specAmotor

Choice of electric motor: Avoid overheating and over-dimensioning

In this white paper Edward Hage, the founder of specAmotor.com, focusses on the problem of overheating of electric motors. This white paper presents a calculation method with which the temperature and heat development of a direct current motor (DC) and a brushless motor can be predicted accurately. This prevents overheating and over-dimensioning.

1 Overheating vs. over-dimensioning: Which is the least evil !

Overheating and over-dimensioning seem to be two quantities that have nothing in common with eachother. However, they are the two sides of the same coin when choosing and buying electric motors....

Overheating namely is the most common failure mechanism for an electric motor which is dimensioned too tightly. Especially in the case of modern electric motors with strong magnets and a compact design the motor has trouble leading away its heat. Overheating can lead to:

1) Failure of the winding-isolation, what results in a shortcircuit and possibly can lead to a burnout of the motor;
2) Failure of the bearings, what results in a jamming motor;
3) Degradation of the magnets (the magnets permanently loose force), so that the motor will never be able to deliver the peak-torque it is designed for.

That is why it is important to prevent overheating. Usually this is achieved by choosing a larger size of the motor than was initially calculated. The necessary degree of overdimensioning is often educated guesswork because the true end temperature is unknown. To gain enough confidence the motor is strongly overdimensioned. This motor is unnecessarily expensive. That is the price for the extra 'security'.

By determining the temperature of the motor in detail it can be prevented that one overdimensions too much. You would know exactly where the boundary is so a motor can be choosen with the right know-how. Here explicitely is not proposed to look for the boundary of permissibility. What is begin stated is that an overdimensioning can be handled tactfully when the boundaries are actually known.

In this white paper will be explained how on prehand one can predict the motor temperature. For this it is necessary to deviate from the 'ideal' representation of a motor where the dissipation is lineairly dependant with the torque. In reality namely the dissipation will increase more than lineair when a larger torque is demanded from the motor. In this white paper 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.

2 Heat development in the motor

When the motor provides a 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:

1) The windings will heat up, and this will increase the Ohmic resistance R of the windings;
2) 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 be able to provide the same torque T. This increased current will also increase the electric dissipation (effect 2). In formula 1 the consequence of these two effects is summarised.

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

formula 1 Electric dissipation and current increase at a larger temperature

This increased electric dissipation will result in a further increase in temperature which in its turn will increase the current I and the resistance R. This is a cumulative effect that finally results in an equilibrium[1] for the dissipation.

The effects of the temperature on R and k are described with formula 2 and 3.

$$R(\theta_{winding}) = R_{ref} \cdot \left(1 + (\theta_{winding} - \theta_{ref}) \cdot \alpha\right)$$ *formula 2 Temperature dependancy of R*

$$k(\theta_{magnet}) = k_{ref} \cdot \left(1 + (\theta_{magnet} - \theta_{ref}) \cdot TK_{Br}\right)$$ *formula 3 Temperature dependancy of k*

The resistance R is dependant 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 formulas tell us is the following:
1) The resistance R will increase lineairly with the winding temperature according to α. This is a material constant and is for cupper (the material of the windings) 0.00393 K^{-1}.

2) The motor-constant k will decrease lineairly 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 therefor differs per species of magnet. See table 1 for an overview of these values.

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%

Tabel 1 Decay of magnetic flux-densityTK_{Br} for different magnet materials

1 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!

3 Dissipation twice as large at higher motor temperature

With formula 1 untill 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 the ease of calculation it is assumed that the winding and magnet temperature are equal to eachother.

