Improve Thermal Performance for Ironless Brush DC and Brushless DC Motors

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Designers of motor-driven systems must account for thermal issues that can hinder a system's performance and efficiency. As a motor converts electrical energy into mechanical energy, power losses occur, and those losses tend to be higher in magnitude when the delivered mechanical power is larger. Inside the motor, thermal energy creates a temperature rise that will result in a heat transfer from warmer to colder due to conduction and convection. Eventually the heat carries outside the motor.

This article will examine heat transfer and mitigation conditions and challenges for both ironless brushed and brushless DC motors. Understanding these considerations will help ensure you select the best DC motor design for your application.

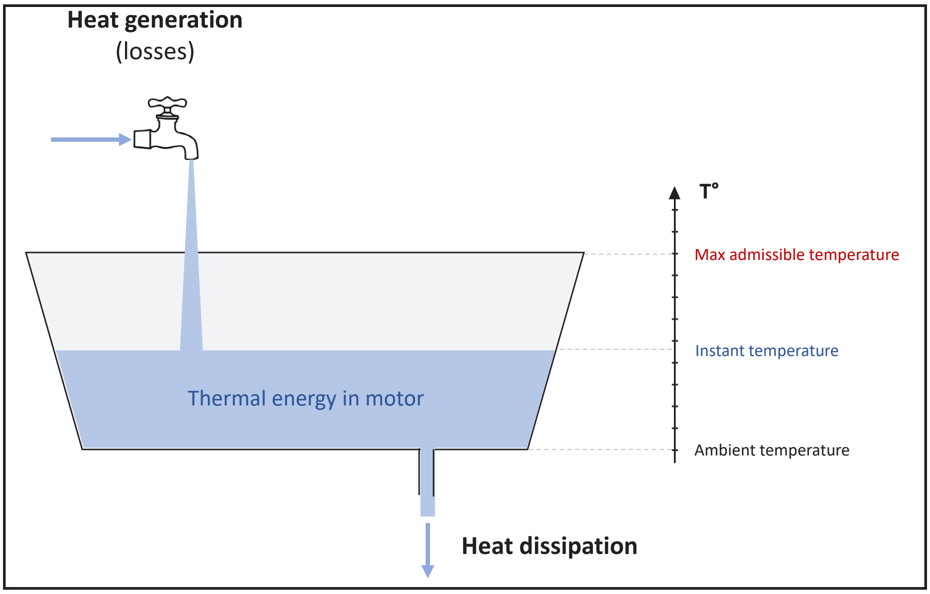

Figure 1 Heat transfer in a motor is analogous to adding water to a bathtub that is simultaneously leaking.

Thermal Phenomena Dictates Motor Performance

Electric motor manufacturers must ensure that the internal temperature of the motor never exceeds its various components' maximum allowable temperature. Depending upon design and materials used, the thermal phenomena will dictate motor performance. When it comes to improving performance without overheating and damaging internal components, designers typically have two options:

- Minimize the losses: Improve power conversion efficiency by generating less heat for a given mechanical power output, thus delivering greater mechanical power without affecting heat.
- Improve the motor's ability to dissipate heat by leading the generated thermal energy to its surrounding environment so that the internal temperature rise lessens. This allows greater thermal energy creation for the same internal temperature rise.

Heat transfer in a motor can be compared to adding water to a bathtub that is simultaneously leaking (Fig. 1).

Water flow from the faucet corresponds to the thermal energy generated inside the motor. As soon as water collects in the bathtub, the pressure at its bottom will cause water to leak, similar to heat dissipation. The higher the water level, the higher the pressure at the tub's bottom and, therefore, a greater flow of leaking water.

