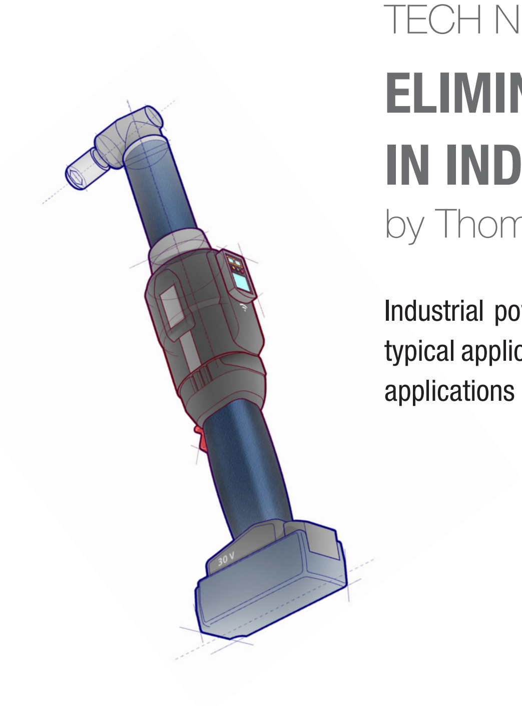
TECH NOTE

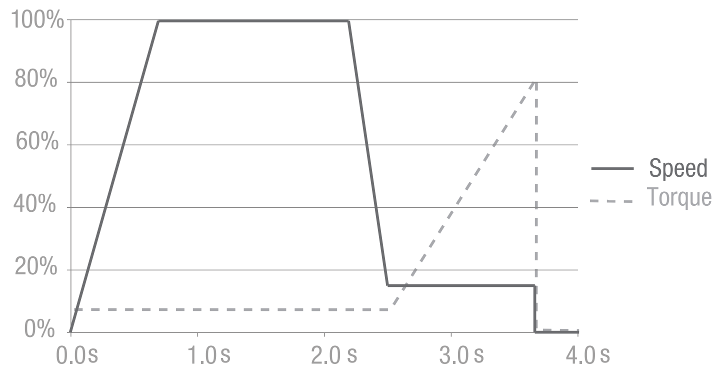
ELIMINATE DESIGN COMPROMISES IN INDUSTRIAL POWER TOOLS

by Thomas Baile



Industrial power tools (IPT) have an operating profile quite different from other motor-driven applications. A typical application requires torque output from the motor throughout the motion. Fastening, gripping and cutting applications have a specific motion profile split into two phases, as shown in the below graph:

TYPICAL WORKING CYCLES FOR INDUSTRIAL POWER TOOLS REPEATED CONTINUALLY



Speed Phase

At first, there's little resistance as the bolt threads in, or as the jaws of a cutting or gripping tool approach the work piece. During this stage, a motor that operates at a faster free run speed saves cycle time and boosts productivity.

Torque Phase

Then, when the tool performs the more forceful work of tightening, cutting or gripping, the need for torque becomes paramount. A motor that delivers high peak torque can perform a wider range of tough jobs without excessive heating.

These alternating speed and torque cycles must be constantly repeated in demanding industrial applications. Applications will require different speed, torque and duration, calling for a special motor design that minimizes the losses to achieve the best solution possible. It's even more critical for battery operated devices, which run on low voltage and have limited power available.

How to Select and Optimize the Optimum Motor

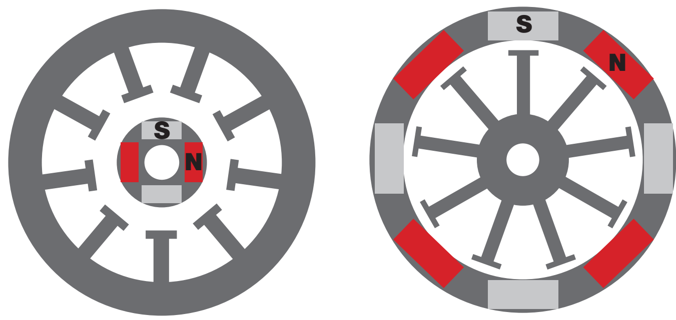
To select and optimize the optimum motor for handheld industrial power tools, we need to first review the motor technology. Let's consider Brush and Brushless DC motors as our primary selections.