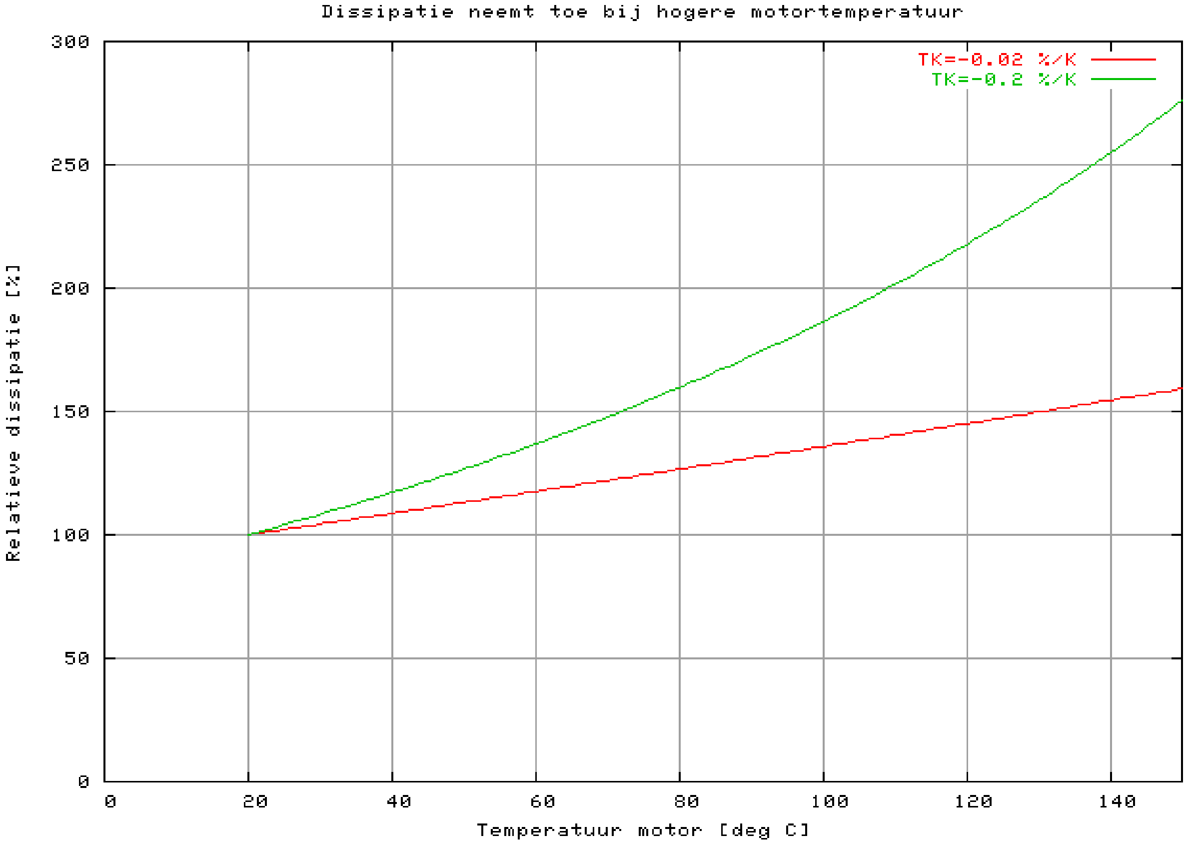


Figure 1 Dissipation increases at increasing motor temperature

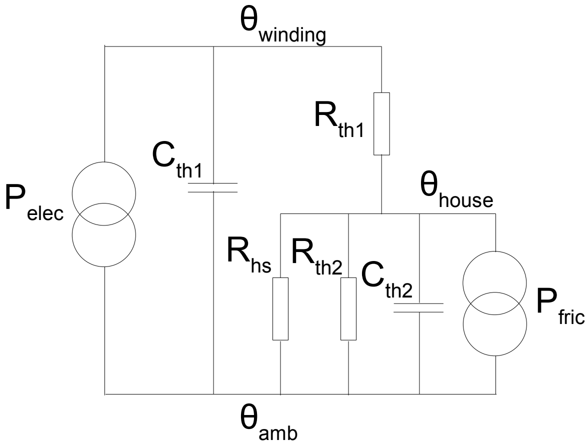
From figure 1 can be concluded that the dissipation rises significantly as a function of the motor temperature. At a temperature of 108 °C the dissipation (for TK_{Br}=-0.2 %/K) is already **200%**, With other words twice as large as the dissipation at ambient temperature.

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 dissipatie increases so strongly it is very important to determine if we are close to the maximum temperature. To be able to determine this firstly we require more information about the motor.

4 Thermal model motor

The final motor temperature is dependant on the construction of the motor. 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.

4.1 Detailed thermal model



P_{elec} *electric dissipation*
P_{fric} *mechanical friction*
R_{th1} *thermal resistance between windings – house*
R_{th2} *thermal resistance between house – ambient*
R_{hs} *additional heatsink*
C_{th1} *thermal capacity between windings – ambient*
C_{th2} *thermal capacity between house – ambient*
$\theta_{winding}$ *winding temperature*
θ_{house} *house vs. stator temperature*
θ_{amb} *ambient temperature*

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

When there is thermal equilibrium (the temperature does not alter anymore) the temperatures can be determined as shown in formula 4 and 5.

