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Portescap

How to Optimize Performance and Minimize Size in High Speed Applications

High Performance Brushless DC Motors

I. Introduction

There is a current increasing trend in requests for Brushless DC motors for high speed applications. For instance, new impeller technology changed the way modern respirators are designed to be more compact and quieter. Such performance requires motors that rotate up to 50 to 60 Krpm, and are capable of delivering high acceleration and deceleration in synchrony with a patients breathing pattern.

Other examples are surgical and dental hand tools. They have to be ever-stronger and smaller. One way to achieve this is to use high speed brushless motors that can deliver the necessary power and performance, within the preferred footprint.

Mechanical power is the product of Torque and Speed. To increase power, we can either increase Torque or increase Speed. Generally, for a given technology, the continuous torque is related to the motor size. The continuous torque is often limited by thermal consideration.

For instance at stall or low speed, the only power dissipated by the motor are joule losses.
Let's consider:

T	= Motor Torque
RTh1	= Thermal resistance Coil-Stator
RTh2	= Thermal resistance Stator-Air
K	= Motor Torque Constant
R	= Motor coil resistance
Pj	= Power dissipated by Joule effect
ΔT	= Max coil temperature increase possible
ΔT	$= (RTh1 + RTh2).\ Pj = (RTh1 + RTh2).R.I^2 = (RTh1 + RTh2).\ R.\ T^2/ K^2$

$(RTh1 + RTh2).\ R / K^2$ represents an excellent figure of merits to characterise the motor.

Without considering high speed constraints a motor designer will try to optimize the torque that the motor can dissipate for a given power. The figure of merits R/ K^2 is a good factor to characterise a motor. The smaller the value is, the better the motor. A good motor should have a small resistance and a high torque constant.

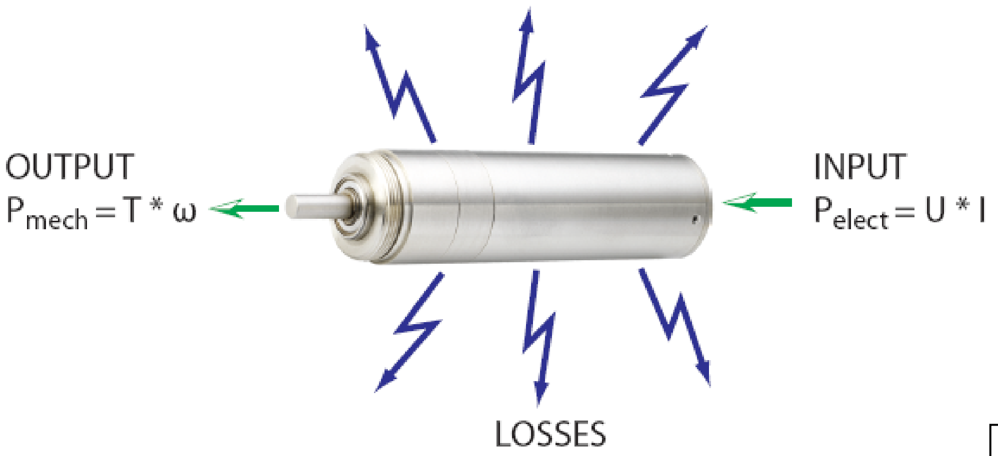
Since the torque constant depends on the magnetic circuit, the objective during motor design is to have the maximum flux generated by the magnet going through the winding. One way to increase the torque constant, is to use stronger magnets, such as NeoFe which today are close of 50 MGoe.

In order to decrease the joule losses, the objective is to have a wire section as large as possible, hence the lowest copper resistance.

After optimization of R/K^2, maximum torque is still limited for a given motor size by its thermal limitation. Consequently, the other parameter to increase the power is to increase the speed.

