With Electric Motors,

Size Indeed Matters

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Introduction

In this paper, Edward Hage, founder of *specAmotor.com*, an online motor calculation and selection tool, focuses on the overheating of electric motors. Presented here is a calculation method with which the temperature and heat development of a direct current (DC) motor and a brushless motor can be predicted accurately. This prevents overheating and overdimensioning.

Overheating vs. Overdimensioning: Which is Worse?

Overheating and overdimensioning (sizing) may seem to be issues that have nothing in common with each other. However, they are the two sides of the same coin when choosing and buying electric motors.

Overheating is the most common failure mechanism for an electric motor that is sized too tightly. Especially in modern electric motors with strong magnets and compact design, the motor has trouble deflecting its heat. Overheating can lead to:

• Failure of the winding isolation, what results in a short circuit and possibly burnout;

• Failure of the bearings, resulting in a jammed motor;

• Degradation of the magnets (the magnets permanently lose force), so that the motor will never be able to deliver the peak torque it is designed for.

All of which is why it is important to prevent overheating. Usually this is achieved by choosing a larger-size motor than was initially calculated. The necessary degree of oversizing is often educated guesswork because the true end-temperature is unknown. Overdimensioning is often the price for the extra security.

But by determining the temperature of the motor in detail, excessive oversizing can be avoided. You would know exactly where the boundary is, so a motor can be chosen with the right know-how. It is not proposed here to look for the boundary of permissibility. What is proposed is that oversizing can be done correctly when the boundaries are actually known.

This paper explains how one can predict the motor temperature. For this it is necessary to deviate from the "ideal" representation of a motor where the dissipation is linearly dependent upon the torque. In reality, the dissipation will increase more than linearly when a larger torque is demanded from the motor. The far-reaching consequences of this fact will be explained. This results in a calculation method with which one can work practically when determining the most suitable motor for your application.

Heat Development in the Motor

When the motor provides torque, a current will flow that causes a dissipation in the finite resistance of the motor windings. This will result in the following effects to take place:

- The windings will heat up, and this will increase the Ohmic resistance R of the windings.
- The magnets will heat up, and this will decrease the motor-constant k.

The increased resistance R will increase the electric dissipation (effect 1). When the motor constant is lower, a larger current I is necessary to provide the same torque T. This increased current will also increase the electric dissipation (effect 2). In Equation 1 the consequence of these two effects is summarized.

$$P_{elec} = I^2 R = \frac{T^2}{k^2} R \qquad \uparrow\uparrow P_{elec} = \frac{T^2}{\downarrow k^2} \uparrow R \tag{1}$$

This increased electric dissipation will result in a further increase in temperature which, in turn, will increase the current I and the resistance R. This is a cumulative effect that finally results in an equilibrium for the dissipation. *(Note: The cumulative heating will not in all situations result in an equilibrium. At a significant overload of the motor, the dissipation and the temperature will rise to the extent that both terms will become infinite. In practice this will result in a burning of the motor. This certainly is not only a theoretical situation.)*

The effects of the temperature on R and k are described with Equations 2 and 3:

$$R(\theta_{winding}) = R_{ref} \cdot \left(1 + (\theta_{winding} - \theta_{ref}) \cdot \alpha\right) \tag{2}$$

$$k(\theta_{magnet}) = k_{ref} \cdot \left(1 + (\theta_{magnet} - \theta_{ref}) \cdot TK_{Br}\right) \quad (3)$$

The resistance R is dependent on the winding temperature $\theta_{winding}$. R_{ref} is the reference resistance, and k_{ref} is the reference motor constant given for a reference temperature θ_{ref} of 20°C.

What these equations tell us is the following:

• The resistance R will increase linearly with the winding temperature according to α. This is a material constant for copper (the material of the windings) 0.00393 K^1. The cumulative heating will not in all situations result in an equilibrium. At a significant overload of the motor, the dissipation and temperature will rise to the extent that both terms will become infinite. In practice, this will result in a burning of the motor.

• The motor constant k will decrease linearly with the magnet temperature, according to TK_{Br} (decrease because TK_{Br} always has a negative value). This is a material constant of the magnet and therefore differs per species of magnet. See Table 1 for an overview of these values.

Dissipation Twice as Large at Higher Motor Temperature

In Equations 1–3, the dissipation at elevated motor temperature can be determined. This is shown in Figure 1 for two values of TK_{Br}. The dissipation is expressed as a percentage of the dissipation at a normal ambient temperature (norm 100% at 20°C). For ease of calculation, it is assumed that the winding and magnet temperature are equal to each other.

Figure 1 shows that the dissipation rises significantly as a function of the motor temperature. At a temperature of 108°C, the dissipation (for $TK_{Br} = -0.2$ %/K) is already 200%, or twice as large as the dissipation at ambient temperature.

