase voltage, limited by insulation

Conversion Factors

- Torque- Newton Meters to Foot Pounds
  - 1 Nm = 0.73756 ft lbs
- Dimensions- Millimeters to inches
  - 1 mm = 0.03937 inches
- Power- Watts to Horsepower
  - 1 watt = 0.001341 Hp US
  - 1 KW = 1.341 Hp US
  - Horse Power = 0.746 Kilowatts
  - Hp = ft-# torque X rpm /33000

Advanced Ultra High Speed Motor for Drilling
Electro-Magnetic-Mechanical Design Points

- Permanent Magnet Synchronous Motor, brushless
- Radial or Axial or Modified/ Hybrid
- Fully adjustable for speed and direction by key embedded in AC current
- Current gives power/ torque, but limited by metal type and amount,
- Voltage gives rpm capabilities
- Nonmagnetic materials required for spacers, journal bearings, shaft
- Stackable power sections to meet HP requirements
- 10amps per mmXX2 area is design with 80-90 utilization factor. Can go to 15amps/mm2 for surge of higher power
- Power sections set at maximum 1 ft in length or 3 Hp , whichever is shorter
- Back emf voltage is induced by motion of PMs
- Field weakening is used to keep power up at higher rpms
- Available PM materials are SMCO alloy good for 100C / NDFEBR for 150C
- Cogging is not a problem at high speeds, just low speeds. This is just resistance to motion when PM are much stronger that induced field
- Anything on the outside of the housing will not impact motor performance (cutters,…)

List of Acronyms, Abbreviations, Conversions and Equations

- $\text{Power (Horsepower)} = \dfrac{\text{Torque(lb-ft)} * \text{rpm}}{5252}$

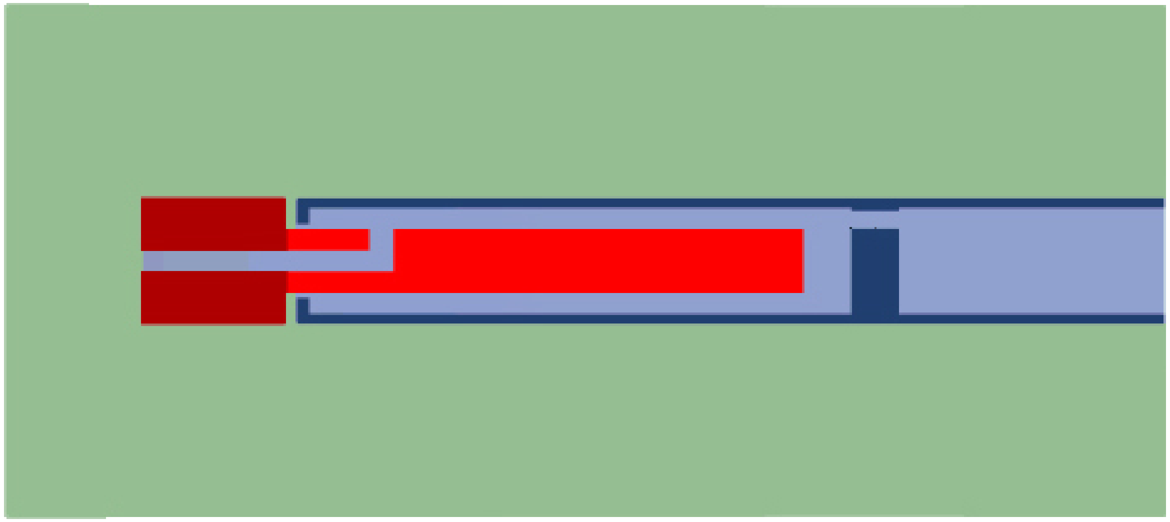
- $\text{Power (Watts)} = \dfrac{\text{Torque(lb-ft)} * \text{rpm}}{7.04}$

- Foot-Pound Torque =

  Newton-Meters Torque * 0.7376

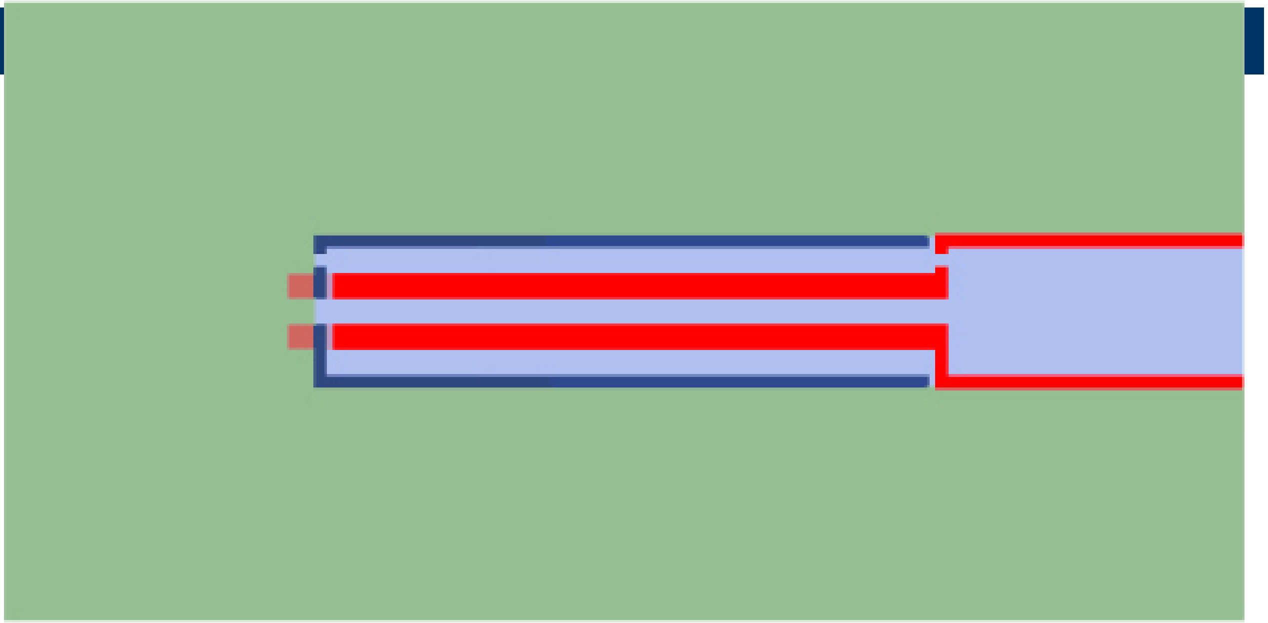
Advanced Ultra High Speed Motor for Drilling

Basic Conventional Motors



Advanced Ultra High Speed Motor for Drilling

Basic Inverted Motor Configuration



Advanced Ultra High Speed Motor for Drilling
Electric IM Drilling System Elements

1. Drill string with connected to motor shaft;
2. Electric (300VAC, 1-2 wire) power cable to surface controller and 3phase AC generator or power lines;
3. Electric wires through shaft and connected to motor' power converter;
4. Converter disc to convert 3phase AC to DC;
5. Controller disc to monitor the motor position and pulse the proper DC current to the stator coils;
6. Wired coils embedded in a stator (axial- disc, radial disc) and attached/wired to the non-rotating shaft;
7. Shaft (non magnetic) with flow and electrical wire channels,
8. Permanent magnets attached to outer housing (axial-disc, radial- inner lining);
9. Journal Bearings (non magnetic) between Shaft – Rotors and Stator- Rotors;
10. Thrust bearings on both ends of housing;
11. Keepers on both ends of housing; and
12. Bit connected to Housing