In theory it seems easy to increase the speed by simply increasing the voltage of the power supply. However, increasing speed will generate more heat due to:

- Iron losses
- Bearing friction losses
- Current ripple creating losses

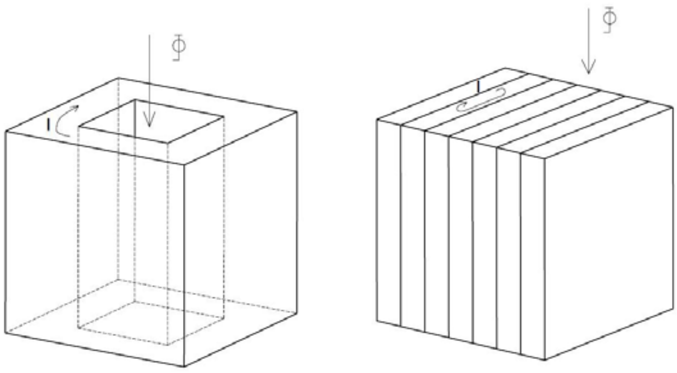


Copper losses (Joule losses):
The copper loss varies with the load in proportion to the current squared.

Mechanical Losses:
Mechanical losses includes friction in the motor (bearings and brushes).

R: winding resistance (Ohm)
I: current (A)
ω: angular velocity (rad/s)
T: torque (Nm)
U: power supply voltage (V)

Iron losses due to Eddy current are the losses generated by the current circulating in the lamination t created by the magnetic flux.



Eddy current in laminations

Let's consider:

Φ = magnetic flux

B = Induction in the iron

$\Phi = \iint B dS$

A flux variation will generate a current inside the material like a transformer does in its secondary coil. The equation for this current I is:

$$O = RI + \frac{d\Phi}{dt}$$

I = current within the iron

R = Resistance of the iron

Iron losses due to Eddy current are = $RI^2 \cong \chi . B^2.w^2$

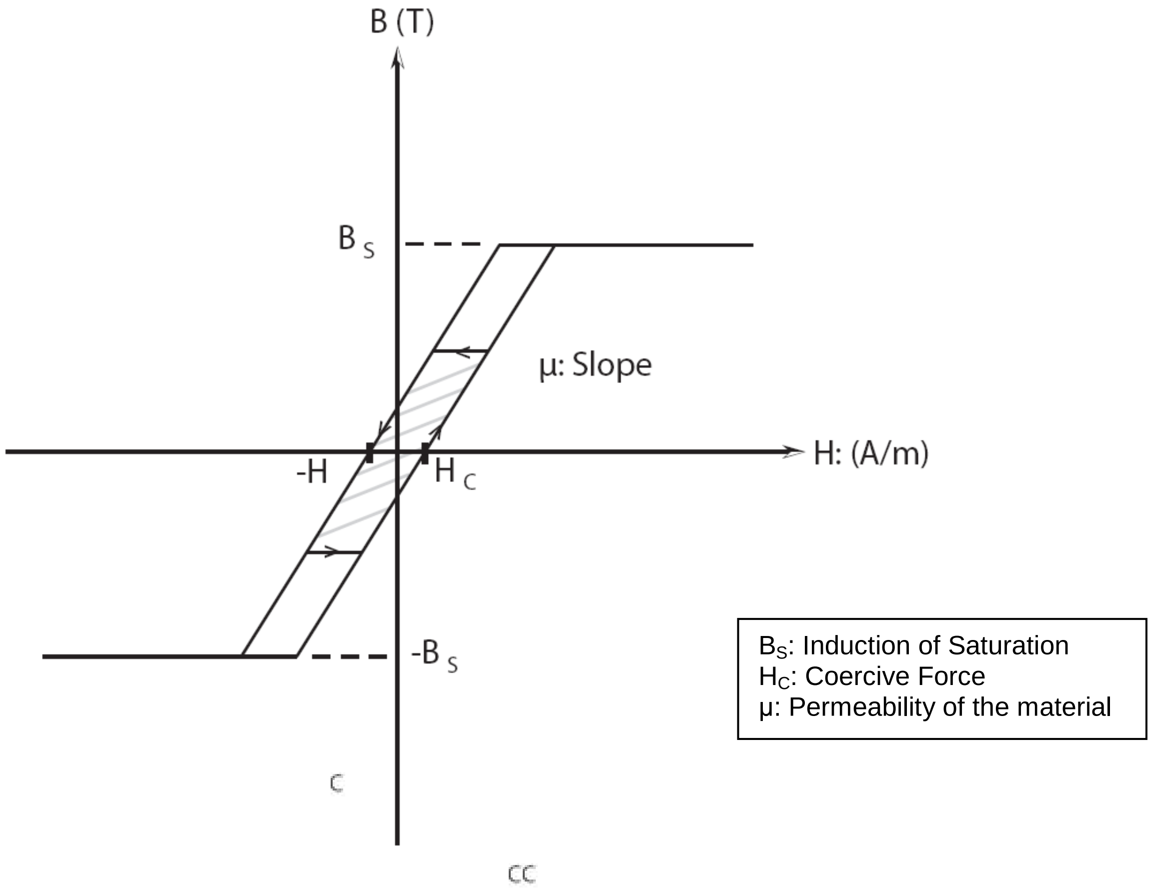
χ is a parameter linked to design and to the material use.