Battery powered industrial power tools run on low voltage (12-60 V). Brushed DC motors are typically a good economical choice, but the life of operation of the motor will become an issue. The brushes will see wear because of electrical (due to the current related to torque) and mechanical (due to the friction related to speed) factors, limiting the number of cycles until end of life is reached. Brushless DC motors are a more reliable motor solution. They are less susceptible to mechanical wear (no brush friction) and can sustain high peak current (no brushes) during the tightening phase, providing far greater life in the hand tool. Brushless DC motors are better suited than brush DC for industrial power tool applications since they require high speed and high peak current.

Brushless DC motors can be constructed in different physical configurations:

- In the conventional (also known as inrunner) configuration, the permanent magnets are part of the rotor with three stator windings surrounding the rotor.
- In the outrunner (or external-rotor) configuration, the radial-relationship between the coils and magnets is reversed. The stator coils form the center (core) of the motor while the permanent magnets spin within an overhanging rotor which surrounds the core.

Cross Section of In/Outrunner Design Motors



The inrunner motor configuration is better suited for hand-held industrial power tools, due to the reduced inertia, lower weight and lower losses. Thanks to the longer length and smaller diameter, its outline form is more ergonomic and easier to integrate into hand held devices. Additionally, a lower rotor inertia brings better tightening and gripping control.

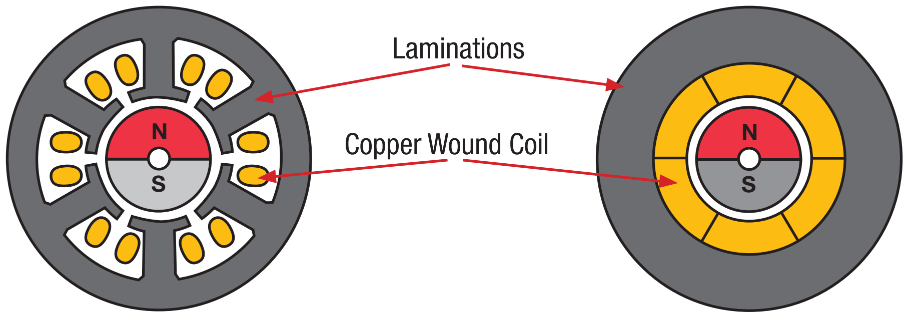
Slotted Motor Coil

Slotless Motor Coil

Brushless DC windings can be constructed in different physical configurations:

- Slotted stators. The coils are wound within the slots around the stator. Magnetic induction in the lamination is 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 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 the lamination, generating a cogging or detent torque. One way to decrease the detent torque is to skew the lamination. The slotted motor by design is robust as the coil is inserted in the lamination.
- Slotless stators. In a slotless motor, the coil is wound in a separate external operation and is self-sustaining (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 a motor is much smaller than in a slotted brushless motor. A larger magnet is typically used to compensate for the loss of induction and may impact the rotor inertia. In terms of power density, a slotless motor has a good figure of merit (R/K^2 - the ability to maintain speed under load, lower is better) since

induction versus copper volume is optimized (slopped curve). Without circulating current, the rotor sees a continuous permeance, therefore a slotless motor doesn't have any cogging or detent torque. By design, iron losses at high speed in slotless motors are greatly reduced.



The slotted design can handle higher temperatures (200 degC) than the slotless design (150degC), thus allowing more torque generation. However, most of the time, the limiting factor in power hand tool usage is the maximum temperature over time (~47deg C max) which is the comfort level of the operator. Indeed, heating over time becomes uncomfortable for the operator holding the tool. Safety regulations also require the maximum temperature to be held lower.