Advanced Ultra High Speed Motor for Drilling
Other IM Benefits

Multiple Motor Types & Designs
Multiple Liquids/Gases/Solids
HP / HT Applications
Hydraulic/Abrasive/ Dir Jetting
Multiple Motors
MWD/LWD thru Motor(s)
Balanced Force Motor Designs
Bi-centered Style Movement
Hole Enlargement
Compact Motor Designs
Ultra-short Turning Radii
Enhanced Hole Cleaning

- **AC Loss estimation (5000 ft.):**
- Wire gauge used: AWG #1
- Effective Inductive Reactance ≈ 0 Ω
- DC Resistance = 0.62 Ω
- Cumulative drop in voltage = 9.3 V
- Power loss = 139.5 W
- **DC Loss estimation (5000 ft.):**
- DC Resistance = 0.62 Ω
- Inductive Reactance = 0.7318 Ω
- Total resistance = 1.3518 Ω
- Cumulative drop in voltage = 20.28 V
- Power loss = 304.16W

- **Though voltage drop across the cable in dc transmission is lower, ac transmission is suggested. Reasons:**
  - DC transmission would require converter to be placed underground with the machine. This reduces accessibility and impedes corrective measures.
  - Signal wires need to be sent in with the dc transmission which would be subject to attenuation. Such an arrangement is not advisable since these wires need to be kept short to avoid introduction of noise and faulty trigger.
- **However drawbacks of this system are:**
  - Three ac cables would mean extra cumulative losses in the cables due to inductive reactances.
  - Shielding of cables needs to be much better than that required for dc.

Advanced Ultra High Speed Motor for Drilling
DE-FC26-04NT15502

16Nov05
MHT Presentation
US DOE- PTTC

Ken Oglesby
Impact Technologies LLC
and
Dr Babak Fahimi
University of Texas - Arlington

Advanced Ultra High Speed Motor for Drilling

History of Electric Motors for Drilling

- USSR
- General Electric -1977, jointed electrical link to BHA.
- The European Drilling Engineers Association (DEA(E)) and XL Technology in Phase II- field testing a DC brushless motor. XL identified the benefits of an electric motor for drilling as-
  - drive power independent of fluid flow,
  - tolerance for energized fluid,
  - high temperature applications,
  - scalable power,
  - real time information,
  - low vibration and
  - reversible direction.

Advanced Ultra High Speed Motor for Drilling
Status Summary

- **Design Only-** 2 sizes, 10,000rpm, electric inverted motor
- Accomplished-
  - Set motor specifications at 1.69” and 3.0”OD , 300V
  - Made Electro-Magnetic-Mechanical designs for radial and axial configurations, scalable/adjustable, reversible
  - Identified and initial design of bearings and seals
- Remaining Work-
  - Design Power and Controller boards
  - Mate final EMM designs with bearings and seals
  - Perform heat transfer analysis of final designs
  - Prepare final machine drawings for prototyping

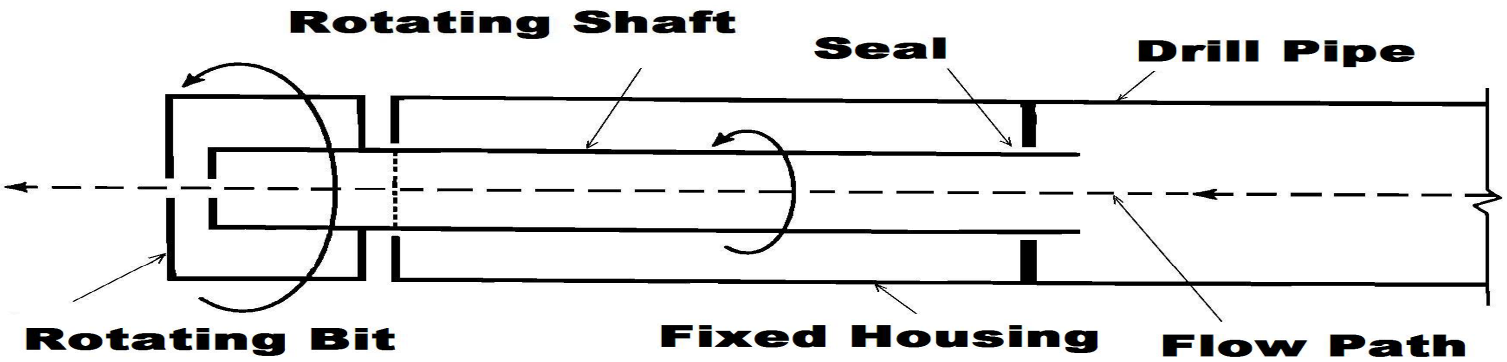


Fig. **2**

Conventional Electric Motor

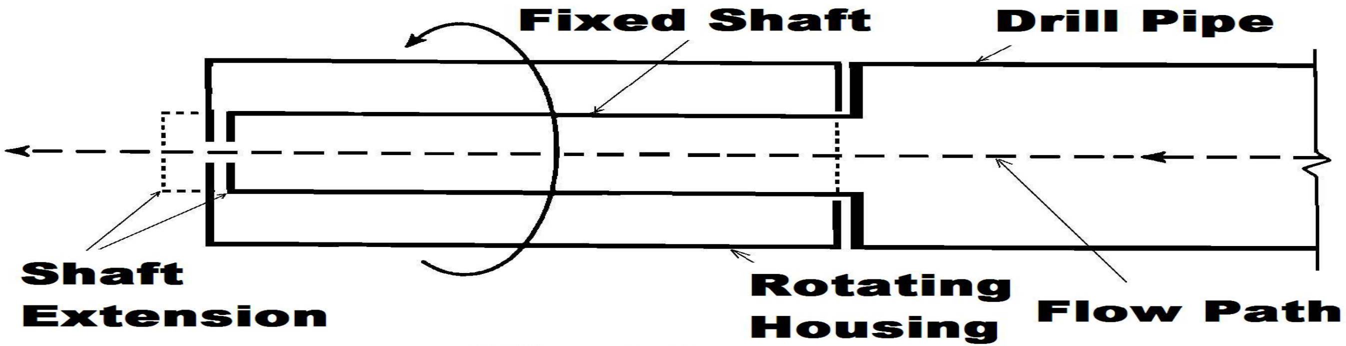


Fig. 3

Inverted Electric Motor

Advanced Ultra High Speed Motor for Drilling Inverted Motor Configuration

- IM Benefits
  - Allows advanced drilling techniques
    - Ultra high pressure / Abrasives / High Energy
  - MWD/LWD at bit
  - Multiple, independent motors
  - High power, short lengths for Ultra short radius turns
- IM Drawbacks
  - New, not tested
  - Shaft holds motor and lower string / tools

