ThinGap®
2064 Eastman Avenue #107 • Ventura, CA 93003
805.477.9741 • fax 805.477.7535

ThinGap Motor Technology

Motors that deliver higher output with lower power consumption are a continuing challenge, especially for the OEM design engineers responsible for innovating new products. These high efficiency and high power density motors must provide smoother operation, fit in a smaller space and weigh less, features that are crucial for getting a new product or feature off the drawing board and into the market.

The leading type of high power density and high efficiency motor is the brushless permanent magnet (PM) motor, especially a category known as slotless or ironless-core motors. The biggest barrier confronting these motors has to do with internal motor losses caused by copper wire windings. The same component that allows a motor to create motion also inhibits power density and efficient operation.

Most manufacturers continue to use wire windings and by developing various designs have been able to improve power density and efficiency. ThinGap developed a patented technology, which replaces the iron core and wire windings of conventional motors with a precision-machined copper sheet. This has eliminated such issues as hysteresis, iron losses, and cogging torque, while substantially reducing the impact of eddy currents and back emf. The copper sheets allow higher copper density and a higher copper to total volume ratio, making ThinGap a performance leader in high efficiency and power density motors.

Internal Losses in Conventional Motors

In most applications, copper winding losses are the largest factor affecting motor efficiency. These losses are computed by multiplying the input current squared by the winding resistance of the stator. The resistivity copper is among the lowest of any current carrying material. As speed increases, eddy current losses become significant. The internal losses of a conventional motor are composed of the following components:

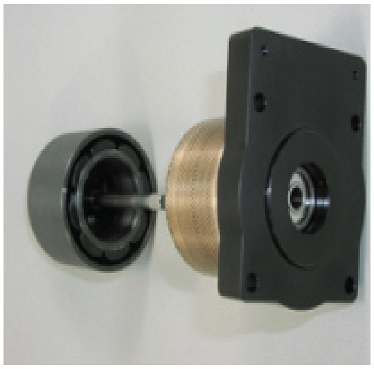
- Copper winding (function of conductivity of copper and the resistance of the stator coils)
- Coulomb friction (brushes, bearings and shaft seals, etc.)
- Viscous friction (bearing lubrication, certain materials damping characteristic as a function of speed)
- Hysteresis (magnetic memory in motor’s soft iron members)
- Eddy currents (primarily soft iron losses caused by material type and thickness of laminations, material induction levels, commutation frequencies. Losses vary as a function of speed squared)
- Windage (aerodynamic effects due to motor geometry and speed)

Precision Copper Sheet Replaces Wire Windings

Traditionally, electric motor manufacturers have employed round insulated copper wire in armature windings for both iron core and ironless brush DC motors. Ironless DC motors made with round insulated copper wire overcome many of the weaknesses of conventional iron core motors but are limited by copper packing density and larger magnetic air gaps. The precision-machined copper sheet used in ThinGap’s motors achieves a high copper packing density (high ratio of copper to total volume). It is utilized in both ironless PM brush and brushless motors.

A ThinGap ironless armature displays a mechanical ruggedness due to a denser, multi-layer construction that creates a robust and very rigid structure. The lower winding resistance provides higher motor power efficiencies. The air gap is minimized, which enhances the air gap flux density, enabling high torque. With ThinGap brush motors, a heavy-duty commutator enhances mechanical commutation.

The Brushless PM (DC) Motor



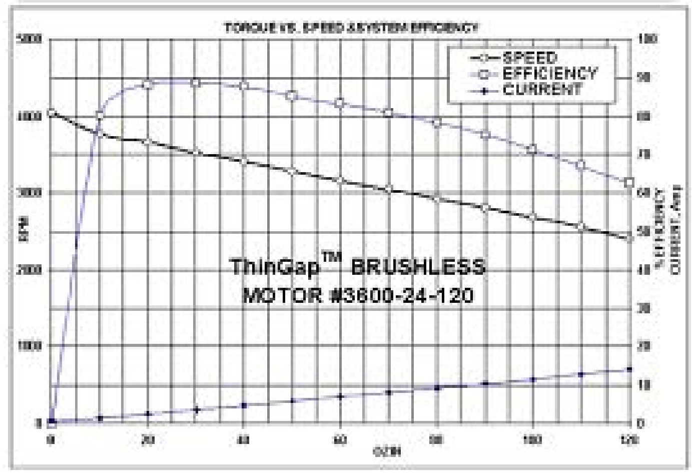
A brushless permanent magnet motor can be classified as either iron core or ironless core. The iron core motor, as the name implies, uses an iron core to hold the copper wire windings. The ironless core motor eliminates the iron core but retains copper windings wrapped around a cylindrical non-iron structure. Ironless core motors can be further divided into fixed return path, where the return iron of the magnets is stationary and the armature rotates; or rotating return path, where the magnets and return iron rotate while the coil is stationary.