The slotless technology is better suited for most industrial power tools, thanks to the smaller induction in laminations yielding no iron-losses.

	Slotted BLDC	**Slotless BLDC (Ultra EC™)**
Pros	• Small thermal resistance (Coil/casing) • Maximum speed in excess of 100krpm • Fully customized motors • Hipot capability (up to 2500V) • Torque	• Smooth operation & no cogging • Little iron losses @ high speed: low temperature and easier control • Low noise & vibration • Winding flexibility
Cons	• Cogging • No standard products	• Autoclavable option not available • High thermal resistance

The electrical performance of a motor is defined by the magnetic circuit. The first component, the magnet, has a fixed value. However, the second component, the copper winding, can be easily modified. By changing with the wire diameter and the number of turns, the torque constant "k_t" and Resistance "R" can be fine tuned.

Fine Tuning the Torque Constant

k_t selection for torque and speed

Let's analyze the industrial power tool operating profile more in detail and the challenges for the motor winding design:

Speed phase: the motor needs to run fast with little resistance:
$\omega = (U - R * I) / k_t$
ω (Speed in rad.s^{-1})
U (Voltage in Volts)
R (Resistance in ohms)
I (Current in Amps)
k_t (Torque constant in Nm/A)

Since the torque constant is in the denominator of the calculation, the lower the k_t, the higher the speed. This allows more operations in the same time period which boosts productivity.

Torque phase: during the second phase, the motor is expected to deliver peak torque at low speeds. As per the laws of physics, the torque is the product of the torque constant and current

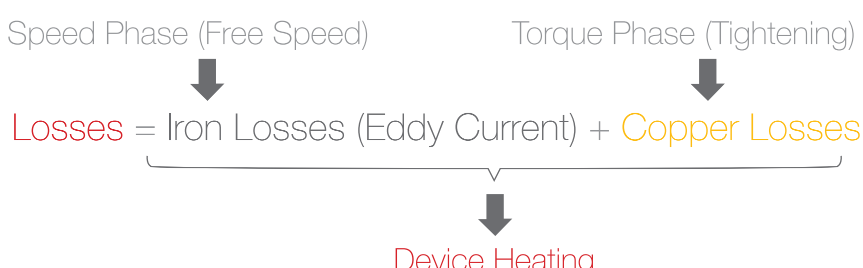
$$C = k_t * I$$

C (Torque in Nm)
I (Current in Amps)
k_t (Torque constant in Nm/A)

The higher the k_t, the higher the output torque at a given current.

By adjusting the k_t of the motor winding, the designer can optimize either the speed or the output torque in order to find a good balance between torque and speed to reduce the overall working cycle time. There is no unique solution: k_t has to be chosen as the best compromise for a range of working profiles. Motor design experts can support you in this coil design process based on simulations and experience.

Reviewing Thermal Losses During the Industrial Power Tool Operating Cycle



Copper Losses and Torque
We might think to select a low k_t value to increase speed, and compensate the low k_t with more current (I) to reach higher output torque. However, a higher current would increase the copper losses.

$$\text{Copper losses} = R * I ^ 2$$

The higher the current, the faster the motor and handtool would heat, thus limiting the maximum torque available. The motor should be designed to draw as low a current as possible to limit the heat dissipation (handheld unit temperature affecting productivity) and conserve battery life.