The maximum temperature usually is determined by the isolation class of the windings. For the highest isolation class H, this amounts to a maximum winding temperature of 180°C (according to standard IEC: 2004 60034-1). Because the dissipation increases so strongly, it is very important to determine if the maximum temperature is approaching. To be able to determine this, more information about the motor is required.

Thermal Model Motor

The final motor temperature is dependent on the motor's construction. With a thermal model, it can be shown how the temperature depends on the parameters of the motor and the dissipation. In Figure 2, the thermal model is shown; it is generic for all electric motors with permanent magnets.

When there is thermal equilibrium—the temperature remains constant—the equilibrium temperatures for windings and house can be determined as shown in Equations 4 and 5.

$$\theta_{winding} = P_{elec}\left(R_{th1} + R_{th2}\right) + P_{fric} R_{th2} + \theta_{amb} \quad (4)$$

$$\theta_{house} = P_{elec} R_{th2} + P_{fric} R_{th2} + \theta_{amb} \quad (5)$$

The magnet temperature. The magnet temperature is not indicated in Figure 2. It is dependent on the construction of the motor. There are three constructions of motors admitted to the *specAmotor* database:

• Brushed motors
• Brushless motors
• Synchronous motors

In the case of brushless and synchronous motors, the magnets are mounted to the rotor, and the windings to the housing. In the case of the brushed motor, the magnets are mounted to the housing and the windings to the rotor.

For the brushless and synchronous motor, the magnet temperature is about the same as the winding temperature.

For a brushed motor, there is an air gap present between the magnet and the winding that dominates the thermal resistance. Therefore, the magnet temperature will be much closer to the housing temperature than the winding temperature.

As such, the magnet temperature can be summarized per motor construction as:

$$\begin{aligned} \theta_{magnet} &= \theta_{house} \;\; \textit{brushed motor} \\ \theta_{magnet} &= \theta_{winding} \;\; \textit{brushed motor + AC synchronous motor} \end{aligned} \quad (6)$$

continued

Table 1—Decay of magnetic flux-density TK_{Br} for different magnet materials

Material	TK_{Br} (%K)
cast or sintered SmCo	-0.005% tot -0.07%
bonded (glued) SmCo	-0.04%
sintered $SmCo_5$	-0.04%
sintered Sm_2Co_{17}	-0.03%
Ferrite	-0.2%
Alnico	-0.01% tot -0.025%
bonded (glued) NdFeB	-0.2%
sintered NdFeB	-0.07% tot-0.16%
$Nd_2Fe_{14}B$	-0.1%

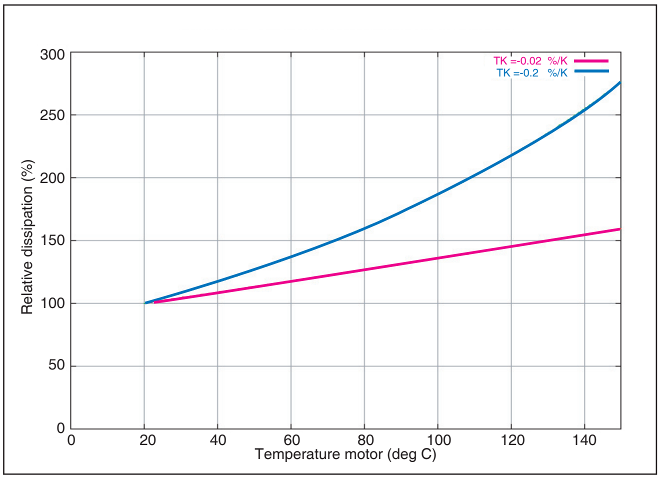

Figure 1—Dissipation increases at increasing motor temperature.

Simple thermal model. With the thermal model—as provided in Figure 2—the winding and housing temperature can be determined separately. To do this, it is necessary to know the thermal resistance between the windings and housing, and between the housing and ambient (R_{th1} and R_{th2}). Sometimes this information is not provided by the manufacturers and the temperatures cannot be determined. *SpecAmotor* is dependent on publicly available data, such as catalogs, from manufacturers. Often the manufacturers will give only one thermal resistance for the entire motor. If this is the case, *specAmotor* will apply the simple model of Figure 3.

In the simple model, there is only one motor temperature; there is no distinction between winding and housing temperature. Because the simple model can show less-accurate results than the detailed model of Figure 2, it is preferred to apply the detailed model.