ThinGap BLDC motors rotate the return path with the magnets, eliminating the relative motion between the rotor and housing return path. This eliminates hysteresis loss and the related drag torque. All iron core BLDC motors utilize a rotating magnetic field and a stationary outer laminated return iron, which causes hysteresis losses. Use of an overall rotor structure shaped like nested rotating cups and a thick coil stator in the gap between cups provides a rugged mechanical structure, low resistance, and very low inductance.

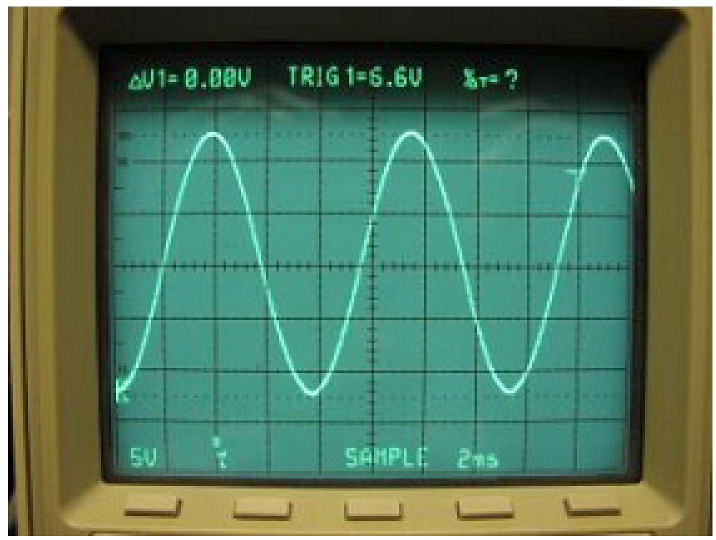
The improvements of the motor, with respect to the various losses mentioned earlier in this article, include:

Copper Losses (I^2R)	Very low winding resistance
Coulomb Friction	Uses ball bearings
Viscous Friction	Small
Hysteresis	None
Eddy currents	Minimal (no Moving iron or steel structures)
Windage	Small-homogeneous structure in small air gap

By way of example, the TG2310 torque-speed-current-efficiency plot shows 84% peak system efficiency at about 25 ounce-inches torque load at 12vdc. The system efficiency value includes both



motor and drive power efficiencies. Of the total system efficiency, the motor-efficiency is estimated to be 94 percent. Line current does not reach 10 amps until the motor develops 90 ounce-inches of continuous torque. Maximum continuous torque is 106 ounce-inches for this brushless DC motor at 30vdc.



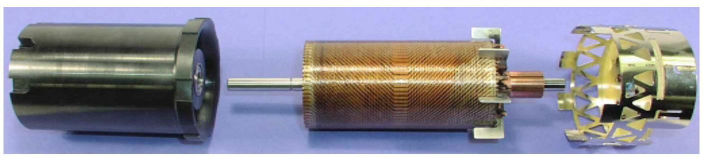
A trapezoidal servo drive was utilized to obtain the data. The back EMF waveforms are sinusoidal and with matching sinusoidal current waveforms, a smooth low peak-to-peak torque ripple is achieved. A back EMF waveform with near-perfect sinusoidal symmetry significantly reduces torque harmonics and mechanical resonance over a wide speed range.

The DC Brush Motor

The ancestor of the high performance brushless DC (BLDC) motor is the PM brush DC (PM-BDC) motor. While many applications are switching to the

BLDC motor, the iron core BDC motor continues to dominate such applications as automotive accessories, wheelchair drive motors, and forklift vehicles. The simplicity of a two-wire electric connection and the cost effectiveness of the PM-BDC motor in higher volume applications facilitate its primacy over other motor types.

An ironless BDC motor still uses conventional copper wire windings but eliminates the need for soft iron or steel armature laminations to hold the windings. The ironless brush DC motor is comprised of a stationary magnetic field and the rotating armature eliminating a large part of the losses due to hysteresis and eddy current losses These ironless PM brush motors have been used in precision small robots, tool changers, X-Y recorders, medical infusion pumps, flight recorders, and video recorders.



Increase Efficiency 10 Percent and Double Output

Improvements in motor efficiency also mean improvements (increases) in continuous torque ratings and reduction in dissipated power. Continuous torque ratings of any electric motor are limited by the internal losses (dissipated power) in a motor, which produces heat. Any electric motor's performance is limited by its ability to transiently store and continuously dissipate heat. Face mounting motors on specified aluminum heat sinks is used to test thermal performance. The table below illustrates the effects of efficiency on power output.

