SMALLER FOOTPRINT, GREATER IMPACT

DAN COOK, WARD LEONARD, ON GETTING THE MOST OUT OF A RIG BY INTEGRATING HIGH POWER DENSITY ELECTRIC MOTORS.

With the ever increasing demands placed upon drilling contractors, getting the most out of the equipment available is more important than ever. Transport costs per tonne continue to increase, available footprint on the rig deck is shrinking, but requirements for continuous and peak power rating, and more efficient productivity, steadily rise.

To remain competitive, operators and rig designers leverage every opportunity available to deliver performance

Table 1. Comparison between standard 400 hp and high power density 600 hp motor

Specification	'Standard' 400 hp motor	HPDM 600 hp motor
Dimensions (W x D x H; inches)	19.6 x 19.8 x 47.9	
Weight (lb)	2800	
Rated power (hp)	400	600
Torque (lb-ft)	1795	2685
Current (Arms)	350	470
Speed (rpm)	1172	1163
Voltage (Vrms)	575	
Frequency (Hz)	40	
Volume-power density (hp/ft^3)	37.2	55.8
Mass-power density (hp/t)	286	428

Figure 1. *Punch the drill string harder with the WL12BB060 high power density drilling motor that provides up to 600 hp in a standard 400 hp 'square style' motor frame.*

capabilities unmatched by existing technology. API standards place constraints on how strong certain load bearing and torque path components must be, which limits the design flexibility and material choices; therefore, wanting to remove metal from a structure that is intended to support hundreds of tonnes is a difficult proposition to consider. However, if other components of the apparatus could get lighter or take up less space without sacrificing performance, a distinct and quantifiable advantage would be achieved.

One strategy that simultaneously reduces weight while increasing profits would be to employ more powerful AC motors in top-drives and rotary tables without making them larger or heavier – an advancement now made available by Ward Leonard's line of high power density AC motors (HPDMs) targeted specifically at the demands of the oil and gas markets.

Defining high power density

In physics, mass density refers to the overall mass (weight) of an object relative to that objects' volume. For example, a container full of water definitely weighs less than the same container full of sand even though the size (volume) has remained unchanged. From this one can conclude that sand has a higher density than water. In the same way, one may define any useful parameter relative to the mass of an object, and in some cases, it may also be useful to define some parameter in reference to the size of the object.

$$Density\left[\frac{lb}{ft^3}\right] = \frac{Object\ Mass\ [lb]}{Object\ Volume\ [ft^3]}$$

As it relates to electric motors, power density can be defined as the ratio that describes the total rated power of the machine relative to its weight. A higher power density would imply that a motor could deliver more power with comparable weight or similarly, comparable power, at a reduced weight. A motor with a higher power density would enable an end user to ultimately reduce transportation costs compared to heavier motors, or increase productivity (through higher power output) without increasing transportation costs. In either case, overall profitability increases.

Another form of power density is defined as the ratio of total rated power of the motor relative to the volumetric footprint required. One can imagine a scenario where a 600 hp motor might occupy 12 ft^3 of space, and the specifications for such a motor would be suitable for either top-drive or rotary table duty. Rotary tables and top-drives tend to be more space constrained than other electric motor applications in the oilfield, making it desirable to keep the size (or volumetric foot print) as small as possible. If it were possible to achieve that same level of performance by consuming only 10.8 ft^3 of space, an additional 1.2 ft^3 that was previously unavailable for use now becomes available. In tightly confined top-drive assemblies, extra space makes removal/installation and maintenance of the motor and other components much easier.

With the above definitions, it is possible to describe mass-power density and volume-power density expressed in any convenient set of units.[1] For example, it may be convenient to express mass-power density in horsepower per tonne (hp/t) and volumetric-power density in horsepower per cubic foot (hp/ft^3).

$$Mass\ Power\ Density = \frac{Motor\ Power\ [HP]}{Motor\ Mass\ [lbf]}$$

$$Volume\ Power\ Density = \frac{Motor\ Power\ [HP]}{Motor\ Volume\ [ft^3]}$$

The Ward Leonard WL12BB060 high power density motor (HPDM) has identical external dimensions and mounting requirements as standard 400 hp 'square style' top-drive motors, yet it is capable of delivering 150% of the torque at the same rated speed. A standard 400 hp top-drive motor is approximately 19.6 in. x 19.8 in. x 47.9 in. and operates at 40 Hz, 575 V, 1170 rpm, and provides around 1795 lbf-ft of torque. The WL12BB060 has the same volumetric envelope (19.6 in. x 19.8 in. x 47.9 in.) but achieves 150% of the torque at the same frequency, voltage, and speed. Because the volume and weight have not changed appreciably, the mass-power density has increased from around 286 hp/t to close to 428 hp/t. The volume-power density has likewise increased from 37.2 hp/ft^3 to 55.8 hp/ft^3.

