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

Breakthrough in DC Motor Technology Allows Innovation in Appliance Design and Manufacture

During the past decade, executives have cut operational costs to the point, there is little left to cut. Costs cuts have almost been eliminated as a strategy for increasing profitability. To create value, executives are left with few options except innovative new features and products. But true innovation isn't a matter of adding a few new features or redesigning the look of a product. Innovation comes from pushing the envelope. The breakthrough motor technology we have developed in turn provides a platform for innovation in the appliance industry that can be configured for various performance characteristics. This allows designers of appliances to innovate features, capabilities and lifecycle extension, as well as improve manufacturing processes.

The breakthrough we discovered is how to eliminate the wire windings and laminations that virtually all motors have used to create a magnetic field. This technology is advancing innovation in a variety of velocity and servo loop applications, such as appliances for the medical, pump and compressor and fan motor industries. The technology enables improved performance, fewer parts, lighter weight, higher efficiency and power density, and higher reliability for lower volume specialty applications. In five to ten years, the cost of this technology will begin to be affordable for high-volume, low-cost applications.

Breakthrough Patented Electomotive Coil

The breakthrough we made was an electromotive coil, which eliminated wire windings and laminations. It doesn't change the physics behind motor operation, but applies them in a different way. To better understand how the motor works and can be used to innovate new appliances and features, a basic knowledge of conventional DC brushless motors is necessary.

The typical DC brushless motor consists of a rotor and stator. The permanent magnets are mounted to the shaft and rotate, representing half of the magnetic circuit. The stator coil is stationary and made of copper wire wound around iron laminations or other material to support the windings. The other half of the magnetic circuit is the stationary iron laminations.

The ThinGap motor coil (stator) replaces wire windings with laminations by creating a precision-machined copper sheet formed into a circular coil. The coil assembly has structure without supporting laminations, creating a free-standing coil. The copper sheets allow higher copper-packing density than copper wire. The stator assembly can be operated from 50V to 280V by either winding the coils in parallel or in series.

The rotor consists of a U-shaped iron channel with a thin inner wall and magnets mounted to the inside of the outer steel ring. The structure forms a channel within the ring that accepts the stator coil. The entire magnetic circuit rotates, which eliminates the iron losses typical of conventional brushless motors. The only remaining parasitic losses are the eddy current losses (AC losses), which exist in the coil and are minimized by the coil conductor design.

Traditional motor construction limits the speed a multi-pole iron core motor can reach because its phase waveform cannot switch fast enough at high speed. This is because of the iron core's high inductance. The very low inductance of the ThinGap coil design allows high frequency operation of the amplifiers (high speed switching of the current). This allows more magnets, which creates a higher pole count reducing the mass of the iron to which the magnets are attached. In turn, this reduces the coil weight. With lower weight and higher pole count, the motor has very few limitations on its high speed capabilities. Basically, the current is switched on and off depending on the location of the rotor to create motion, torque and inertia. A conventional iron core motor uses a high-inductance coil, which cannot switch current on and off fast enough to reach its full speed potential. In high pole count iron core motors, the eddy current losses become extreme at high speeds. So iron core motor designs are not designed with high pole counts.

Different Configurations for Different Applications

By varying the winding configuration of the stator coils, different speed and torque requirements can be achieved. For instance, either parallel or series wired circuits can be used. This allows velocity loop and servo loop applications requiring high speed, high torque, direct drive and battery-powered. For example, a variant of this technology is a ring motor. It can be used in such applications as fans with the blades mounted inside the motor, direct-drive motive force for wheel chairs and in-plant electric vehicles.

Lower Appliance Manufacturing Costs

A conventional fan motor has ball bearings at both ends, requiring a structure to keep the two ball bearings aligned. This is necessary to eliminate radial deflection, a primary cause of premature bearing failure. By using a ThinGap motor for this type of application, the bearing assembly can be cantilevered. This means the ball bearings are mounted on one post. So, there are only two parts to bolt into most appliances, including the stator and rotor. Since laminations have been eliminated and the rotor containing the magnetic circuit (magnets, back and return iron) is fixed, the magnetic field of the rotor is invisible when inserting the rotor onto the stator. This reduces the number of tools, steps and time required for assembly. In addition, the bearings are covered and not on the end post, reducing contamination.