Advanced Ultra High Speed Motor for Drilling

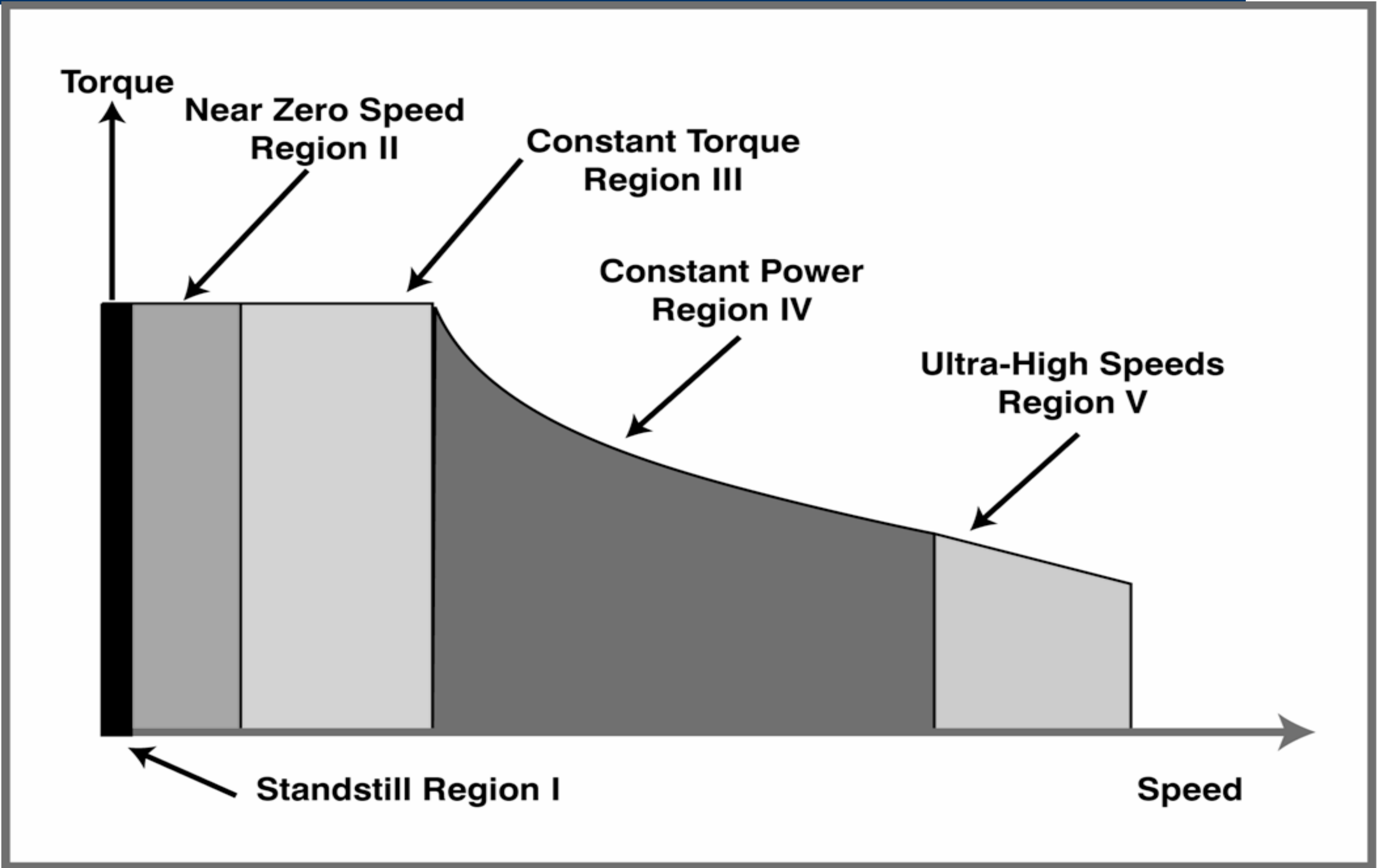
Permanent Magnet Synchronous Brushless Motor

- PMSM Benefits
  - Favorable torque profile
  - High power density
  - scalable
  - Reversible

- PMSM Drawbacks
  - Small airgap

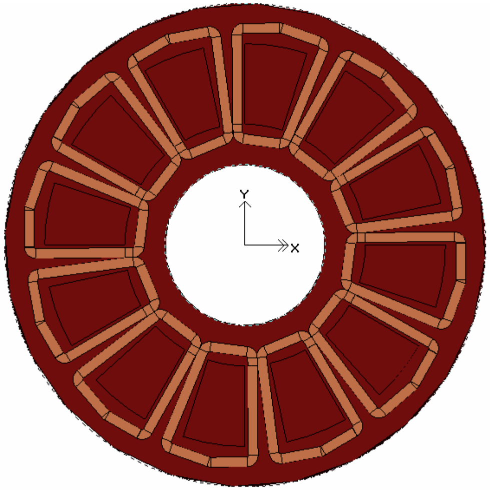
Advanced Ultra High Speed Motor for Drilling