Iron losses due to Eddy current will depend on square of the induction in the iron and on the square of the frequency.

To decrease iron losses we will use thinner laminations with high electrical resistance.
The thinner the laminations are, the longer the current loops are, which increases the resistance of the circuit.

Iron losses due to Hysteresis

The magnetic material used to conduct the magnetic field is presenting Hysteresis. The induction within this material follows a cycle as described in the figure below.



Hysteresis Curve of Soft Magnetic Material

The losses due to the hysteresis in the material are of the type:

$P\ hyst = \int H dB$

Therefore,

$Physt = \mu.\lambda.B^2.w^2$

With μ which is related to the permeability of the material used, λ parameter linked to material volume and coercivity. For motors designed for high speed, we will use material having small coercive field such as Fe Ni

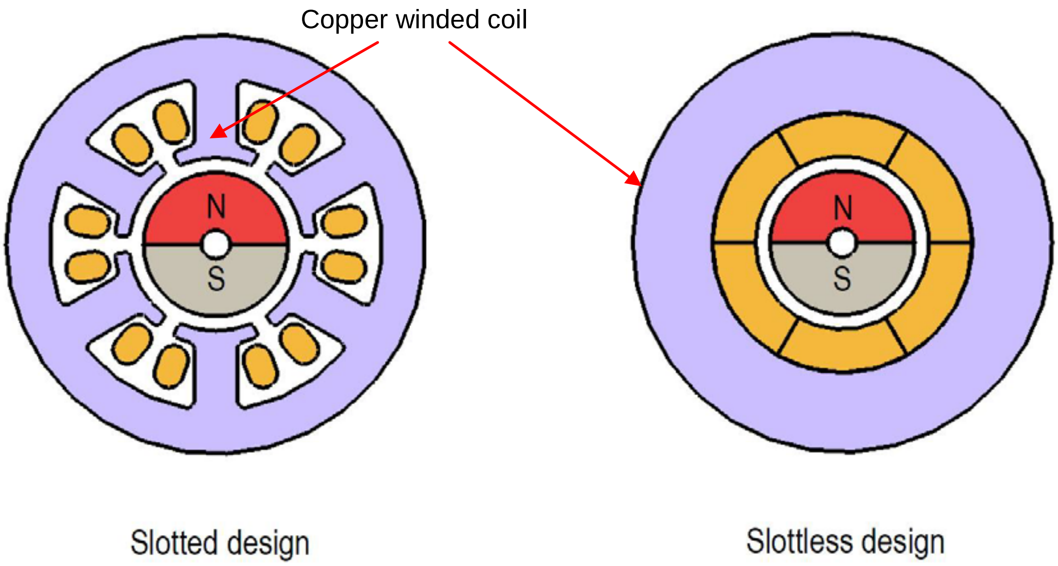
As described before, iron losses depend on square of the induction in the iron laminations and on the square of the frequency. For this reason, generally, motors having a high number of pole-pairs will have speed limitations. In many cases, according to the design, a motor with 2 pole-pairs will have more iron losses than a motor having 1 pole pair, but it's likely that this motor will have a better
R/K^2 .