Similarly, heat dissipation of a motor is proportional to the delta between the inside temperature of the motor and the outside, or ambient, temperature. But as water flow depends on the diameter of the outlet hole, heat dissipation also depends on thermal resistance, which defines the difficulty involved in transferring heat out of the motor. The lower the thermal resistance, the easier and faster the heat will carry outside the motor, as shown in Equation 1:

$$P_{dissipated} = \frac{T_{motor} - T_{amb}}{R_{th}} \quad (1)$$

where:

- $P_{dissipated}$ Heat dissipation power (W)
- T_{motor} Motor internal temperature (K)
- T_{amb} Ambient temperature (K)
- R_{th} Thermal resistance (K/W)

A bathtub has a finite capacity and will overflow if its water level is exceeded. Similarly, motor components have a given thermal capacity. When the motor's internal temperature exceeds a certain level, components can suffer damage within seconds. The motor's rated performance must also meet the requirement of maintaining a temperature within the allowable operating range.

The coil is typically the motor's most critical component since this is where Joule heating occurs. Excessive temperatures will cause the insulation coating around the copper wire to melt and permanently harm the motor.

Steady-State Operation: Ironless Brush DC Motors

A coreless brush DC motor is typically designed as a self-supporting coil rotating in the air gap between a permanent magnet and the housing, which are both part of the stator.

The joule heating power produced in the rotating coil is directly linked to its electrical resistance and to the current running through it. There is no iron loss since the rotor is ironless, as seen in Equation 2:

$$P_{joule} + R \times I^2 \quad (2)$$

where:

P_{joule} Joule heating power
R Electric resistance of the coil (Ω)
I Electric current flowing in the coil (A), depending on the torque constant of the motor and on the load torque.

As the coil temperature rises, heat transfers in two steps: from the coil to the tube, and from the tube to the ambient environment (Fig. 2). These two steps have different thermal resistances since individual materials have distinct thermal conductivities, and the shape, mass and surface area of each part also influence heat transfer.

Heat generation and dissipation are balanced at steady-state. Assuming the electrical current flowing through the coil is not excessive, the coil temperature will rise and the heat dissipation will increase up to a point where heat dissipation and heat generation will be balanced. At this point, the thermal energy in the motor is constant over time and component temperatures will no longer vary.

Similar to the bathtub simultaneously losing exactly as much water per second as the faucet is adding, the coil stabilizes at a certain temperature as the water level stabilizes at a given height. Should the coil temperature be slightly above this stabilized value, the slightly increased dissipation power will allow the temperature to return to the stabilized value and reach steady state.

It is possible to calculate the steady temperature of the coil as a function of the electric current, the electric resistance, the thermal resistances and the ambient temperature, since the heat dissipation is balanced with heat creation at steady state (Eq. 3):

$$P_{Joule} = R \times I^2 = \frac{T_{coil} - T_{amb}}{R_{th1} + R_{th2}} = P_{dissipated} \quad (3)$$

$$T_{coil} = R \times I^2 \times (R_{th1} + R_{th2}) + T_{amb}$$

Electrical resistance increases as the temperature rises. Considering that the electrical resistance of the coil depends on its instant temperature, and that the coil temperature is now much higher than the ambient temperature, the real electrical resistance of the coil at a given temperature must be taken into account (Eq. 4):

$$R_{Tcoil} = R_{22} \times (1 + \alpha \times (T_{coil} - 22)) \quad (4)$$

where:

R_{Tcoil} electrical resistance of coil (Ω)
R_{22} electrical resistance of coil at 22°C (Ω)
α temperature coefficient of resistance for copper (0.0039/°C)
T_{coil} coil temperature (°C)

Over time, depending on the thermal time constant, the coil temperature increase slows down until it reaches its final steady-state temperature (Fig. 3). If the electric current is now higher due to, for example, a heavier torque load, the coil stabilizes at a higher temperature. The highest acceptable stabilized coil temperature must not exceed the coil's maximum allowable temperature as specified by the copper wire manufacturer. This defines a maximum electric current value that can be back-calculated with the previous formula, which is usually referred to as "rated current" or "maximum continuous current" in motor specifications. Because torque and current are proportional if there isn't saturation, it also defines the "rated torque" or "maximum continuous torque."