When there is thermal equilibrium, the motor temperature can be determined as described in Equation 7. This formula applies to the simple thermal model.

$$\theta_{motor} = \left(P_{elec} + P_{fric}\right) R_{th} + \theta_{amb} \quad (7)$$

For the sake of completeness, the following applies to the motor temperature (independent of construction of motor):

$$\theta_{motor} = \theta_{magnet} = \theta_{winding} = \theta_{house} \quad (8)$$

formula 7 Temperature motor for simple thermal model

Example: calculation of correct motor temperature. Now the motor temperature can be determined so that the influence of the enlarged dissipation becomes clear. For the calculation we assume for the ease of use the simple thermal model and an electric motor with the data and drive situation as mentioned here:

We have a workpoint (T;ω) = (1 Nm; 2000 rpm) and the motor has the following features R = 10Ω, k= 0.4714Nm/A (both at 20°C) and R_{th} = 1 K/W. The ambient temperature is 20°C. Species of magnet is bonded NdFeB where TK_{Br} = -0.2%/K. Friction is left aside. (9)

According to Equation 1, the dissipation is determined and substituted in Equation 7. This will yield the motor temperature:

$$P_{elec} = \frac{T^2}{k^2} R = \frac{1}{0.4714^2} 10 = 45W$$
$$\theta_{motor} = P_{elec} R_{th} + \theta_{amb} = 45 \cdot 1 + 20 = 65°C \quad (10)$$

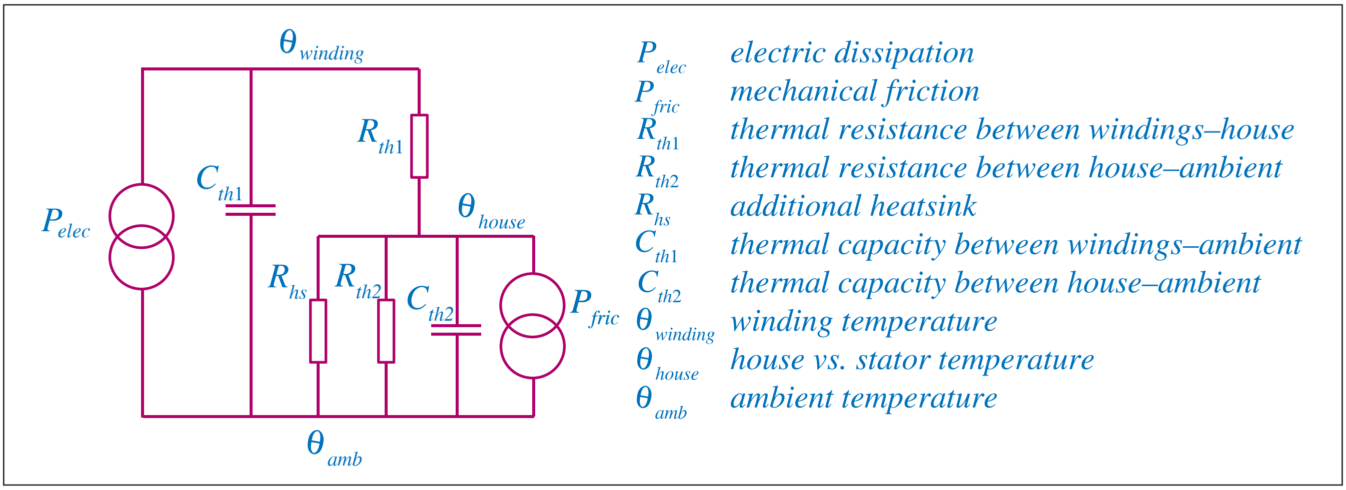

Figure 2—Detailed thermal model for PM (Permanent Magnet) motor.