An application example

A popular style of top-drive incorporates twin 400 hp motors connected mechanically in parallel to a common drive train via a single bull gear for a total of 800 hp. In operation, each motor at full power provides approximately half of the required drill string torque. Since they are mechanically in parallel, they will rotate at the same speed. In the event that there is an issue with one of the motors or the electrical system supplying the motor, the drive can continue to operate – but because both motors are rated at 400 hp, the entire top-drive will be limited to 50% capacity until the issue can be resolved, which might require an un-scheduled shutdown.

If instead the top-drive had been upgraded to twin WL12BB high power density motors, each rated at 600 hp each, several benefits immediately become apparent:

- In the event of a single failure, the opposite motor can provide continuous power up to the rated 600 hp, effectively improving on the single motor operating limit from the prior 400 hp to a very respectable 600 hp: a 50% improvement.
- Since both of the motors are rated at 600 hp but will normally only be run at 400 hp, the total heat production internal to the motor and overall temperature of the motor will be much lower. Lower motor temperatures result in longer insulation life than would otherwise be expected if running at full power.
- Since the machine is externally identical to the incumbent 400 hp motor and has around the same mass, a thorough review of the torque path components up to the bull gear is all that is required mechanically to provide more robust single motor operation and longer life from twin motor operation.

Because a single motor can now operate at 600 hp, a thorough review of electrical cabling and VFD capabilities will be required to ensure that both the mechanical and electrical systems will be capable of transmitting the additional power.

Technology primer

In order for any technology to experience a step change in capabilities, something within that technology must have changed. For example, micro-processors get faster because transistors get smaller, cars get faster and more powerful due to advanced computerised engine controls, and home lighting gets more energy efficient because manufacturers switch from incandescent bulbs to CCFL or LED.[2] In each of these cases, significant improvements have been made through ingenuity, a thorough understanding of the science, and because another new technology or manufacturing process has enabled the enhancement.

Perhaps the most significant change to induction motor performance has occurred over the past 25 years due to developments in variable frequency drive (VFD) technology and the associated digital controls. Initially, VFDs were coupled with existing induction motors in an effort to provide variable speed but the aggressive switching imposed by VFDs stressed the motor insulation in many motors beyond the design limits since they had been designed to operate only on sinusoidal or line power. Motor models were subsequently released to the market capable of being driven by a VFD by improving the motor's insulation system and making it more resistant to inverter generated voltage spikes. These newer inverter duty motors are, in most cases, adaptations from 60 Hz line-start designs with insulation upgrades that make them more durable when powered from a VFD. Because of this, the motor design naturally incorporates certain design features that are important for a normal line-start motor that really do not apply to a VFD specific motor. It is, essentially, a design carryover.

For example, line-start motors would have been designed to operate very efficiently at the rated nameplate voltage, frequency and load, but performance away from that ideal operating point would likely result in indeterminate performance, because performance away from that operating point was not considered at design time. Additionally, line-start motors, as the name implies, are started from the main power source 'across the line'. The starting currents experienced as an induction motor input goes from 0 V, 0 Hz to 480 V 60 Hz are typically 6 - 8 times full load current; this excessive current results in excessive heat production from starting and significant stresses on many parts of the machine; a motor started from a VFD will not experience such harsh transients.

Ideally, a new motor design intended only for use on a VFD must take into account the intended use of the motor over the entire operating speed, frequency, voltage, and power range. A vigilant motor designer will take the following things into account at every step of the design process:

