Technical White Paper: Evaluation of Electrostatic Motor Efficiency

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I. Abstract

In this white paper we examine the fundamental loss properties of electrostatic motors. We compare these properties to the loss mechanisms of the most common electric machines used in industrial applications including induction motors and permanent magnet motors. The evaluation shows that the electrostatic motor has no winding losses, thus eliminating the dominant source of loss in traditional electric motors; and that the dominant loss mechanism in an electrostatic motor is analogous to the conductive portion of core losses in magnetic motors. These properties facilitate an increased efficiency for electrostatic motors when applied to low-speed industrial applications such as material conveyors, high volume low speed fans, and positive displacement pumps.

II. Discussion of Electrical Losses in Electric Motors

Conventional electric (magnetic) machines typically consist of conducting coils (i.e., windings), a permeable core, and a magnetic flux source. The flux source is often permanent magnets or in the case of induction motors, rotor conductors and core material form an electromagnet. Therefore, in its most reduced form, a conventional electric machine equivalent circuit is an inductor. Inductors, "L", store energy in a magnetic field when current flows through them and in the case of a machine, spatial variance of the field energy produces torque. Inductor losses are generally represented by two lumped circuit elements, shown in Figure 1 below. A series resistance "R_s" represents winding losses and a parallel resistance "R_p" represents core losses. Machine designers try to minimize R_s and maximize R_p for a given L to facilitate an efficient machine. Of these, R_s is often the biggest threat to machine efficiency because it bears the total phase current of the machine. Generally, R_s is reduced by increasing the quantity of conductive material, e.g. adding more copper, in the design. R_p is often the second consideration for efficiency, where a core is made by laminating thin layers of electrical steel to reduce eddy currents and hysteresis. More expensive higher-grade electrical steels can be used to reduce core loss in traditional electric machines.

> **Summary:** Winding conduction losses represented by R_s are the dominant machine loss mechanism. Permanent magnets and/or copper windings, which are relatively costly commodities, are the primary drivers of increased materials cost to maintain efficiency. Core losses are lower than conduction losses though remain significant, especially in the case of induction machines.

Electrostatic machines are the dual to the magnetic kind and are fundamentally represented by capacitors. The C-Motive electrostatic motor consists of parallel stator and rotor "plates" with patterned electrodes. The plates are separated by a dielectric fluid with low viscosity that does not constrict motion. An electrostatic machine stores charge, which serves as the flux source, when the capacitances have voltage across them. A variable frequency drive creates the applied voltage wave that pushes and pulls the stored charge on the plate surfaces, creating torque. Like inductors, capacitor losses are generally represented by two lumped circuit elements, R_s that represents conductor loss and R_p that represents dielectric loss (the equivalent of core loss) as shown in Figure 1. For electrostatic motors, the dominance of the loss mechanisms is reversed. Electrostatic machines do not contain copper windings and the associated lengthy, resistive wires. Instead, the electrodes have a very large surface area and a miniscule axial length, resulting in a negligible R_s. Therefore, copper mass can be minimized to 90% or less than that required in a magnetic machine. The dielectric core loss in R_p is the dominant loss mechanism and must be considered carefully in the design. Dielectric loss can be divided into two categories: dielectric hysteresis and leakage conductance through the fluid. In the case of C-Motive's motors the relative *permittivity* of the dielectric fluid is much lower than the relative *permeability* of steel (typical *permeability* in the 1000s) in a magnetic machine, making hysteresis losses negligible in the practical fundamental frequency range of 0 to 300Hz. Therefore, fluid leakage conductance is the primary loss mechanism within lumped element R_p. The ability for C-Motive's electrostatic motor technology to achieve high efficiency hinges on the fluid being a good insulator, with low conductivity (lower conductivity results in a larger R_p).

> **Summary:** Core loss caused by the conductivity of the insulating dielectric fluid is represented by R_p and is the dominant loss mechanism. Minimizing this loss does not require any copper or any permanent magnets, it requires a better insulator. C-Motive's proprietary dielectric fluid is a low-cost, non-toxic and biodegradable insulator that demonstrates very low conductivity, resulting in low electrical losses without the use of expensive materials.

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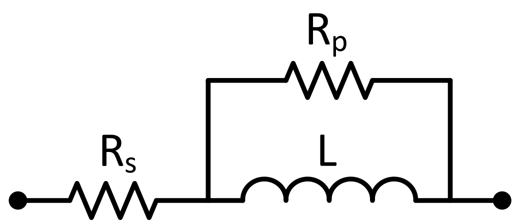
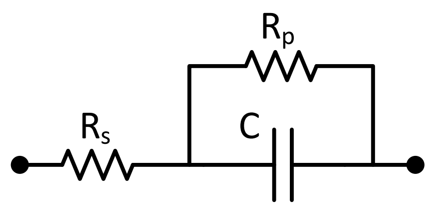
<td>

Permanent magnet or induction motor circuit</td>
<td>

Electrostatic motor circuit</td>
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<td>RR_s: the coil winding resistance results in $i^2 * R_s$ conductor loss and is the dominant source of loss in a magnetic machine, typically accounting for at least 75% of the electrical losses.

R_p: the core loss is caused by eddy currents and hysteresis losses in steel laminations. Core loss can be significant in a magnetic machine, typically accounting for 10-25% of electrical loss.</td>
<td>R_s: the plate resistance is negligible in an electrostatic machine thus eliminating the largest source of electrical losses in traditional machines.