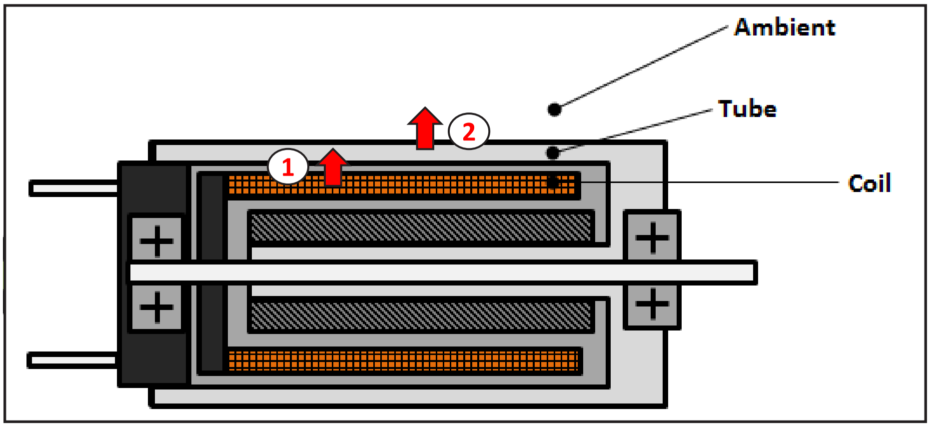

Figure 2 Heat dissipation in a coreless brushed DC motor.

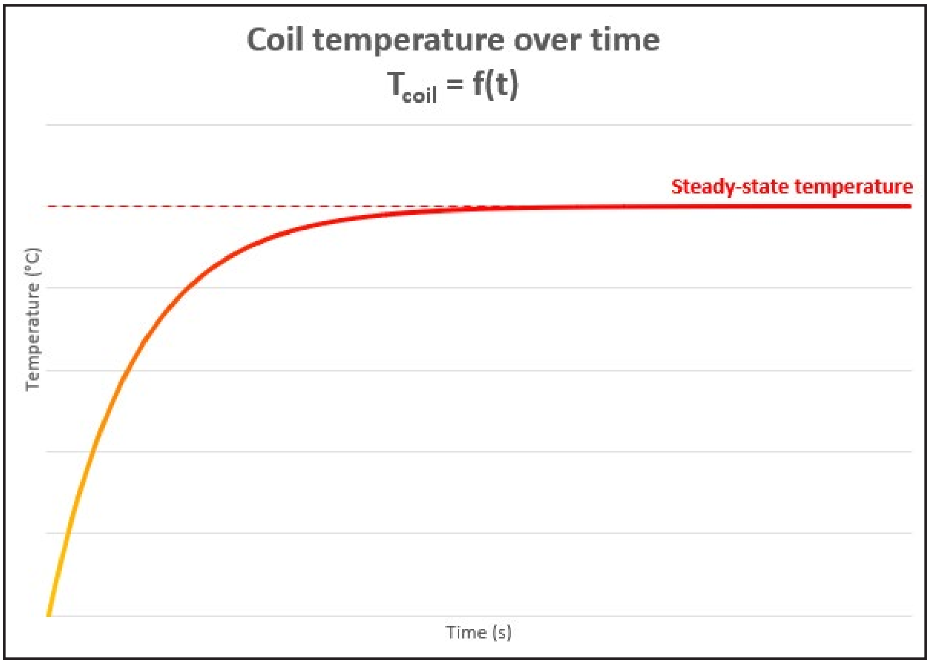

Figure 3 The coil temperature stabilizes at a given temperature when the current is constant over time.

Steady-State Operation: Brushless DC Motor

Brushless motors use the same working principle as brushed motors: Laplace force applied to an electron moving in a magnetic field. The brushless motor is different in two ways: the coil is fixed in the stator, and the permanent magnet rotates with the shaft. Phase commutation is performed electronically (Fig. 4).