Power-Watts

Efficiency	In	Out	Dissipated
80%	100	80	20
90%	100	90	10
90%	200	180	20

By increasing power efficiency from 80% to 90%, output power capability is more than doubled (180/80) to 2.25 times assuming the same thermal resistance.at the same power loss. The lower power losses are available from the same size motor with a lower resistance and/or a lower ac loss.

Comparing Supplier Performance

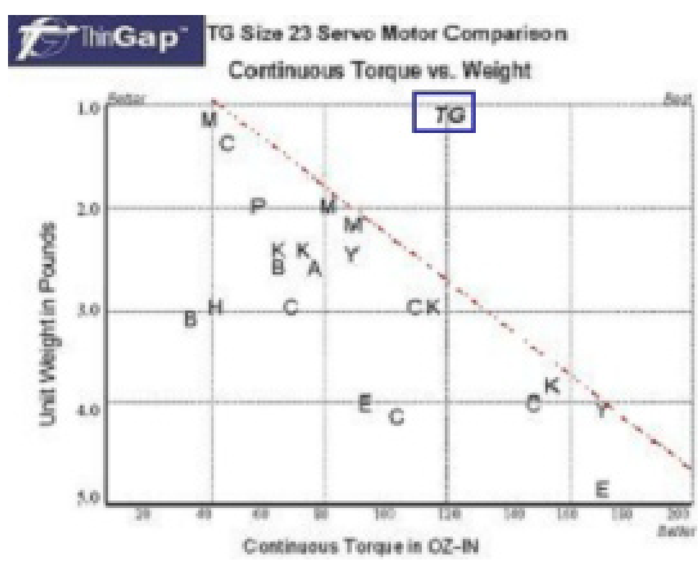
There are many ways to compare overall precision motor performance. The comparison criterion used for examples in this article was continuous torque per motor weight, since this figure-of-merit accounts for thermal performance, as well as unit size. The motor size was limited to NEMA size 23 and 24 (60 mm) square or outside diameter shape. The unit weight was employed because it provides a better comparison to the motor materials cost (not necessarily manufacturing costs) than unit volume.

The data for continuous torque and unit weight was taken from a wide range of brushless PM iron core motor suppliers' data sheets. The letter designations are used to differentiate various suppliers. There is one other slotless brushless motor type tabulated and shown.

The perfect motor would be located in the upper right corner of the plot. The best motor is the one that comes closest to this area (for example: low weight, high torque).

Further Performance Comparisons

The new rotating return path BLDC ironless motor configuration is focused on applications needing larger inertias and on applications that will benefit by eliminating gearboxes or gear trains. For example, the ThinGap TG family possesses rotor inertias 5 to 10 times higher than today's slotted iron core versions. The much higher continuous torque capabilities are also important in direct drive applications or in those that use lower ratio gear trains. The best planetary gear trains exhibit 95 to 97 percent transmission efficiency per gear train pass or stage.



Higher peak torque and power values can be obtained in ironless brush and brushless DC motors. Since there is no iron in the stator, There is no magnetic saturation of the stator at high peak currents. As a result, peak torque can be much higher. The only peak current limitation is the ability of the motor to dissipate heat.

Non-Cogging Operation in PM Brushless Motors

Cogging torque in permanent magnet motors is caused by magnetic attraction between lamination slots in the stator and the permanent magnets in the rotor in brushless motors. The rotor and stator seek rotary detent positions dictated by the slot spacing. Magnetic detent can cause significantly unsmooth rotation of the rotor if the effect is not minimized.

The effect is usually minimized by skewing the slots and/or by using non-integer ratios of slots to poles. It is often difficult to eliminate cogging entirely and that is where some problems occur. For those applications that cannot tolerate any cogging, however small, the slots need to be eliminated and replaced with a winding in the air gap without slots.

As a side benefit, there is some reduction of eddy current and hysteresis losses that were in the teeth that formed the slots. The end result of using an air-gap, slotless winding is that rotational motion can potentially be extremely smooth. There are other torque variations that can cause torque ripple. These effects take place when the winding currents and the back emf waveforms are non-sinusoidal. This issue of winding-induced torque ripple is dealt with in another white paper.

ThinGap's coils are made without any iron parts, slotted or otherwise. All the iron parts rotate around the coil in the brushless motor. This configuration eliminates magnetic detent cogging and hysteresis drag torque, allowing very smooth velocity and position control of the motor rotor.

Conclusion

ThinGap's technology relies on a precision-machined copper sheet instead of wire windings to extend the life of battery-powered products, save on energy costs and reduce thermal overload damage. By lowering internal power losses ThinGap motors provide higher power efficiency, which allows a wide range of speed and torque; and generates less heat and electrical resistance. This allows ThinGap motors to run cool and deliver a wide operational bandwidth that surpasses conventional motors in almost every benchmark.

ThinGap®

2064 Eastman Avenue #107
Ventura, CA 93003
tel: 805.477.9741
fax: 805.477.7535