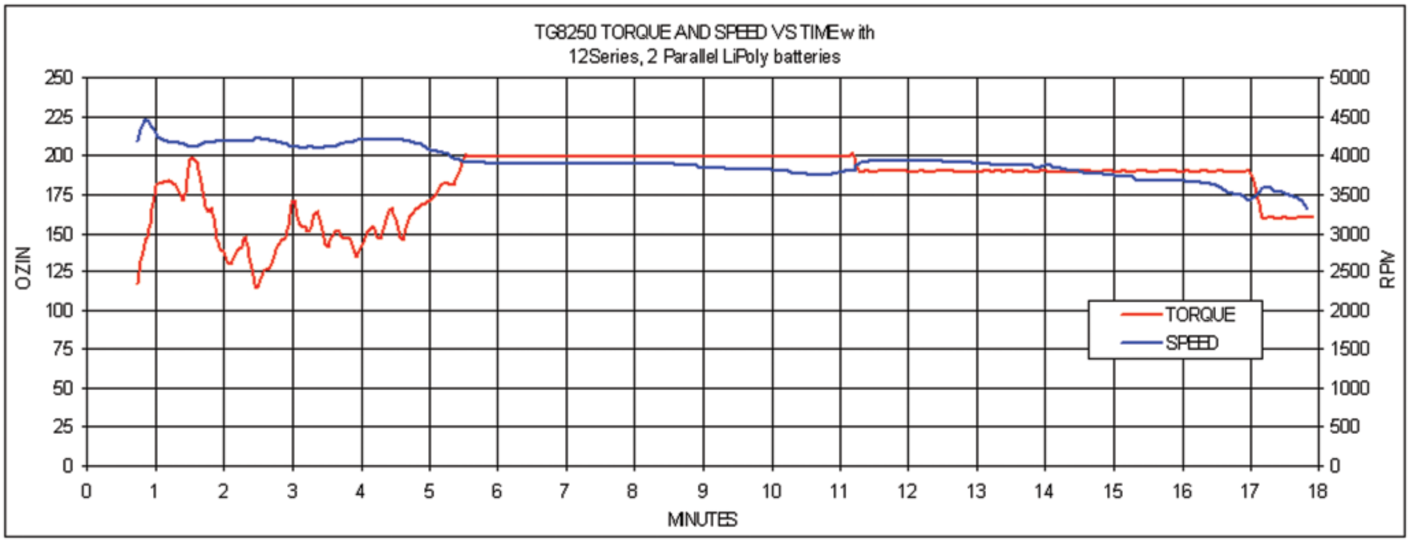
In a compressor application, the coil and lamination structure has to be glued into the casing. A tool is used to insert the rotor and prevent its attraction to the laminations from cracking the case. Another tool is used to align the plates and insert the bearing plates. Outside screws were used for compressing the assembly. With the ThinGap motor, the stator is held in place with two screws. The shaft is pressed on the ball bearings. A structure to hold the two bearings in alignment is eliminated.

Better Performance

Not only can the ThinGap motor be configured differently, it can be designed for form fitting applications to reduce the cost of assembly. For example, fan blades provide more thrust as they get closer to the hub. Typically, the fan blade and hub assembly is mounted directly to the motor, which means the hub is large and the fan blades can't move air as efficiently as they are capable. With the ThinGap technology, the fan blades are mounted inside the motor, allowing them to operate at maximum efficiency. In addition, the blade tips are enclosed for safety and the motor runs cooler. The assembly becomes as flat as the blade profile.

By delivering higher inertia the torque ripple is very smooth. Combining this high inertia with very low harmonics makes for even smoother velocity. This reduces vibration and provides a wider dynamic range. As a result, the motor can deliver higher shaft output than a comparably sized conventional motor. Following are some examples of ThinGap motor performance.

A compressor with all the inside and outside magnetic components rotating creates higher inertia in the moving component. Higher inertia smoothes



Speed and current vs. torque for the coil options, including 4 parallel, 4 series and 2 parallel with 2 series coils.

the torque ripple in the appliance. This particular compressor is a lobe-piston type, which under normal conditions would utilize a flywheel. The ThinGap motor is its own flywheel. Combining high inertia, smooth torque and a magnetic field with an insignificant level of harmonics also provides very smooth velocity. This results in a wider RPM operational range. In the compressor application, a conventional brushless motor was unable to operate below 900 RPM. The ThinGap motor operated at RPM's as low as 300.

Part of the difficulty with a conventional brushless motor is torque ripple caused by cogging. When the requirement for a high torque output spike is combined with the torque ripple, the motor will get lost and not be able to get over that torque at higher RPM. The ThinGap motor delivers a higher dynamic range because laminations which cause cogging have been eliminated.

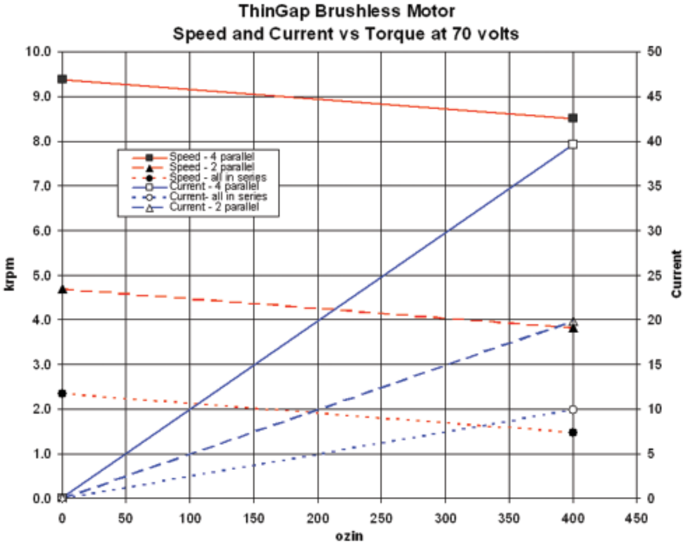
Very low voltage harmonics are present in ThinGap motors due to the precise location of the coil elements and the inherent smoothing of the flux density in the air gap. This feature provides exceptionally smooth, constant torque independent of rotor angle with sine drive controllers.