II. <u>Optimization of a Brushless DC motor for High Speed applications</u>

A- Different types of Brushless DC Motors

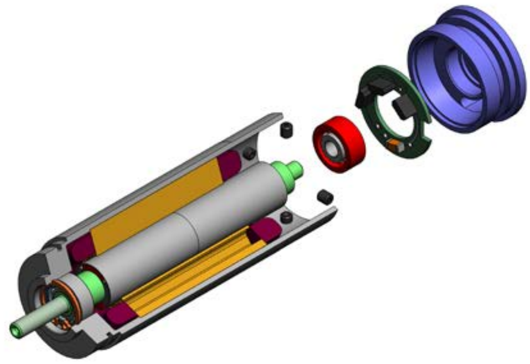
In terms of technology, there are two major types of Brushless DC motors, slotted and slotless. This Notation refers to the configuration of the motor stator.

The following drawing illustrates slotted and slot-less stator designs.



Motor Design

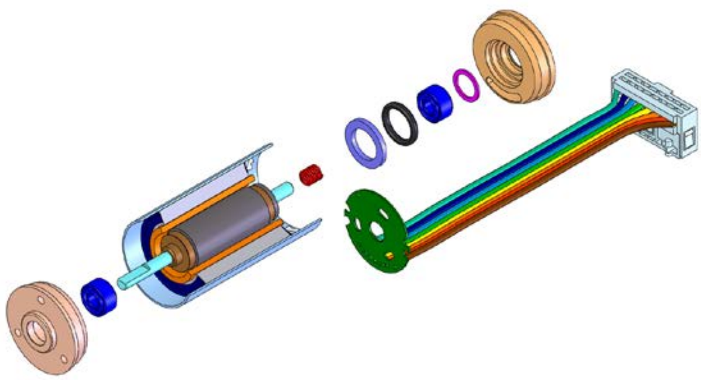
Slotted stator motors.



The coils are wound within the slots. Magnetic induction in the lamination is pretty high since the air gap between the laminations (stator) and magnet is small. Therefore, we can use a small magnet diameter. The volume of the copper is limited by the slot space and by the difficulty to wind within the slot. Having the coil inside the stator slots offers the advantage to reduce the thermal resistance of the coil/stator assembly

Without current the rotor has preferred magnet positions in front of lamination, generating a cogging torque or detent torque. One way to decrease the detent torque is to skew the lamination. The slotted motor by design is very robust as the coil is inserted in the lamination. By design it's possible to build motors having a large ratio length / diameter.

Slotless stator motors



In a slotless motor, the coil is wound in a separate external operation and is of the "self-sustaining" type (see picture below). This coil is then inserted directly into the air gap, during motor assembly.

In this design, the magnetic induction in the coil is decreasing since the air gap is increasing. Therefore, the motor diameter is usually optimized to have the ideal magnetic induction with the optimum copper volume. Usually, by design induction in such motor is much smaller than in a slotted brushless motor. A larger magnet is usually used to compensate for the loss of induction. Since the inertia of a rotor follows the square of its diameter, the inertia in a slotless motor is usually higher than the slotted motor.

In term of R/K^2, a slotless motor has a good figure of merits since induction versus copper volume is optimized. Without circulating current, the rotor sees a continuous permeance, therefore a slot-less motor doesn't have any cogging / detent torque. By design, iron losses at high speed in slotless motors are greatly reduced.

<u>Comparison sheet</u>

Performance Indicators	Slotted Design	Slotless Design
R/K^2		Advantage: slotless with new magnets and new winding technology
RTh^1	Advantage: slotted Better heat dissipation: coil-stator	
RTh^2	Same	Same
Inertia	Advantage: slotted due to the smaller air gap allowing smaller magnet diameter.	
Iron Losses		Advantage: to slotless due to smaller induction in lamination
Resistance to Mechanical and Thermal shocks	Advantage: slotted. The coil being inserted in the lamination	
Impact of new magnets on Design		Advantage: to slotless. Stronger magnets meaning larger air gap.

Depending on the application requirements, Portescap has the advantage to be able to recommend either slotted or slot-less motors, for optimum performances: Maximum torque, reduced heat, increased efficiency, reduced vibrations among others.