Iron losses and speed

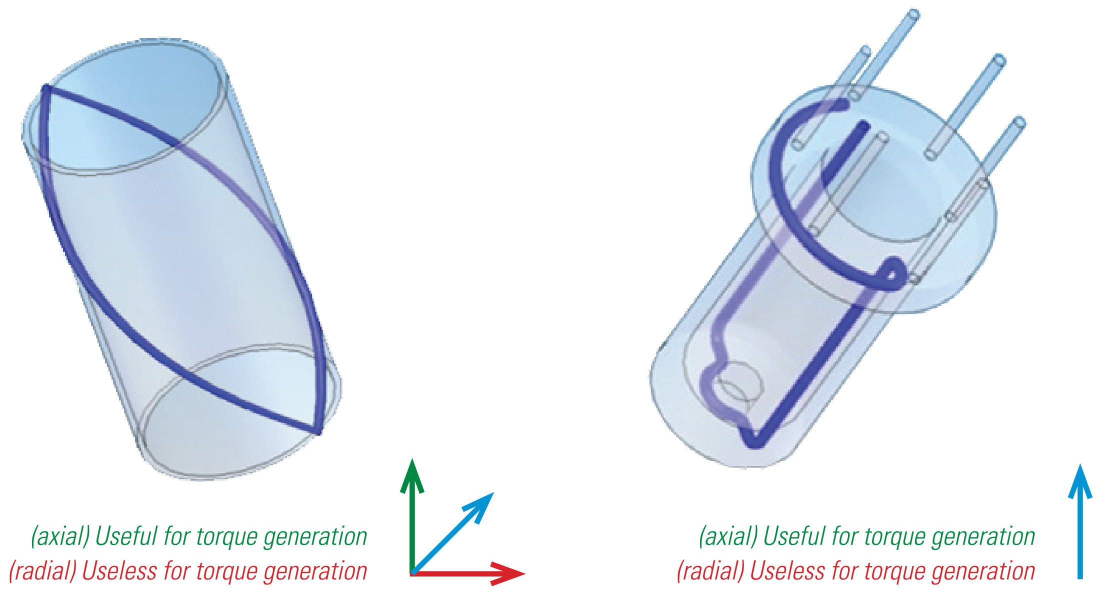
The iron losses are related to speed. Eddy current losses increase with the square of speed, heating up the motors simply when rotating - even in a no-load condition. High speed motors need special design precautions to limit eddy current heating.

Innovation And Optimization of Motors for Industrial Power Tools

To provide the optimum solution, Portescap engineers have developed the new Ultra EC™ brushless slotless motors with a revolutionary patented U coil technology.

First, copper losses are reduced because unlike a typical slotless skewed winding, the Ultra EC is wound parallel to the motor axis, maximizing perpendicular magnetic force, thus developing more power.

Schematic - winding force - straight spire vs skewed spire + graph sinus force k_t



Second, by design, iron losses at high speed in slotless motors are greatly reduced. With this straight winding, Ultra EC motors have a shorter rotor length compared to the skewed winding, which allows for a lower rotor inertia and reduced iron losses.

This revolutionary new design optimizes speed and torque in a compact package for the most challenging applications. Fasteners, grippers and cutting tools can all benefit from this increased performance, lower weight and greater energy-efficiency.

Features

- Straight turns
- Inner and outer heads
- Special output to prevent loose wires
- Axial and radial forming

Benefits
- Greater efficiency of copper turns, minimized joule losses
- Optimum package size
- Maximized useful volume of copper
- Stronger coil integrity
- Perfect integration into motor design
- Ability to reach a wide range of torque constants