Permanent Magnet Synchronous Brushless Motor

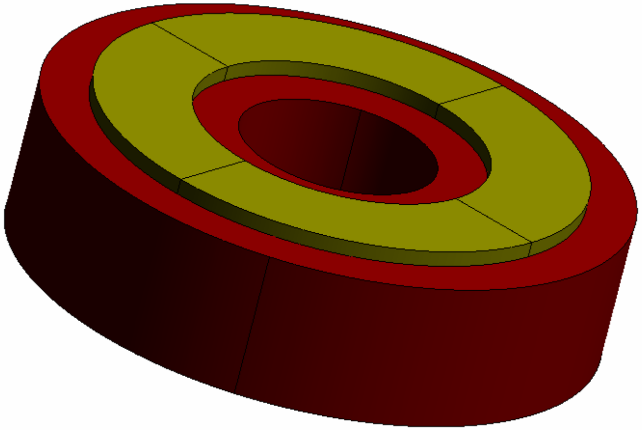


Advanced Ultra High Speed Motor for Drilling

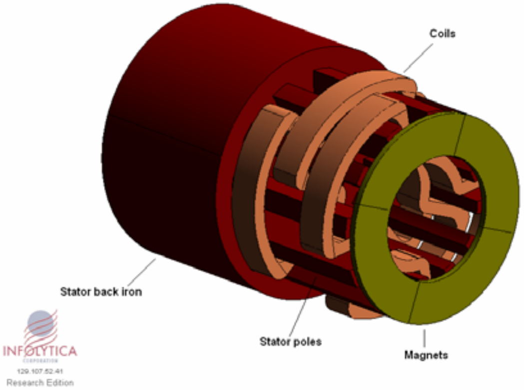
Finite Element Modeling of Axial Design



STATOR WINDING AS SEEN FROM THE ROTOR

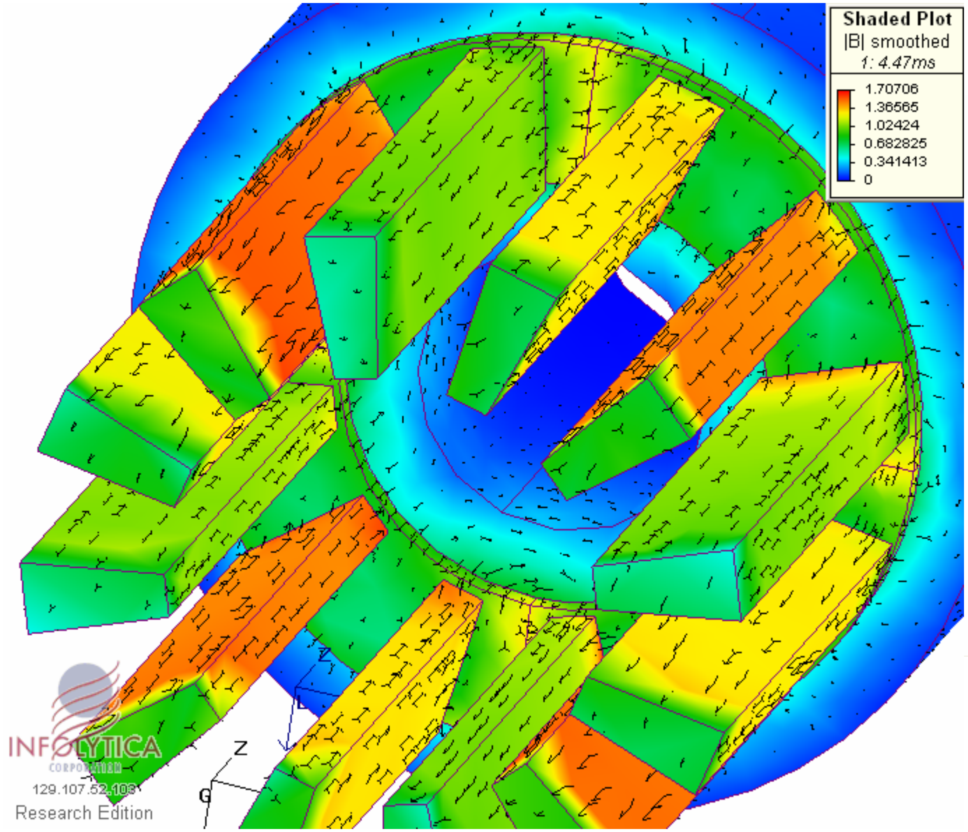


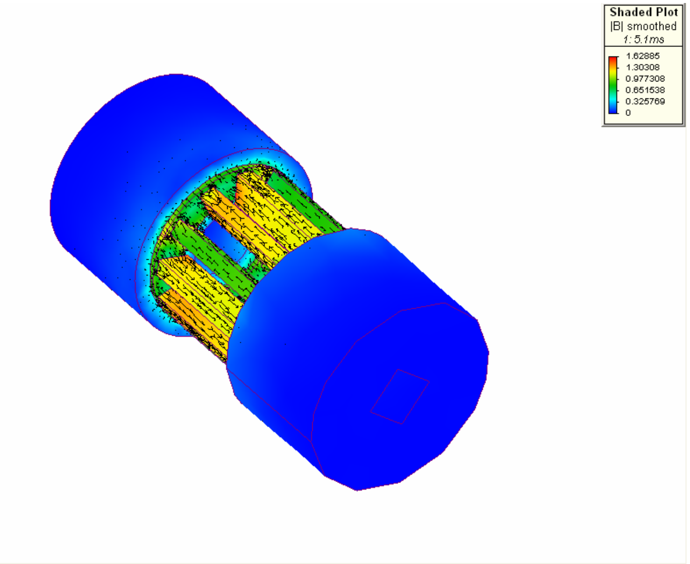
MAGNET ARRANGEMENT ON ROTOR



Advanced Ultra High Speed Motor for Drilling

Finite Element Modeling of Axial Design





Advanced Ultra High Speed Motor for Drilling

EMM Design Preliminary Results

- Not derated for bearings and seals
- 3.0” OD X 5 ft power section

  Horsepower at 10,000rpm……59Hp

  Torque at stall conditions……..99ft-#
- 1.69”OD X 5 ft power section

  Horsepower at 10,000rpm…… 12Hp

  Torque at stall conditions……...74 ft-#

Advanced Ultra High Speed Motor for Drilling

End of Talk

Advanced Ultra High Speed Motor for Drilling Electro-Magnetic-Mechanical Design Points

- Permanent Magnet Synchronous Motor, brushless
- Radial or Axial or Modified/ Hybrid
- Fully adjustable for speed and direction by key embedded in AC current
- Current gives power/ torque, but limited by metal type and amount,
- Voltage gives rpm capabilities
- Nonmagnetic materials required for spacers, journal bearings, shaft
- Stackable power sections to meet HP requirements
- 10amps per mmXX2 area is design with 80-90 utilization factor. Can go to 15amps/mm2 for surge of higher power
- Power sections set at maximum 1 ft in length or 3 Hp , whichever is shorter
- Back emf voltage is induced by motion of PMs
- Field weakening is used to keep power up at higher rpms
- Available PM materials are SMCO alloy good for 100C / NDFEBR for 150C
- Cogging is not a problem at high speeds, just low speeds. This is just resistance to motion when PM are much stronger that induced field
- Anything on the outside of the housing will not impact motor performance (cutters,…)

Advanced Ultra High Speed Motor for Drilling Motor Specifications- Setting

- Set Dimensional specifications
  - DOE Microbore Effort
  - 1.69” OD with 0.5” shaft OD
  - 3.0” OD with 1.0” shaft OD
  - Each power section 1 fool long
- Set Voltages and current type- 300 VDC motor with 220VAC 1phase line feed (at motor),
  - Line loss DC power- 10 amp 300VDC 5000’ length - 9.3Volt loss, 279 watt loss
  - Line loss AC power - 8.5 amps 208VAC - 304 watt loss. With AC can embed keys on AC signal for control of motor
  - Requires 2 lines for power transmission (only 1 if drillstring is used)
  - Higher voltages require special and /or thicker insulation and equipment
- Set Horsepower and Torque-
  - Bench Test Drag study showed 16 ft-lbs drag in horizontal position (400% SF)
  - Torque= 0.5*Bit diameter (inches) * WOB (#) * formation hardness factor (range 0.2-0.4)/ 12
    - Unknown source, estimated at +/- 25% accuracy
  - Estimate 2.0 - 10 ft-lbs required for WOB and sizes anticipated,
  - Target 3Hp stackable motor power sections within housing
  - maximum 1 ft length due to bending

- Set Airgap requirements/ concerns -1mm too small, target 3mm.
- Flow requirements for cooling due to heat generated by electronics in motor, bearings under loads, cutters in action

Advanced Ultra High Speed Motor for Drilling Remaining “To Do” List

- Heat transfer model/ calculations, flow required to cool
- Method to attach rotors to housing, stators to shaft to transfer torque, maintain fixed stand-off/airgap
- Seals- barrier, bag or labyrinth options, difficult since gas medium needed. ESP models, Weatherbee materials, Kalsi
- Journal Bearings- difficult due to gas environment and narrow placement (shaft up to rotor). Can be used to ensure airgap between discs. Non-magnetic, ad best non-conductant
- Thrust Bearing Options- PDC-PDC, Kalsi
- Identify Motor design consultant to address manufacturing concerns…good design but cannot be made!
- Vibration (balancing) harmonics
- Final Design drawings