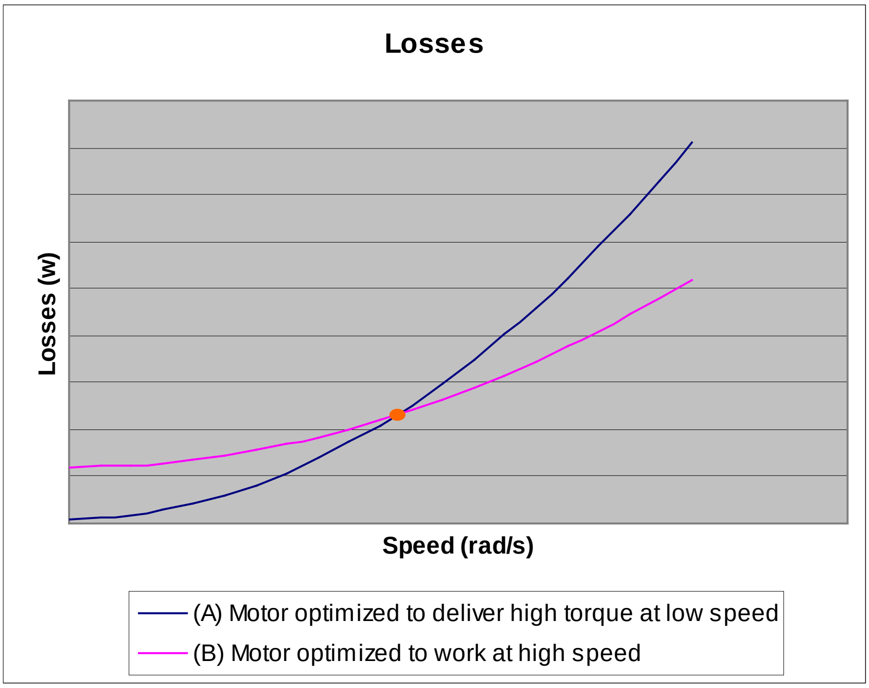
B- Optimization of the motor for high speed application

We have previously covered the different types of motor technologies, but both are following the same physics equations.

In fact, to obtain torque, we should consider a motor having a good R/K^2. As we know, this figure will increase if we increase the induction generated by the magnet. Although we have also seen that the iron losses are depending on the square of the induction as well as the square of the rotor speed.
The figure below illustrates 2 motors:

A. A motor having a strong R/K^2 dissipating low losses at low speed (mainly joule losses), but high losses at high speed (joule losses + iron losses).
B. A motor having a lower R/K^2

During the optimization phase, our design engineers will optimize the losses according to the working point of a given application. The working point is defined by Torque and Speed.



III. Examples of applications.

- High speed motors for respirators.

Blower with motor for respiratory device

A motor in such application has to be able to ramp from few thousand rpm up to 50 Krpm in few milliseconds in synchrony with a patient's breathing pattern. The torque needed to spin the impeller is in the range of few Oz inches. Most of the torque is used to accelerate and decelerate the

impeller. Controlling motor temperature is critical for the environment (the air inhaled by the patient), but also for the life of the ball bearings within the motor.
Portescap, pioneer in ventilation motors, has recently developed a new motor family for this specific application where joule losses versus iron losses have been optimized to fulfil the ever more stringent needs.

- Motors for surgical hand tools.

Motors for surgical hand tools have to run at high speed to produce power in a light weight package, run at low temperature for surgeon comfort, and in addition have to be able to survive the autoclave sterilization process.

Optimization of the magnetic circuit has allowed Portescap to design a 16 mm diameter motor capable to deliver few Oz.in of torque at a speed of up to 80,000 rpm without exceeding 43°C on its housing.

Portescap's 20+ years experience in the making of Autoclavable motors has lead to a design that its customers have reported to be able to remain fully functional within their surgical hand tools through excess of 1,000 autoclave cycles.

IV. Conclusion

Electric motors are continuously evolving with the constant release of new material in the market. Today, NeoFe magnets are reaching 50 MGoe and new lamination materials offering limited losses, allow the use of electric motors at very high speed. For each application it's crucial to understand in detail the specifications in order to offer the optimum design, Portescap has developed few motor technologies in order to be address each application with an optimal solution.

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