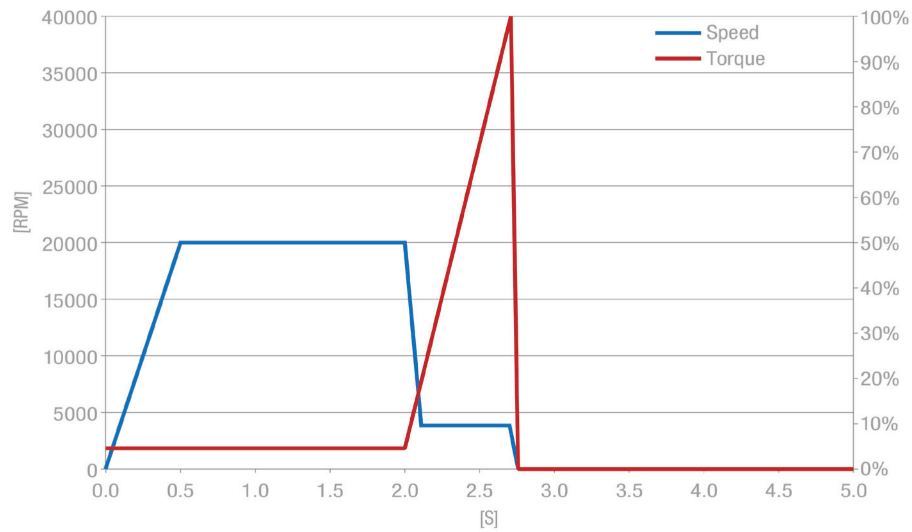
Benefits of the Ultra EC Winding in an IPT Application

In this paragraph we will review the impact of Ultra EC on motor performances in typical industrial duty cycles.

Working conditions:

Average duty cycle: free speed during 2s at medium speed

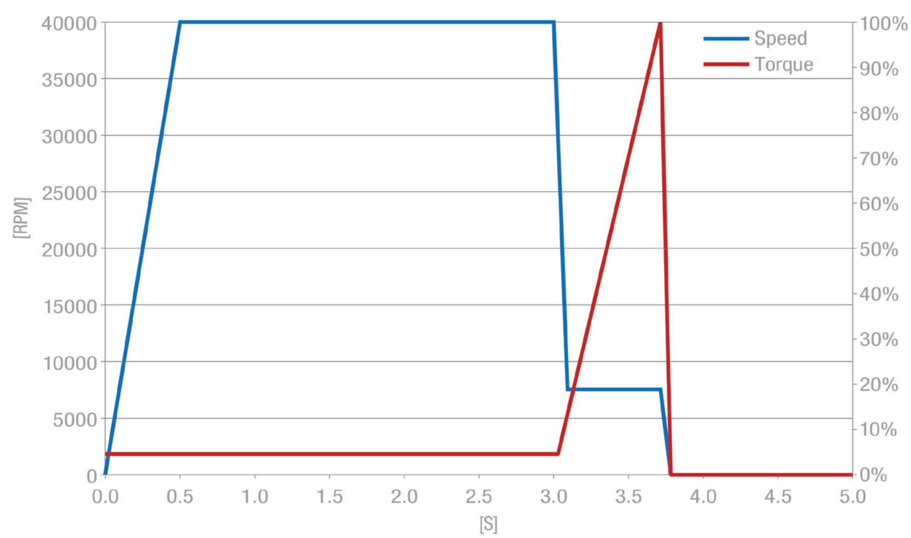
Example: pruning shear, nutrunner, gripper, stapler