Advanced Ultra High Speed Motor for Drilling

Key Dates of Project

- 6Dec04 TerraTek presenttion to DOE on ulra high speed bits
- 14Dec04- Meeting with Dr Fahimi, Dr Dunn-Norman for initial design
- 4Jan05 Shop experiments on rotational drag
- 5Jan05 Fahimi report on 1.69" radial design
- 4Feb05 Fahimi visit to Tulsa
- 28Feb Fahimi report on revised 1.69 design
- 28 April 05 Fahimi report on 3" radial design
- 30April05 status report to Rhonda Jacobs
- 15June 05 Fahimi report on 3.0" axial design
- 22July05 Oglesby visit to UTA lab, review status
- 27July05 presentation to DOE/ Rhonda Jacobs
- August Houston meeting
- 16Nov05 DOE PTTC Houston Meeting

Conversion Factors

- Torque- Newton Meters to Foot Pounds
  - 1 Nm = 0.73756 ft lbs
- Dimensions- Millimeters to inches
  - 1 mm = 0.03937 inches
- Power- Watts to Horsepower
  - 1 watt = 0.001341 Hp US
  - 1 KW = 1.341 Hp US
  - Horse Power = 0.746 Kilowatts
  - Hp = ft-# torque X rpm /33000

Advanced Ultra High Speed Motor for Drilling

DOE Contract No. DE-FC26-04NT15502

Status Report 12 April 2006

by
Kenneth D Oglesby
Impact Technologies LLC

Dr. Babak Fahimi

University of Texas-Arlington

Advanced Ultra High Speed Motor for Drilling

Executive Summary

- Review of bits/cutters for ultrahigh velocities
- Radial and Axial designs of Inverted configurations made
- 1.69 and 3.0 inch OD motors
- Design Only
- Torque, Horsepower at 10,000rpm

Advanced Ultra High Speed Motor for Drilling

Tasks to be Performed

- Phase 1- identify bit and cutter characteristics for 10,000+ rpm speeds
- Phase 2 Prepare CAD drawings for 2 sizes
- Phase 3- Construct magnetic model
- Phase 4- FE Modelling for optimization
- Phase 5- Final design for prototyping

Advanced Ultra High Speed Motor for Drilling

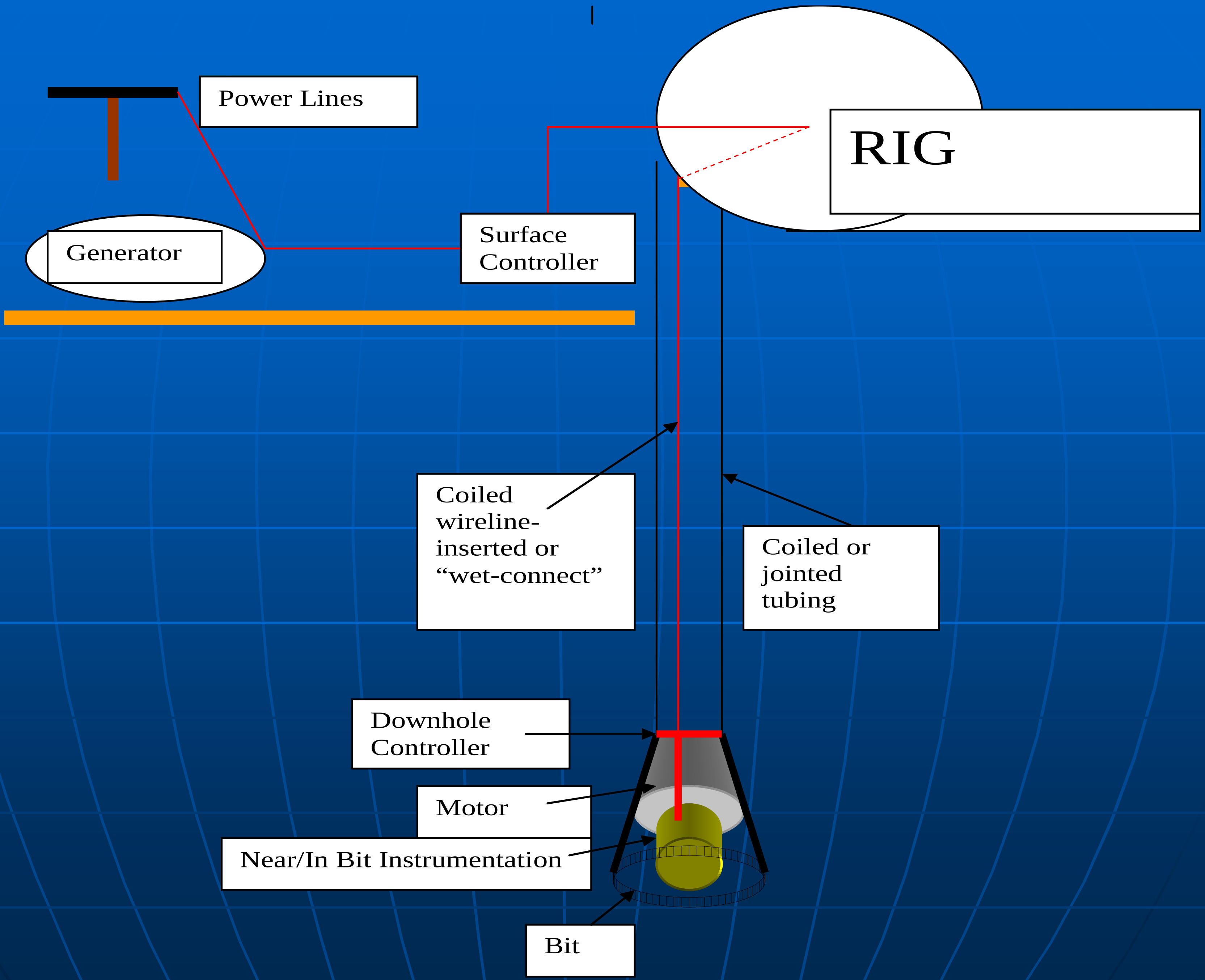
Key Dates

- 6Dec04 meeting TerraTek presentation at NETL on ultra high speed PDC tests
- 14Dec04 HSM Kick off meeting in Tulsa with Fahimi, Dunn-Norman and Oglesby
- 4Jan05 Shop experiments on rotational drag
- 5Jan05 report by Dr. Fahimi on initial 1.68"OD radial inverted motor design results
- 4Feb05 Fahimi visit to Tulsa
- 28Feb05 report by Dr. Fahimi on updated 1.69"OD radial motor results
- 28Apr05 report by Dr. Fahimi on 3.0" OD radial motor design results
- 30Apr05 status report to Rhonda Jacobs
- 15Jun05 Fahimi report on 3.0" axial design
- 22July05 Oglesby visit to UTA lab, review status
- 27July05 presentation to DOE/ Rhonda Jacobs
- 17Aug05DOE MHT presentation in Houston
- 18Aug05 Meeting in Houston with Kalsi Seals
- 16Sep05 University of Tulsa Graduate Seminar presentation
- 9Jan06 Hired EngATech to prepare Engineering Drawings of HSM 3"
- 10Jan06 Meeting with EngATech on HSM 3" physical layout and design
- 3Mar06 Fahimi to Tulsa for review of motor physical layout and design
- 22Mar06 DOE Microhole Meeting in Houston, visit with TerraTek on use of motor
- 31Mar06project no cost extension to 31Sep06
- 31Mar06Project manager change from Rhonda Jacobs to Paul West
- 25Mar06 ICEM2006 paper No.245 entitled "Comparative Evaluation of Axial Flux versus Radial Flux Permanent Magnet Synchronous Machines" authored by M. Krishnamurthy, B. Fahimi and K. D. Oglesby was accepted for presentation
- May 1-5 meetings in Houston
- Final report due 31September2006