With a traditional AC or brushless motor, some sort of damping device is needed to minimize harmonics. In a pump application with a gearbox, harmonic resonance can lead to shorter gear life and the use of larger and heavier motors. In one application, an AC motor was replaced, reducing volume, weight and energy consumption. In addition, the gears lasted longer.

Another characteristic of the motor is low acoustical noise. Brushless motors can be noisy. In the compressor application mentioned earlier, when the conventional motor was replaced the appliance went from 49 dB to 43 dB. Because decibels use an exponential scale, this represents a significant drop in noise levels.

Power for brushless motors generally is a trapezoidal AC wave form, although ThinGap motors operate extremely well with trapezoidal drives, they operate with almost a perfect sine wave back EMF. Sinusoidal-powered motors have less torque ripple and operate smoother at lower speeds. Reducing torque ripple to very low levels is achieved by shaping the back EMF to match the sine wave drive signal as closely as possible. This achieves almost perfect coupling of the back EMF and the sine wave, which eliminates torque ripple and noise, while providing smooth operation and flat torque.

Higher Efficiency

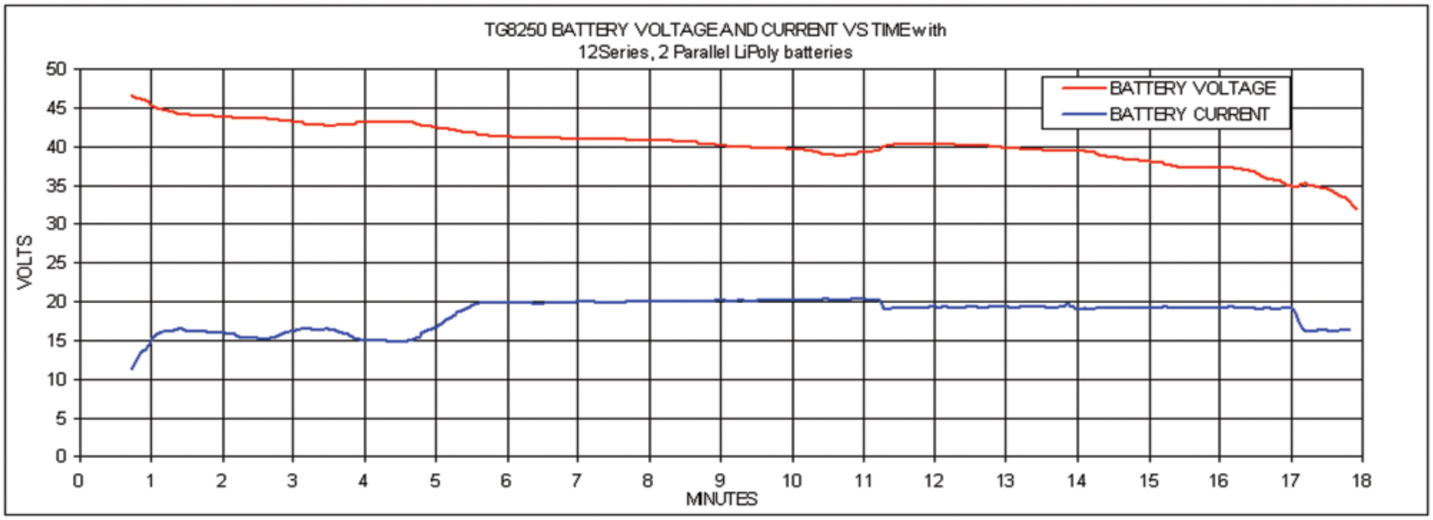


Speed and current vs. torque for the coil options, including 4 parallel, 4 series and 2 parallel with 2 series coils.

Power density (watts per pound) has been increased with high pole counts and thin magnetic iron in the poles. Because the coil is low inductance, phase advance is not required as with high inductance conventional motors. Motor current builds immediately, with low voltage overhead required for transient moves, especially at higher speeds. A problem with traditional iron core motors and their high inductance coils is the significant voltage required to change the current for more acceleration, which depletes the battery charge. With the ThinGap coil, the controller current loop easily controls current because the low inductance presents the characteristics of a mostly resistive circuit, allowing current to quickly follow voltage. This reduces the hysteresis between the control and the motor, allowing tight velocity or torque response.

Innovation in Appliance Design

By pushing the envelope for electric motor design, we developed a substantially improved electric motor. If we had continued down the path of most motor manufacturers, we'd still be working with wire windings – the same components that have been in use since the invention of the electric motor in the 19th century. The ThinGap motor is a leap forward and provides appliance manufacturers with a motor platform that eliminates many of the barriers to innovating new features, energy efficiency and new products.



Typical voltage and current characteristics of battery powered ThinGap motor.

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