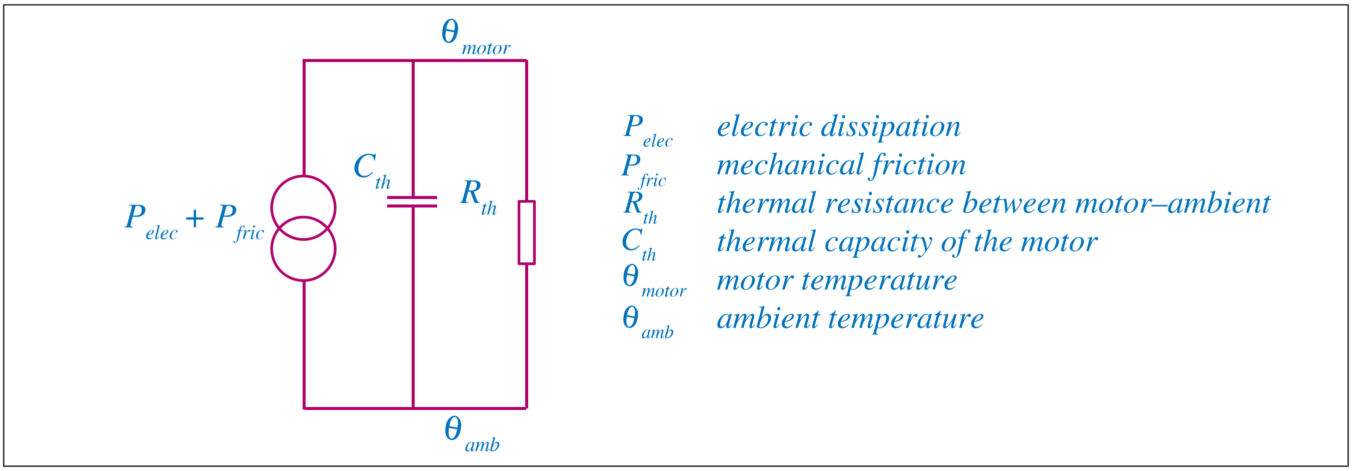

Figure 3—Simple thermal model for PM motor.

The motor temperature thus becomes 65°C if k and R are independent of temperature. As we know, the dissipation will increase because R and k do change. These quantities become (Equations 2 and 3 substituted into Equations 8):

$$R(\theta_{motor}) = R_{ref} \cdot (1+ (\theta_{motor} - \theta_{ref}) \cdot \alpha) = 10 \cdot (1 + (65-20) \cdot 0.00393) = 11.77\Omega$$

$$k(\theta_{motor}) = k_{ref} \cdot (1+ (\theta_{motor} - \theta_{ref}) \cdot TK_{Br}) = 0.4714 \cdot (1 + (65-20) \cdot -0.002) = 0.429 \; Nm/A \tag{11}$$

These values substituted in the same equations result in:

$$P_{elec} = \frac{T^2}{k^2} R = \frac{1}{0.429^2} 11.77 = 63.95W$$

$$\theta_{motor} = P_{elec} R_{th} + \theta_{amb} = 63.95 \cdot 1 + 20 = 84°C \tag{12}$$

The motor temperature is now 84°C and is 19° higher than initially determined. But this is not the final motor temperature, since R and k at 84°C are different again. Values for R and k must be substituted in Equations 1 and 7 repeatedly until the result does not change. In Table 2, the results of this iterative calculation are given. The real motor temperature is only revealed after 21 iterations and amounts to 112°C instead of 65°C.

Table 2—Results of iterative calculation.

Iteration	Θ motor (°C)	R (Ω)	k(Nm/A)
1	65.0	10.00	0.4714
2	84.0	11.77	0.4290
3	94.0	12.51	0.4111
4	100.0	12.91	0.4016
5	103.9	13.15	0.3959
6	106.4	13.30	0.3923
...11	111.1	13.56	0.3859
...16	111.9	13.61	0.3848
...21	112.0	13.62	0.3846

Result

From the example shown in paragraph five, we can conclude that the influence of the Ohmic resistance R and the motor constant k on the motor temperature is very significant. If this influence is not taken into account, a false end-temperature is calculated of 65°C, instead of the correct 112°C. It is easy to understand that such errors can lead to a premature failure of an electric motor.

Here a calculation method is presented with which you can now determine the end temperature of a motor in great detail. With some adjustments you can achieve similar results for the detailed thermal model.

The only thing left to do is collect the necessary motor data from different catalogs and websites of manufacturers. With that information, the way is free to make an objective comparison between the performance of different brands; the motors, after all, are all calculated in a similar manner. You won't be dependent on the subjective advice of a manufacturer.

The *specAmotor* Database

Finding the necessary motor data requires a lot of research. It would be ideal to be able to consult a database where all this data is collected, and to have something that will perform these calculations automatically.

- *specAmotor* is a website that will do that for you for free.
- *specAmotor* calculates more than 6,000 motor configurations from 11 brands in this manner and uses, where possible, the detailed thermal model to produce an accurate result. The validity of a motor, however, is not only determined by the temperature. Other criteria that *specAmotor* uses are:
- Maximum current; the current is allowed to be very high for a short period, but not too high so that the magnets will demagnetize.
- Maximum speed; for a brushless motor this speed is determined by the bearing that is suitable up to a certain speed. For brushed motors, the maximum speed is usually limited by contact loss of the brushes as a result of the shape of the collector, which is accompanied by severe formation of sparks.
- Maximum power; for brushed motors this is usually limited by the commutation boundary.
- Maximum torque; when a reduction or gearbox is mounted to the motor, this reduction will allow for maximum peak torque. Larger torques will lead to mechanical damage of the reduction.
- Maximum voltage; especially relevant for brushed motors where an excessive voltage will cause sparks between brushes and collector and shorten the lifetime of the motor.

The calculations are validated by John Compter, an authority in the field of electric motor design who is employed by Philips Applied Technology.

Visit *http://www.specamotor.com* to try the service. It is free-of-charge and allows you to make an independent comparison between motors.