Advanced Ultra High Speed Motor for Drilling

History of Electric Motors for Drilling

- Russians
- FERC/ pre-DOE with General Electric
  - Conventional configured electric motor
  - Problems were in wiring and not motor



Power Lines

RIG

Generator

Surface Controller

Coiled wireline-inserted or “wet-connect”

Coiled or jointed tubing

Downhole Controller

Motor

Near/In Bit Instrumentation

Bit

HSM Details

- Inverted Motor Concept
- HSM 3.0 SolidWorks Model Version5

List of Acronyms, Abbreviations, Conversions and Equations

- Power (Horsepower) = $\dfrac{\text{Torque(lb-ft)} * \text{rpm}}{5252}$
- Power (Watts) = $\dfrac{\text{Torque(lb-ft)} * \text{rpm}}{7.04}$
- Foot-Pound Torque =

  Newton-Meters Torque * 0.7376

DOE HSM Presentation

End of Talk

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APPENDIX I

Technical Paper presented to the 2006 IEEE Meeting

entitled

"Comparative Evaluation of Axial Flux and Radial Flus Permanent Magnet Synchronous Machines"

Comparative Evaluation of Axial Flux and Radial Flux Permanent Magnet Synchronous Machines

Mahesh Krishnamurthy, Babak Fahimi and Kenneth D. Oglesby

Abstract- **In an effort to enhance efficiency, reducing cost and optimizing compactness, researchers have investigated various machine geometries based on specific requirement of a given application. Axial flux machines are viewed as a part of one such exploration in competition with the radial flux counterparts. A general comparative study of axial and radial types is not meaningful due to the various arts of machines available. This paper concentrates on these two magnetic configurations for a Permanent Magnet Synchronous machine (PMSM) and investigates the generation of forces in both geometries. A qualitative evaluation of the two machine designs has been presented using finite element analysis. Distribution of forces at the surface of the motional components have been presented along with torque productivity of the machine versus parameters such as volume of the rotor, copper, back emf generated and ampere-turns required for each machine. This provides useful information in the choice of machine and converter requirements for a specific application.**

I. INTRODUCTION

The past two decades have witnessed significant advancement in various scientific and technical fields. Automation of all the major applications in our daily use has produced a constantly increasing demand for improvements in existing technologies. Electric machines have been a major part of this development. Therefore even a slight increase in efficiency in electric drives amounts to huge energy saving on a global scale. With the advent of advanced power electronics and material science, drive specialists have been able to explore new options to enhance efficiency while reducing cost and optimizing space. Such an investigation includes analysis of different magnetic configurations according to application constraints. Axial flux machines are viewed as a part of one such exploration in competition with the radial flux counterparts. A general comparative study of axial and radial types is not meaningful due to the various arts of machines available. This paper concentrates on these two magnetic configurations for a Permanent Magnet Synchronous machine (PMSM) and investigates the generation of forces in both geometries. A qualitative comparison of the two machine designs has been presented using finite element analysis.

Axial flux permanent magnet (AFPM) machines refer to category which has magnetic flux flowing in the axial direction rather than radial as in conventional machines combined with the permanent magnet structure of a PMSM. Various applications have been investigated for the axial machines. This technology attracts considerable attention in the automotive industry [1] – [4]. Other applications include ship propulsion drives [5], direct drive elevator systems [6], and wind generation [10] among others.

Cavagnino et al [7] have made a comparison of the radial and axial configurations from mechanical and thermal points of view. Joule losses have been calculated in both the machine topologies and generated electromagnetic torque is related to the size and weight of machine for different geometries. Krishnan et al [8] have presented the comparison from an analytical point of view in which also physical aspects have been discussed. Comparison of the required materials for construction, their weights and power per unit volume of each machine performed. The investigation carried out in this paper presents an evaluation of these two configurations from an electromagnetic point of view. Radial and tangential components of flux and force in the airgap have been computed along with the force distribution in various parts of the machine. Similar dimensional constraints have been assigned to the models in finite element analysis (FEA). Parameters such as magneto-motive force, magnet strength and outer diameter were kept identical in both machines. Following sections present the background on both machines, modeling concepts using Finite Element (FE) analysis and the results obtained from the simulation.

II. FUNDAMENTALS OF AXIAL AND RADIAL PMSM

The radial and axial structures of a PMSM present similar operating principles. A major part of the magnetizing flux is provided by a surface mount permanent magnet. Electrical excitation applied to the stator coils is responsible for the generation of motional component of force. In this paper, an investigation of the generated tangential and normal force densities at the surface of each component is carried out. This has been done using Maxwell Stress tensor at the surface of the rotor.

A radial flux permanent magnet (RFPM) machine is the conventionally used PMSM with torque proportional to the stack length of the machine. An AFPM machine has various topologies. Based on specifications by an application, various single and multiple disk structures have been suggested. The common feature that binds these models is the flow of flux in the axial direction, along the stack of the machine. In an axial PMSM, electromagnetic torque is mainly a function of the machine outer diameter. For an application which puts strict constraints on the outer diameter of the machine, required torque can be obtained by a multistage arrangement. This paper considers the simplest construction with a single-sided arrangement (one rotor and one stator disk).

A) *Modeling using Finite Element Analysis*

The modeled machine presented in this paper was set a target of 2.1 Nm at a speed of 10000 rpm. The machines designed have a very small outer diameter and stack length. For this purpose, materials had to be chosen that would tolerate higher values of magnetic field densities to allow for more magneto-motive force (MMF). M-19 and M-45 are commonly used materials for motor/transformer laminations. However they were found unsuitable for the field density anticipated. Therefore laminations used for construction was made of aircraft grade steel, which have a higher strength and saturation point (1.7 T) as compared to conventional M-19 or M-45. This alloy finds typical applications in aircraft motors and generators.

Both machines were rated at 2 kW with a 3-phase, 4- pole, and one slot per pole per phase configuration. For the target application, strict constraints were placed on the outer diameter of the machine. While the radial machine had a minimum airgap requirement of 2 mm, they were designed for the same shaft diameter. No specific constraints were set on the airgap length in the axial design. Optimizing parameters for these machines were stack length, amount of copper and steel used and weight of the machine. Some constructional details of the machines are included in appendix A.

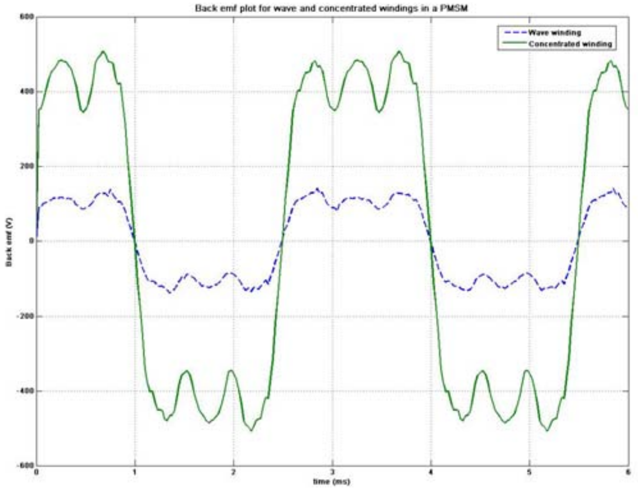

Fig. 1: Back EMF plot for wave (solid) and concentrated (dashed) winding 3-phase PMSM for one electrical cycle.