Iron losses also create heat inside the motor. When a moving magnetic field interacts with the stator, which contains iron laminations in order to close the magnetic field inside the motor, iron losses occur. Iron losses are caused by current circulating in the lamination created by the magnetic flux and create heat inside the stator, adding to the joule heating already produced in the coil. Since iron losses are proportional to the motor speed, they can be neglected at low speed. However, they tend to become greater than joule losses at high speed. Therefore, the torque must be kept lower at high speed.

Returning to the water analogy, the bathtub would be supplied by two water sources: one depicting joule losses and the other iron losses (Fig. 5).

Brushless motors can reach much higher speeds than brushed motors because they are not limited by a mechanical brush-collector commutation system. The split between the two heating sources can be seen as a trade-off between joule losses at high torque and low speed, and iron losses at high speed and low torque. However, the thermal challenge remains the same: keep the coil temperature below its maximum, allowable temperature.

Thermal Resistance Impacts Motor Performance

When heat travels from the coil to the outside environment, one thermal resistance is intrinsic to the motor design and the other depends on both the motor's design and surroundings. Creating a contact between the motor and another body having a high thermal conductivity will help the motor dissipate heat and operate at a cooler temperature. Options include:

- Wrapping the motor body with an additional tube or sleeve.
- Adding an air flow around the motor body to promote convection.
- Mounting the motor front face onto a metallic body.

Depending on the configuration and more importantly the material thermal conductivity, those surrounding elements can either help or prevent the

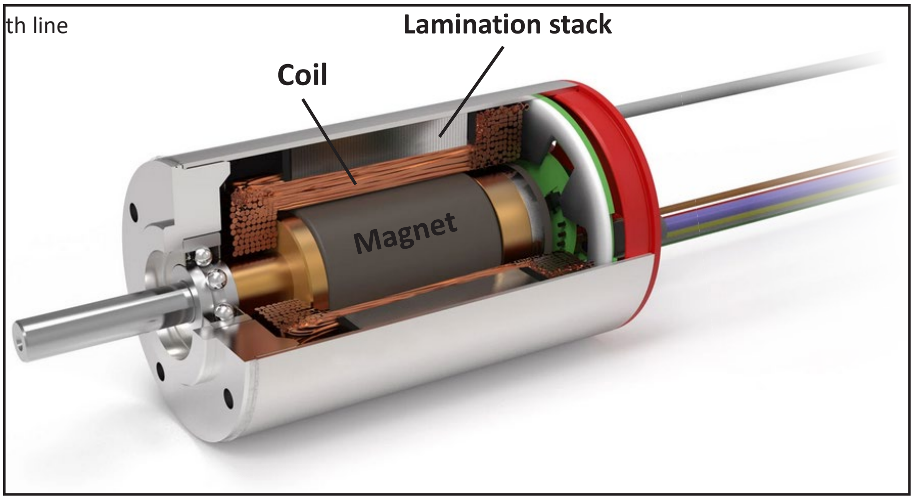

Figure 4 Brushless DC motor construction.

