ThinGap®
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LAMINATION-FREE MOTOR REDUCES BATTERY POWER CONSUMPTION 30%

ThinGap Motor Technologies Increases Motor Efficiency Allowing More Time Before Recharging and / or Additional Power for Other Devices.

With today's feature-rich and power-hungry battery-operated devices, motor efficiency is critical. Even with extended-capacity batteries, every watt saved still translates into additional operating time between charges and/or power for additional features. While battery capacity has been extended during the past decade, electric motors, especially low horsepower motors, have had limited efficiency gains. This is largely because traditional motors utilize electromotive coils designed with copper wire windings supported by iron laminations, which have inherent inefficiencies. However, a new technology developed and patented by ThinGap Motor Technologies demonstrates up to 92% efficiency in a slotless brushless DC (BLDC) motor by replacing traditional wire windings, iron or ironless-core laminations with a self-supporting and precision-machined copper sheet.

Leading Causes of Motor Inefficiency

Whether brush or brushless, iron or ironless core (slotless), mechanical and magnetic losses affect the efficiency of an electric motor. Some losses are inherent in the motor design, while others are caused by variation in materials and manufacturing tolerances. Mechanical losses include friction (drag) caused by the brush (in a brush motor), friction caused by bearings, seals and grease, windage (wind drag) from the amount of air circulating when the coil moves. While mechanical losses increase power consumption, they tend to have less effect on efficiency than electrical losses. Electrical losses include iron losses (eddy current and hysteresis). Brush motors also exhibit a phenomenon called brush contact losses where the brush film causes higher resistance to the current flow, in turn causing heat losses.

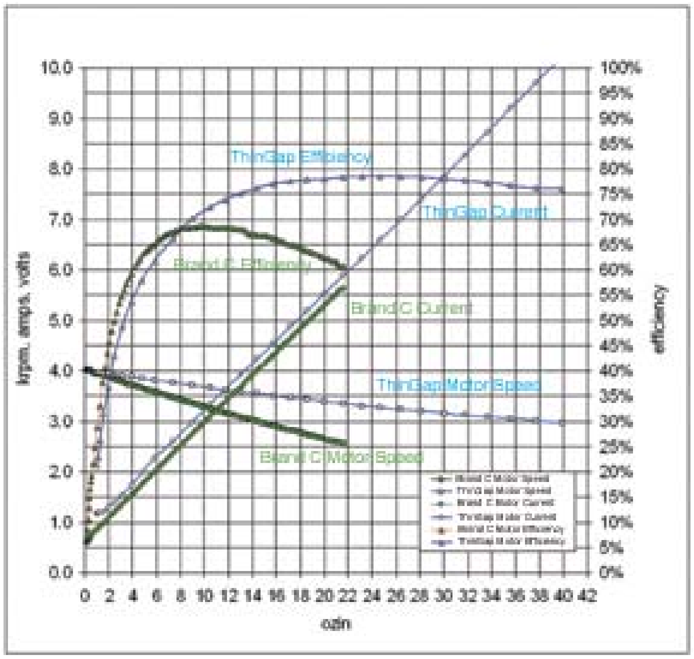
Traditional wire windings, iron or ironless-core laminations are eliminated with ThinGap's self-supporting and precision-machined copper sheet. A slotless brushless BLDC motor with a ThinGap electromotive coil demonstrates up to 92% efficiency.

Eddy currents are created when the conductive iron core is swept by a changing magnetic field. These currents have a significant heating effect on the motor, especially at high speed. These losses are a function of speed (ω) or frequency (f) and increase by the square of the frequency. For example, losses are increased fourfold by doubling the speed. Typically, laminations made of thin silicon steel sheets separated by insulation reduce the formation of eddy currents. Other types of materials have been used in the laminations to minimize eddy currents, however any motor with laminations swept by a magnetic field will demonstrate eddy current losses.

Hysteresis losses are the result of the iron core experiencing a changing magnetic field. As the iron core turns through the magnetic field in a brush motor or is swept by the turning magnetic field in the brushless motor, the magnetic domain boundaries of the iron core shift. The resistance to magnetic shifting causes heat losses, which increases with motor speed and varies according to the type of iron lamination being used.

Motor Efficiency

Measuring motor efficiency determines the effectiveness of a motor in converting electrical



This graph shows the superior efficiency of a ThinGap TG3600 brushless motor when compared to a well-known traditional brushless motor. For instance, at 21 oz-in of torque the Thingap motor is 16% more efficient.

energy into mechanical energy. Typically, efficiency is expressed as the equation: input = output + losses.