In order to reduce the current drawn from the converter while increasing the applied MMF, a practical alternative has been to increase the number of ampere-turns (A-T). However with an increase in the number of turns, there is a corresponding rise in the induced back EMF voltage. For the axial design of the PMSM, two different windings arrangements are possible- wave and concentrated. Figure (1) shows this phenomenon obtained for wave and concentrated winding arrangements for 100 turns. As can be seen, the voltage induced in each phase coil for concentrated winding is inversely proportional to the number of poles in wave winding. This seriously increases the voltage required from the converter unit for the wave arrangement. Coles et al in [9] have also reported a higher torque productivity using concentrated windings. For the present study, a concentrated arrangement was chosen for the axial design. The advantage of having this arrangement is that the coils which compose each phase can be connected to the power supply unit in parallel arrangement. This reduces the stress on the converter and allows for better flexibility in the stator winding. It also introduces an inherent fault tolerance in case of discontinuity in any one of the windings.

B) *Force estimation by Maxwell Stress Tensor Method*

Electromechanical energy conversion in electric machines can be evaluated in terms of tangential and normal components of force densities. These forces are local units that have different effects on different parts of the machine. Radial forces in an electric machine are generally classified as the “unwanted” component of force. They are not in the direction of rotation of the machine and cause unwanted vibration and deformation of the stator & rotor structures. Therefore they do not allow for the optimal utilization of energy by producing unwanted radial vibration in the stator frame. Tangential component of force density is the useful part and is usually responsible for motional torque. Using Maxwell stress tensor method in a radial arrangement, distribution of the radial and tangential force densities in the airgap of the machine can be expressed in terms of flux density components as [10]:

$$f_n = \frac{1}{2\mu_0}({B_n}^2 - {B_t}^2) \tag{1}$$

$$f_t = \frac{1}{\mu_0}(B_n B_t) \tag{2}$$

where f_n, f_t, B_n, B_t, and μ_0 denote normal and tangential component of the force density in airgap, normal component of flux density, tangential component of flux density, and absolute permeability respectively. There are some basic observations regarding force density distribution that can be noted -

- Magnetic field density and magnetic energy inside the unsaturated ferromagnetic material are very small. Therefore the force contribution from these components is very small. Such parts include the stator, and rotor back iron.
- The relative permeability of permanent magnet is very close to unity. We know that air also has the same permeability. Therefore the force distribution in air and

PM are almost identical for the same position if the points that are probed are close enough.

- Local saturation is seen at pole tips owing to a large concentration of flux. This causes a much larger force at the tip of the stator poles than the rest of the pole. This is more significant for geometries with salient poles or axial PMSM configuration with segmented magnets.

The main attributes targeted in this comparison include force distribution at the surface of the rotor, torque productivity, field distribution, cost-efficiency and suitability to applications. A wide range of operating speed has been considered from 50 rpm to high speeds at about 10,000 rpm.

C) Torque calculation by power balance equation

There is a wide variety of electromechanical energy converters (EMEC) in everyday use. Electric machines are by far the most common of these. An electric drive system is comprised of an electrical system, a mechanical system and a means of conversion from one form to the other. From an energy modeling point of view, induced voltage by the changing electromagnetic stored energy (back EMF) delivers mechanical energy. Thus, neglecting the core losses, torque generated by a machine at any given speed can be related to electric power applied as given in equation (3).

$$T.\omega = e_a i_a + e_b.i_b + e_c.i_c \qquad (3)$$

Where T, ω, denote torque and instantaneous speed of the machine and e_a, e_b, e_c, i_a, i_b, i_c denote the generated motional back EMF and current flowing through each phase of a three phase machine respectively. This equation can therefore be used to estimate the instantaneous torque of a machine if the values of back EMF, phase currents and speed of the machine at that instant of time are known.

III. SIMULATION RESULTS FROM FEA

Maxwell Stress Tensor method was used to calculate force density in both arts of machinery as described in section II (B). From our study, it has been seen that there is a variation in the flux density at different layers of the airgap. This numerical technique was applied at the layer of air just outside the motional component to estimate the effective tangential and normal components of force on the rotor.

A) Radial flux PMSM

Figure (2) shows the solution for the radial model obtained from 2D FEA at an arbitrary time instant. As explained in section II (B), saturation is seen at the pole tips of the stator. From figure (3), it can be observed that the effect of slots on the flux distribution at the surface of the PM is significant. Local force distribution at the surface of the permanent magnet shows that the maximum tangential forces are generated near the edge of each magnet. Distribution of tangential and normal force component is not uniform throughout the circumference of the machine. The magnitude of local force is a function of the phase current flowing through the adjacent pole at the chosen instant of time. Furthermore, the ratio of normal force to the motional (tangential) component is appreciable. This is shown in figure (4). These forces cause unwanted vibration in the moving components along the radial direction thereby giving rise to vibration and acoustic noise.

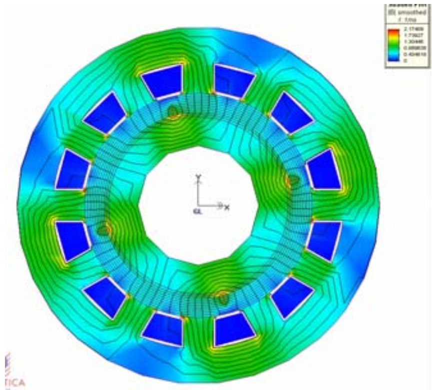

Fig.2: B-field distribution for 350 A-T in the RFPM.

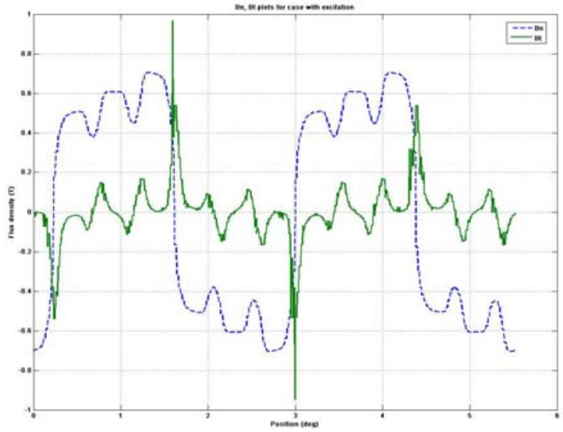

Fig.3: B-field distribution for 350 A-T in the RFPM showing slot effects and the formation of a 4 pole configuration.

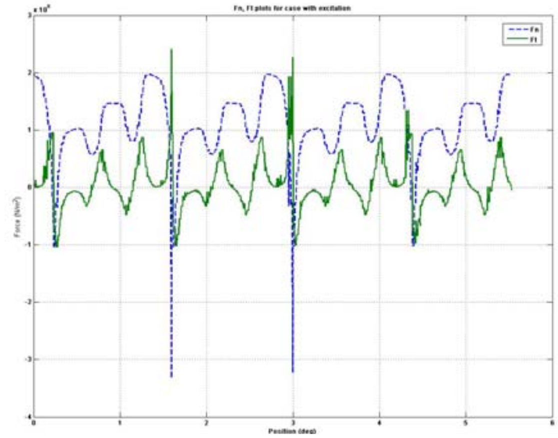

Fig.4: Force density distribution showing normal (dashed) and tangential components (solid) for 350 A-T in the RFPM.