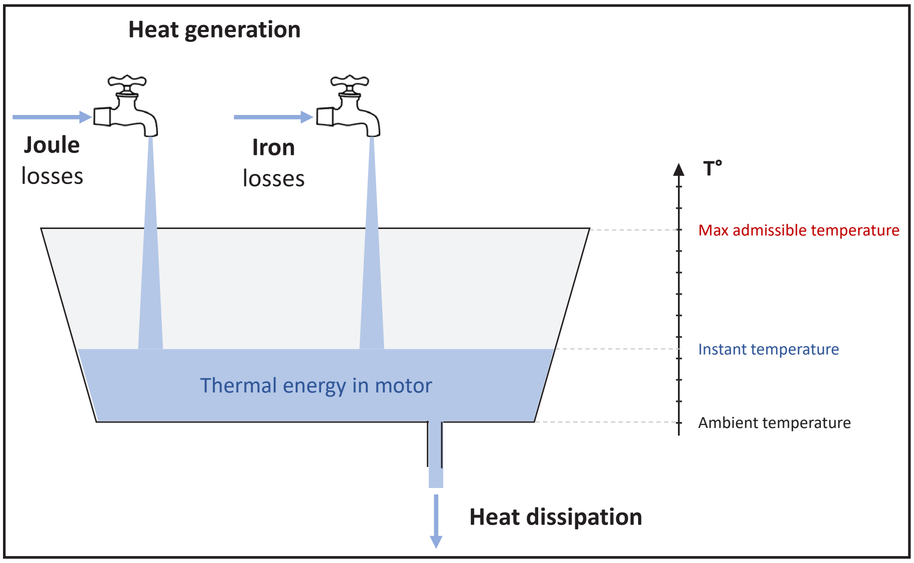

Figure 5 A water analogy depicting heat transfer in a BLDC motor with dual heat sources.

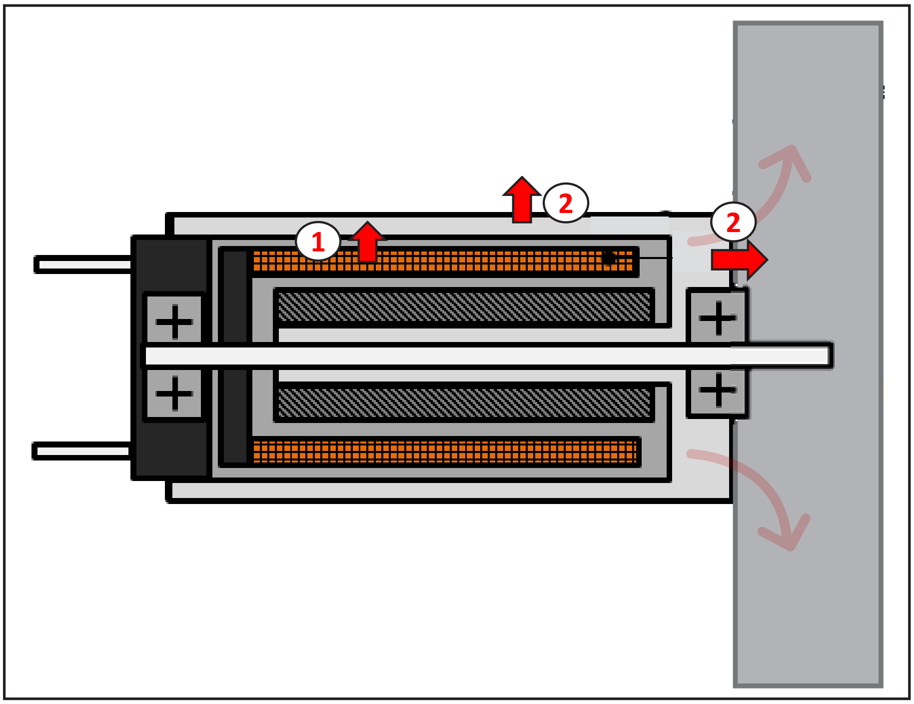

Figure 6 Heat dissipation through external elements in contact with the motor body.

motor from dissipating its heat to the outside environment.

In most cases, a motor is installed on metallic parts and mounted from its front face onto a metal stand or frame. The favorable thermal conductivity of metal will help drain heat out of the motor (Fig. 6), providing better cooling than surrounding the motor with air only. For this reason, the thermal resistance value can be modified to reflect greater cooling capability. This modification will depend on the motor's mounting configuration in the application as well as material, size, surface area and thermal capacity. Similarly, a bathtub with a larger outlet diameter can drain water faster, without a higher water level (or pressure) (Fig. 7).

While every application is different, a good rule of thumb is to consider half the R_{th2} thermal resistance value in the thermal calculation. This results in a higher rated torque — and maximum continuous torque — for the same maximum coil temperature.

Motor designers and manufacturers like Portescap engage with customers early in their development process to assess the dissipation capability of a motor or a motor-gearbox assembly — once installed in the application — to ascertain the working conditions and leverage the full potential of the motorized system.