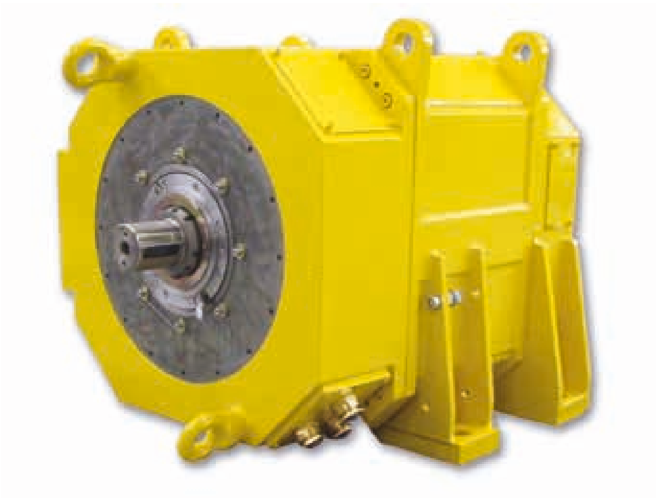

Figure 2. *WL16BC080 'short' high power density drilling motor delivers 800 hp in a standard 600 hp frame and comes in vertical and horizontal configurations.*

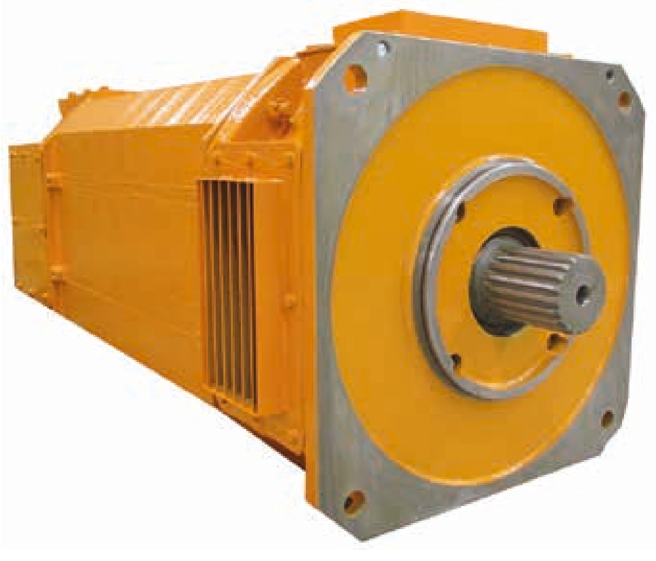

Figure 3. *WL13BB080 'long' high power density drilling motor delivers up to 33% more torque and horsepower within the same standard 600 hp frame size.*

- The motor will only have the features required to perform the job allowing the designer to eliminate any 'typical' features that will not ever be needed over the entire life of the machine.
- Analysis of an electric machine used to require copious hand calculations and estimates based on experience – today, those calculations are carried out in seconds by computers and finite-element techniques have eliminated much of the uncertainty and guess-work from the design of induction motors.
- By leveraging modern computing resources, numerous competing designs can be evaluated quickly at numerous operating points so that the several competing designs can be fairly evaluated and optimised over the entire operating envelope rather than at a single operating point.
- On a VFD, the power delivered to the motor is strictly managed over the entire operating envelope. Starting currents do not exist because the VFD applies power in a controlled manner, smoothly accelerating the machine from a dead stop to full load; advances in VFDs have even enabled starting an induction motor at full torque.
- Even though an induction motor is typically >93% efficient, it will generate significant amounts of waste heat when loaded at nearly every operating speed. Since it is feasible to operate a motor at a low speed but with high heat production, shaft mounted fans are not practical and continuous forced air cooling is required. One of the most thermally sensitive parts of a motor is the electrical insulation system; the better a designer can remove heat from the heat producing parts of a machine, the more powerful that machine can be.

Since the limits of an induction motor are largely determined by temperature, thermodynamic principles must be at the forefront during the preliminary design stages. In any thermodynamic system and all other things being equal, a temperature increase is a result of too much heat production or inadequate heat removal. By leveraging an intimate understanding of the underlying physics involved, the motor designer can attack one or both of these antagonists to temperature control by ensuring that cooling capacity is delivered to the portions of the machine that need it most, and implementing design changes in areas of the machine that are close to temperature limits by improving cooling efficacy or decreasing heat production.

In such cases, computer analysis tools can be used to flush out these weaknesses early in the design to minimise compromises later in the design. Often, simply specifying better quality materials or more of the 'working' materials will be sufficient to address a weakness and results in a comparatively marginal impact on product cost.

The Ward Leonard WL12BB serves as an example of these principles by including more, higher quality materials in construction and employing cooling strategies such as intra-slot cooling. Combined, the result is a mass-power dense, volume-power dense, VFD specific motor targeted at the demanding top-drive and rotary table rig applications.

Notes

1. Equivalent SI units could be kW/kg and kW/m^3.
2. CCFL – cold cathode fluorescent lamp; LED – light emitting diode.