Figure 5 shows the output torque profile obtained for the radial PMSM for a 3 inch stack length. This stack length was found sufficient to meet the required target of 2.1 Nm.

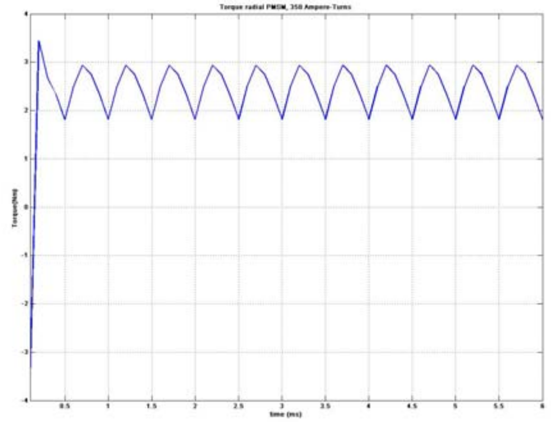

Fig. 5: Torque profile for 350 Ampere-Turns in the RFPM giving an average value of 2.32 Nm for a 3 inch stack length.

B) Axial flux PMSM

Figure 6 shows the flux density distribution in the AFPM showing the 4-pole formation along the axial length. Most applications usually focus on the tangential component of force. However with the advent of modern control schemes, fast switching devices and DSP processors, the option of implementing complex control algorithms has been made possible to manipulate the normal and tangential forces simultaneously. Similar to the RFPM, the presence of a strong permanent magnet generates significant normal forces which can be minimized by application of suitable excitation to the stator.

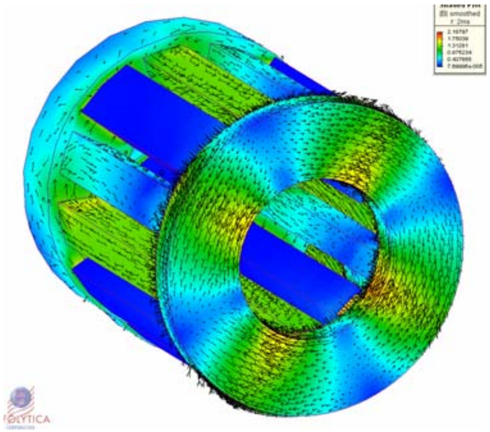

Fig. 6: B-field distribution for 600 Ampere-Turns in the AFPM

Some of the major forces that need to be considered in the design of the mechanical setup include the attractive force between the magnets mounted on the rotor and the stator poles and centrifugal forces acting on the magnets. By evaluating the local distribution of force components, we get a good idea regarding the sections of the machine where significant forces are generated. Such a distribution of flux density at an arbitrary instant of time is shown in figure (7). The corresponding distribution of force density components is shown in figure (8). This can be used for adequate sizing of the bearing, tolerance and life-span of the system. If field weakening is to be performed in the axial structure by varying the air-gap of the machine, suitable mechanical setup can be designed based on knowledge of the magnitude of local forces generated.

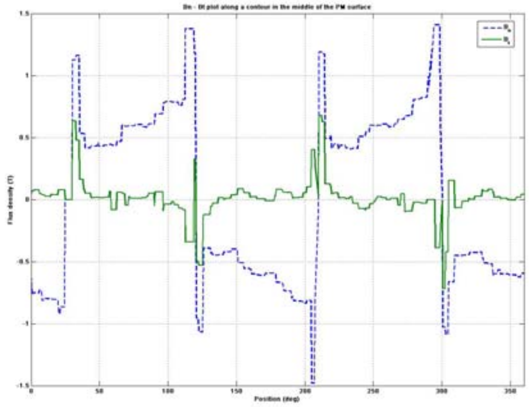

Fig.7: Axial and tangential components of the B-field for 600 A-T in the AFPM showing maximum flux density at the edge of the permanent magnets.

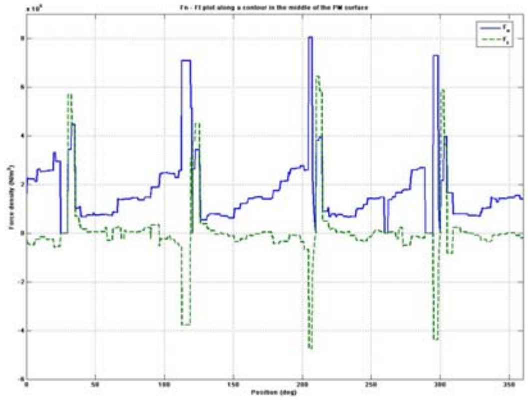

Fig. 8: Force density distribution for 600 Ampere-Turns in the AFPM.

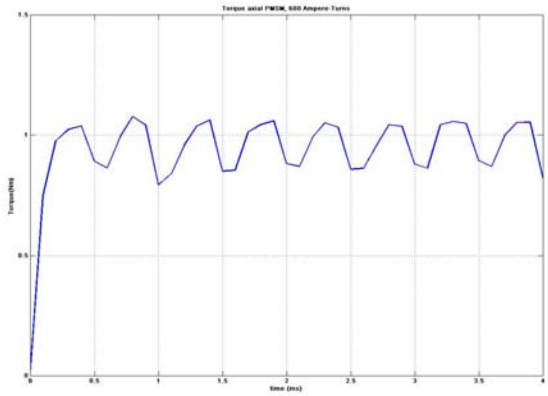

Fig. 9: Output torque profile obtained for the axial PMSM for a 3 inch stack length. Average torque generated = 0.98 Nm.

Figure 9 shows the torque profile that was obtained for a single-disk arrangement of the axial flux PMSM. The average value of torque obtained for 600 A-T was calculated to be 0.98 Nm.

IV. CONCLUSIONS

A performance evaluation of the axial and radial permanent magnet synchronous machine designs has been presented. Distribution of forces at the surface of the motional components have been presented along with torque productivity of the machine versus parameters such as volume of the rotor, copper, back emf generated and ampere-turns required for each machine. This provides useful information for the design of the electrical supply unit and the mechanical requirements for a specific application.

Table I: Evaluation Summary

Quantity	***Value***	
	RFPM	***AFPM***
Volume of rotor [cu. inch]	3.6	1.46
Volume of stator [cu. inch]	2.48	5.75
Volume of Copper [cu. inch]	800	1440
Volume of Magnet [cu. inch]	1.66	0.31
Ampere-turns applied [A-T]	350	600
Average torque generated from 3 inch stack [Nm]	2.32	0.98

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Appendix A

Table II: Geometrical details for target system

Parameter	***Value***	
	RFPM	***AFPM***
Machine configuration	3-phase, 4-pole	
Stator outer diameter	2.72 in.	
Number of turns	100	200
Winding configuration	Wave	Concentrated
Airgap length	0.0787 in. [2 mm]	
Thickness of magnet	0.0787 in. [2 mm]	
Rotor outer diameter	1.76 in.	3 in.
Overall machine stack length	3 in.	3 in.
Number of stator slots	18	
Shaft diameter	1.25 in.	

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