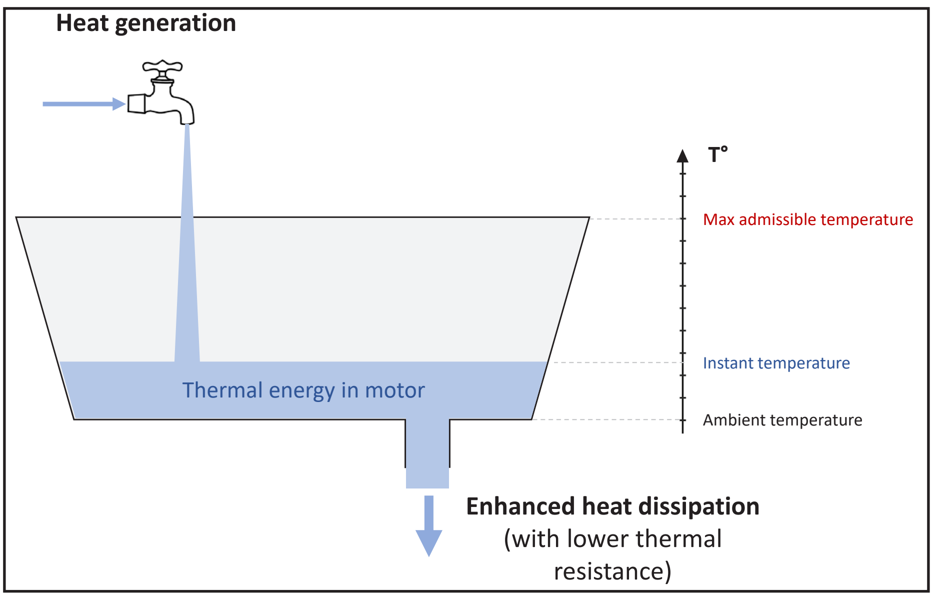

Figure 7 A water analogy depicting increased heat dissipation due to lower thermal resistance. Because the water level is lower, more torque can be used with more heat generation before the level reaches its maximum allowable temperature.

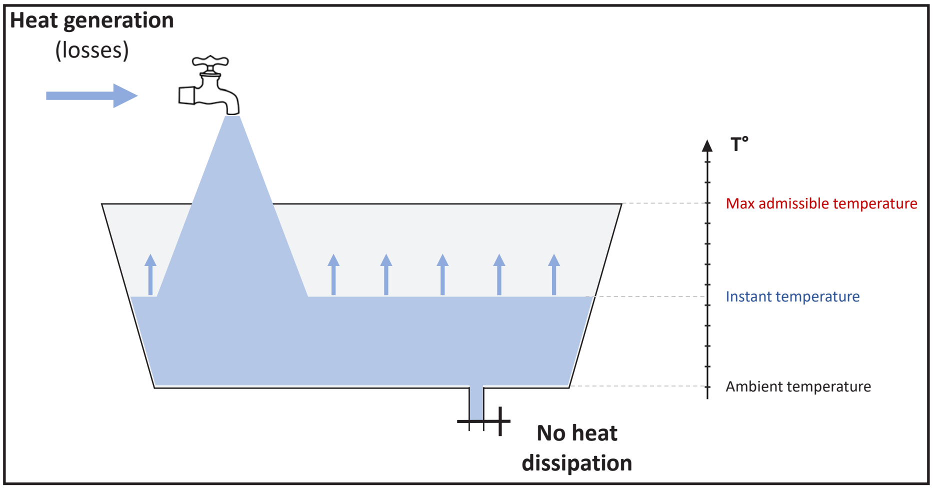

Figure 8 A very high current is considered for a short time, to the extent that designers neglect the dissipation.

Peak Torque During Transient Operation

Some applications require high torque for a short duration only. Industrial screwdrivers require speed during the run-down phase and then peak torque during the tightening phase which lasts approximately a second or less. You can supply a motor with an electric current that exceeds the motor's maximum continuous current as long as the coil temperature does not exceed its maximum allowable temperature. This means that the duration of this operation should be limited.