R_p: the core loss in an electrostatic machine is caused by the conductivity of the insulating dielectric fluid and effectively represents 100% of the electrical losses. With a high-performing fluid, electrical losses are typically less than the losses in a magnetic machine of similar rating.</td>
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<td colspan="2">Note: Mechanical losses are removed for conceptual clarity. Mechanical losses for both motor types are included in the graphical comparison section of this whitepaper.</td>
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Figure 1. Simplified equivalent circuit models for traditional electric motors (left) and for an electrostatic motor (right).

III. Graphical Comparison of Motor Losses

To provide a practical illustration, Figure 2 provides a modeled stack-up of relative losses for a 1 HP motor at a speed of 90 RPM (representative speed in conveyors and low speed fans). For induction motors, it is well-established that the mechanism for inducing currents into the rotor from the stator windings is extremely inefficient at low excitation frequencies. To partially work around the poor low speed efficiency of induction motors, designers have widely adopted the practice of specifying high ratio gearmotors (20:1 to 40:1 are common reduction ratios). The gearbox allows the motor to operate at much higher speeds, for example 1800 RPM, where motor efficiencies above 80% are feasible. With a high-performing bevel worm gear, a high ratio gearbox typically achieves 80%-85% efficiency. The resulting combined efficiency is typically in the range of 65-75% for gearmotors with nameplate ratings up to 3HP.

The direct drive permanent magnet motor improves system efficiency by eliminating the need for the mechanical gearbox. In order to achieve high output torque at low speeds without a gearbox, the direct drive permanent magnet motor relies upon an array of rare-earth permanent magnets. The magnets are needed to establish a strong magnetic flux source, and in addition, the motor requires the use of dense copper windings in the stator. Especially due to the use of rare-earth magnets, the end user's cost for a permanent magnet direct drive motor typically exceeds the cost of a gearmotor by a factor 2-3x (gearmotor includes the induction motor and the gearbox).

As shown in Figure 2, the electrostatic motor has no copper winding losses in either the stator or the rotor, thus eliminating the primary source of loss in traditional electric motors. The core losses (i.e., losses in the dielectric fluid) are the dominant loss while the mechanical losses due to viscous drag constitute less than 5% of motor losses at 90 RPM. C-Motive's motors should be operated at shaft speeds below 400 RPM to minimize drag losses and maintain the efficiency advantage enabled by electrostatic technology.

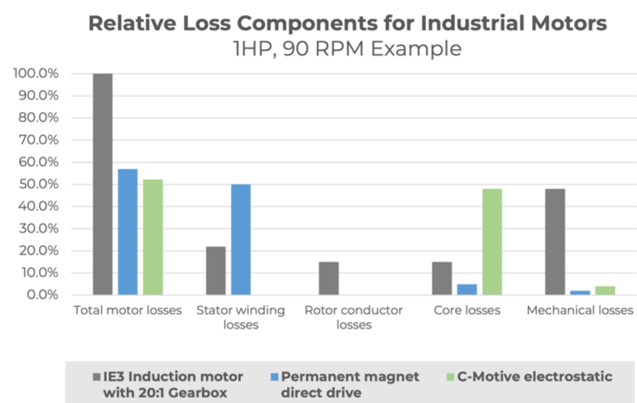

Figure 2. Chart illustrating the loss components in electrostatic motors and traditional motors used in industrial applications.

The graph shown in Figure 3 below shows a typical efficiency curve of a C-Motive motor for a range of shaft speeds. C-Motive has achieved measured motor efficiencies of 85% up to 250 RPM for 1 HP and 2 HP motors, exceeding the efficiency of direct drive permanent magnet motors in this speed range and substantially exceeding the efficiency of induction motors with gearboxes. Continual fluid research and development has the technical potential to further reduce fluid "core loss" and achieve motor efficiencies greater than 90% in low-speed industrial applications.

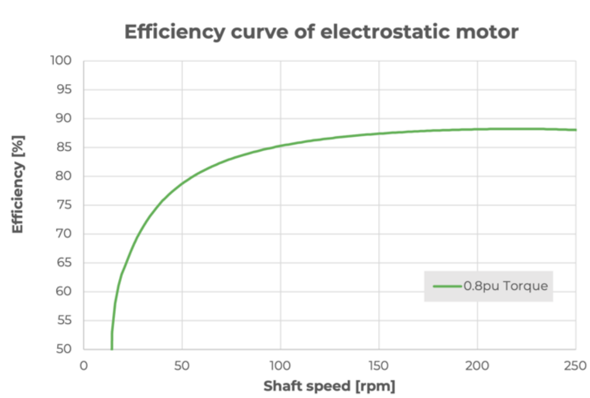

Figure 3. Efficiency curve of a C-Motive electrostatic motor operating at 80% of rated torque.

IV. Summary and Key Take-aways

Below is a summary of the key findings discussed in this white paper:

1. Electrostatic motors have no copper winding losses, thereby eliminating the most costly loss mechanism present in traditional electric motors.

2. The high efficiency of C-Motive electrostatic motors depends only upon a low-cost, non-toxic and biodegradable dielectric fluid. The motor does not rely upon mining-intensive commodities such as permanent magnets, copper windings, etc.

3. Electrostatic motors with fluid insulators do not need a high-ratio reduction gearbox for low-speed applications – thereby eliminating another costly source of loss in applications such as conveyors, positive displacement pumps, and low speed fans.

4. Electrostatic motors with fluid insulators are optimized for applications below 400 RPM where the impact of fluid drag is minimized, and therefore, are not intended for use in high-speed applications.

5. C-Motive has achieved measured motor efficiencies of 85% at speeds up to 250 RPM for 1 HP and 2 HP motors, exceeding the efficiency of direct drive permanent magnet motors and substantially exceeding the efficiency of gearmotors using induction motors. Further learning improvements with the dielectric fluid have the potential to exceed 90% motor efficiency.