Various motor designs have been developed to increase motor efficiency, including brushless motors and slotless brushless motors. However, they have provided only nominal gains in efficiency because they are slight variations of the same basic components, namely laminations and wire windings. Typical brushless motors rely on iron laminations, and slotless brushless motors use toothless silicon iron and epoxy laminations.

Brushless Motors

A typical outer rotating brushless motor features a rotor made of a steel shaft with permanent magnets and a magnetic ring fixed around the circumference of the shaft to produce torque. As the flux density of the magnet circuit increases, so does the torque capability. The brushless stator is comprised of circular copper wire wound in the slots of an internal laminated iron core. The stator current creates magnetic flux that is transferred through the laminations to interact with the magnetic flux of permanent magnets in the rotor. The stator magnetic circuit includes the iron core surrounding the copper windings. The stator flux density is constrained, because circular copper wire is limited as to how densely it can be packed. Higher copper density increases flux density.

Like brush motor armatures, the slotted iron core stators in brushless motors experience winding (i^2R), eddy currents, and hysteresis losses which means lower efficiency and performance. Cogging torque is caused when rotor permanent magnets seek stator slots. As the magnets pass the lamination teeth, there is greater attraction to the iron at the ends of the teeth than to the air gaps between them. Cogging causes vibration and noise at a frequency of RPM times the number of teeth. In response to rising torque, cogging produces a current ripple. Cogging interferes with precise positioning because the armature of rotor tends to lock into a position where it is aligned with the magnetic field. Cogging can be reduced by changing the magnet width relative to the slot pitch and by slanting the stator teeth relative to the rotor magnets or vice versa, but this adds a level of complexity and is cost prohibitive.

Slotless Brushless Motors

Dr. Fritz Faulhaber introduced the slotless, ironless core brush motor in 1958, with the objective of minimizing hysteresis by eliminating laminations. Ironless core coils made with magnet wire overcame many of the weaknesses of iron core motors but are still limited by the copper packing density of circular wire, as well as larger air gaps, higher electrical resistance, operating speeds limited by the structure of the wire winding and generally lower power performance. The slotless brushless motor also uses conventional copper wire windings but replaces the iron laminations with thermoplastic materials. By utilizing a stationary magnetic field and rotating armature, some lamination losses, cogging, and torque ripple are eliminated, but higher resistance and thus higher copper losses (i^2R) are introduced.

Instead of winding copper wires through slots in a laminated iron stack, as is the case with conventional brushless motors (see diagram), slotless BLDC motor wires are supported against silicon-steel laminations. These laminations provide the return iron for the magnetic structure. Then they are encapsulated in thermoplastic to maintain their orientation with respect to the stator laminations and housing assembly. This configuration replaces the stator teeth and minimizes cogging. However, only 50% of the space the winding occupies is wire, i.e. in a large magnetic gap, reducing magnetic flux density. The air gap between the stator and rotor is very wide, further reducing magnetic flux density. Other problems include heat and centrifugal force. Thermoplastic becomes soft at high temperatures and centrifugal force causes the windings to shift, limiting the motor's speed and causing additional losses.

ThinGap® Electromotive Coil Technology

The ThinGap electromotive coil technology replaces the iron core and wire windings of conventional motors with a coreless circular copper coil. The coil is a thin, freestanding composite structure made of copper sheet, glass fiber, aluminum, and polyimide. The inside and outside surfaces are exposed to moving air, maximizing heat dissipation. The stator and armature conductors are formed as a freestanding thin shell. The wire windings have been replaced with a precision-machined copper sheet, using automated and repeatable process control, which ensures consistency of the conductor configuration to tolerances of 0.001".

ThinGap brushless motors do not utilize an iron core, eliminating eddy current losses and improving efficiency. Typically, brushless motors (iron core and ironless) rely on a rotating magnetic field, causing hysteresis losses. In ThinGap brushless motors, relative motion between the rotor and housing return path is eliminated by using a fixed magnetic field with a rotating return path, which does away with hysteresis losses. This also eliminates the cogging, which enables very precise control. The back EMF waveform is a smooth and nearly perfect sinusoidal, resulting in substantially reduced harmonics and mechanical resonance over a wide speed range. Torque ripple is nearly immeasurable, a factor also contributing to the smooth power delivered by the motor. As a result, the benefits of ThinGap's technology include high efficiency, enhanced power density, smooth, precise control and lower weight.

The enhanced copper density and elimination of the iron core allows for a reduced coil thickness as compared to conventional motors. This allows a physical reduction in the gap between the magnets and the return iron. As a result, magnetic flux density is increased, which allows the motor to produce extra torque. In addition, the coil is better able to take full advantage of the magnetic energy created by the higher density of copper between the magnet and the return structure.

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.

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