In our parallel bathtub, the faucet opens suddenly with a very strong flow of water. The prevalent choice of considering a peak torque for a short duration of just a few seconds typically allows a designer to neglect the heat dissipation due to its longer time constant and consider the system adiabatic (Fig. 8).

The water level quickly rises, and the bathtub fills within seconds. Similarly, the coil temperature will reach its maximum allowable temperature within seconds. This formula gives the temperature of the coil over time when heat dissipation is neglected for a short time:

$$T_{coi}(t) = \frac{R \times I^2}{C_{th}} \times t + T_{amb} \tag{5}$$

where

t time (s)

C_{th} Thermal capacity of the coil (J/K)

This shows that the thermal capacity of the coil also matters. A higher thermal capacity allows the coil to withstand a peak current for a longer time or a higher peak current for the same duration. Indeed, the larger a bathtub, the longer it takes to fill.

Slotless brushless motors are particularly well-suited motors for short peak torques:

- The slotless stator design makes it possible to reach high torque with high current, typically 10 times the motor's maximum continuous torque with 10 times higher current. Different slotted designs have the torque limited due to magnetic saturation, making such a high current pointless as it pertains to torque outcome.
- Slotless coil designs can accumulate a large amount of thermal energy thanks to their higher thermal capacity.

Motor suppliers should have an engineering team that engages with customers interested in peak torques to help define the best solution, given each application's specific challenges.

Periodic Duty Cycle During Transient Operation

In some cases, the application's torque requirement is a given torque profile that is repeating over time. To some extent, the highest torque during the cycle can exceed the motor's maximum continuous torque, depending on the torque profile and the duration of each step in the cycle.

If the duration of one cycle, or repeating period, is significantly shorter than the thermal time constant, designers typically consider an equivalent continuous torque value, or current value, that can be calculated as a quadratic mean (RMS, root mean square), due to joule heating being proportional to I^2:

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} \qquad (6)$$

where:

I_{RMS} Root mean square value of the current (equivalent to a continuous current, in terms of heat generation) (A)

T Duration of a given duty cycle (s)

$i(t)$ Instant electrical current (A)

Once the root mean square (RMS) current is defined, it can be considered a continuous value over time as long as it is not greater than the motor's maximum continuous torque. Remember that the impact of the thermal resistance — depending on the motor's environment in the application — also plays a role, since we are assimilating this case to a steady-state operation while still supposing the period of the duty cycle is shorter than the thermal time constant.

Brushless DC Motor with Active Air Flow Cooling

Because heat management is key to a motor's performance, engineers have found alternative ways to further improve the way motors handle heat. For example, some stator designs have an integrated air path so that air flow can carry heat away from the motor. This would focus on the massive heat convection inside the motor instead of relying mainly on heat conduction. This additional heat sink can be viewed as a reduced thermal resistance as it helps drain heat out of the motor.

In some cases, the air flow can be driven by an external source such as compressed air. But when the motor is embedded in a portable device or in any environment with no compressed air available, a fan integrated on the motor shaft can drive the airflow through the motor body as it is operating. In this case, the higher the motor speed, hence fan speed, the stronger the airflow and the lower the thermal resistance. Therefore, the torque capability of such motors can be surprisingly higher at high speed than at low speed since the heat dissipation is drastically improved when the fan runs faster. This is true, to some extent, because the fan driving air applies a load torque to the motor and eventually creates additional heat at very high speed.

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When it comes to electric motor performance, heat management is critical. Motors can be improved to address many challenges, according to each application's duty cycle, environment and critical success factors such as delivering the highest torque, highest speed, best energy efficiency to prolong battery life, or operating at the coolest possible temperature. Be sure to seek a motor supplier that offers extended support, understands customers' challenges and can drive their customers' success by helping them choose the best fitting DC motor for each application. **PTE**

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Daniel Muller joined Portescap in 2014 as an application engineer, working closely with customers from various industries in Europe to define motion solutions that best meet their application needs. He graduated from the Ecole Nationale Supérieure en Génie des Systèmes et de l'Innovation in Nancy, France.