Speed: 20,000 rpm – 2s Torque 0.84Nm

Heavy duty cycle: free speed during 3s at high speed

Example: automotive nutrunner optimized for productivity

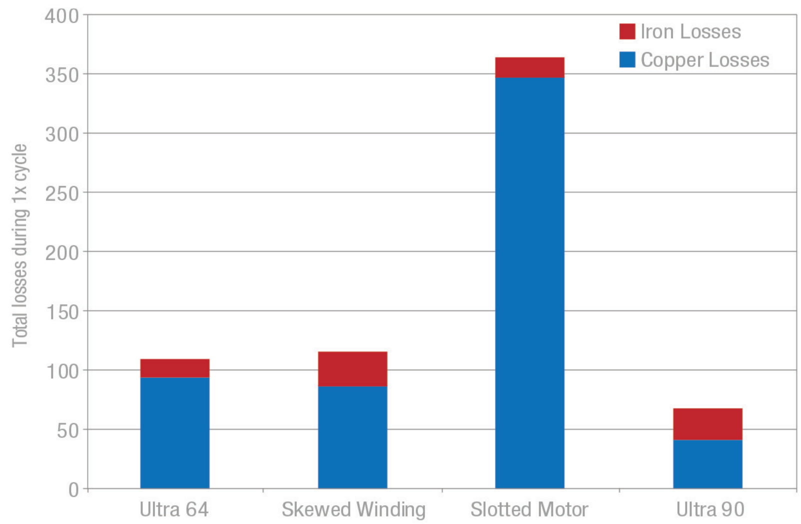


Speed: 40,000 rpm – 3s Torque 0.69Nm

Average Duty Cycle – Motor Comparison

Let's compare motor performances during the average duty cycle:

Motor	Ultra 64	Skewed winding	Slotted motor	Ultra 90
Dimensions Diam * L (mm)	30 * 64	30 * 64	28.5 *88.5	30 * 90
Pole number	4	4	4	4

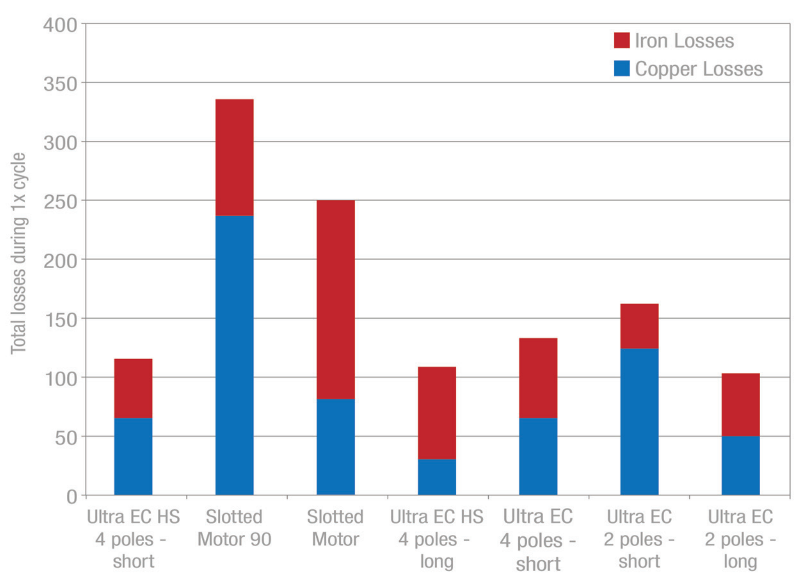


We observe the straight coil (Ultra) is more efficient (less losses) in comparison with either skewed winding or a slotted motor.

Heavy Duty Cycle – Motor Comparison

Let's compare motor performances during the heavy duty cycle:

Motor	Ultra 64 HS	Slotted motor 90	Slotted motor 100	Ultra 90 HS	Ultra 64	Ultra Speed 60	Ultra Speed 80
Dimensions Diam * L (mm)	30 * 64	28.5 *88.5	34*99	30 * 90	30 * 64	35 * 60	35 * 80
Pole number	4	4	4	4	4	2	2



We observe higher iron losses, because the speed is doubled. The straight coil (Ultra) is still more efficient (less losses) in comparison with either skewed winding or slotted motor.

Conclusion

By boosting the speed, the iron losses are quickly going to generate more losses than the copper losses. Therefore, the design of the winding should be tuned for each duty cycle in order to optimize the losses. Thanks to the Ultra winding technology, iron and copper losses are greatly reduced allowing more flexibility for the designer.

About Portescap

For more than 25 years, leading manufacturers have relied on Portescap's innovative products, expertise and support to develop advanced corded tools and transition successfully to battery-powered tools while improving quality control, flexibility and error-proofing. Portescap innovation has enabled the transition from pneumatic to electric tools while setting the performance standard for industrial power tools. In 2013, Portescap patented the first Ultra EC™ coil, the next generation of power and performance.

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