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

formula 4 Equilibrium temperature windings for detailed thermal model

$$\theta_{house} = P_{elec}R_{th2} + P_{fric}R_{th2} + \theta_{amb}$$

formule 5 Equilibrium temperature house for detailed thermal model

4.2 The magnet temperature

The magnet temperature is not indicated in figure 2. It is dependant 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 airgap present between the magnet and the winding that dominates the thermal resistance. Therefor the magnet temperature will be much closer to the housing temperature than the winding temperature.

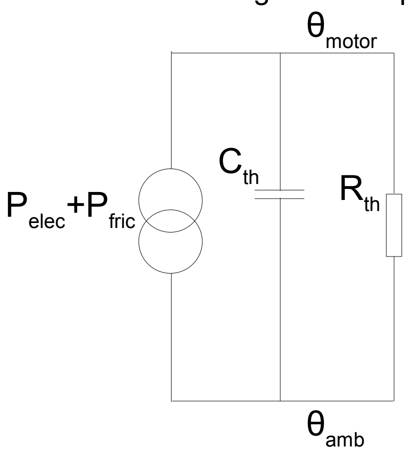
As such the magnet temperature can be summarised per motor construction as:

$$\theta_{magnet} = \theta_{house} \quad \textit{brushed motor}$$
$$\theta_{magnet} = \theta_{winding} \quad \textit{brushless motor} + \textit{AC synchronous motor}$$

4.3 Simple thermal model

With the thermal model as provided in figure 2 the winding- and housing temperature can be determined seperately. To do this it is necessary to know the thermal resistance between the windings and house, and between house and ambient (R_{th1} and R_{th2}). Sometimes this information is not provided by the manufacturers so that the temperatures can not be determined. specAmotor is dependant on publicly available data such as catalogs from manufacturers. Often the manufacturers suffice with giving 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.



P_{elec} *electric dissipation*
P_{fric} *mechanical friction*
R_{th} *thermal resistance between motor − ambient*
C_{th} *thermal capacity of the motor*
θ_{motor} *motor temperature*
θ_{amb} *ambient temperature*

Figuur 3 Simple thermal model for PM motor

When there is thermal equilibrium the motor temperature can be determined as described in formula 6. This formula applies to the simple thermal model.

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

formula 6 Equilibrium temperature 'motor' for simple thermal model

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

$$\theta_{motor} = \theta_{magnet} = \theta_{winding} = \theta_{house}$$

formula 7 Temperature motor for simple thermal model

5 Example: calculation 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 = 10 Ω, k= 0.4714 $^{Nm}/_{A}$ (both at 20 °C) and R_{th} = 1 $^{K}/_{W}$. The ambient temperatuur is 20 °C. Species of magnet is bonded NdFeB where TK_{Br} = -0.2 %/K. Friction is left aside.*

According to formula 1 the dissipation is determined, and substituted in formula 6 this will yield the motor temperature:

$$P_{elec}=\frac{T^2}{k^2}R=\frac{1}{0.4714^2}10=45\,W$$

$$\theta_{motor}=P_{elec}R_{th}+\theta_{amb}=45\cdot 1+20=65\,^oC$$

The motor temperature thus becomes **65 °C** if k and R would be independant of temperature. As we know the dissipation will increase because R and k do change. These quantities become (formula 7 substituted in formula 2 and 3):

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

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

These values substituted in the same formulas result in:

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

$$\theta_{motor}=P_{elec}R_{th}+\theta_{amb}=63.95\cdot 1+20=84\,^oC$$

The motor temperature is now **84 °C** and is nineteen degrees higher than initially determined. But still this is not the final motor temperature, since R and k at 84 °C are different again. Values for R and k must be substitued in formula 1 and 6 repeatedly untill the result does not change anymore. In the table below 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.

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

6 Result

From the example shown in paragraph 5 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 endtemperature 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.

A calculation method is presented that with which you can now determine the endtemperature 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 to collect the necessary motor data from different catalogs and websites of manufacturers. With that 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 dependant on the subjective advice of a manufacturer. This advice is not seldom driven by the hesitation for overheating, what can lead to the purchase of a motor which is too expensive.

7 How specAmotor can aid you

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 something that will perform these calculations automatically. This would safe you a lot of time.

specAmotor is a website that will do that for you for free.
specAmotor calculates more than 6000 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:

1) Maximum current; the current is allowed to be very high for a short period, but not too high so that the magnets will demagnetise.
2) Maximum speed; for a brushless motor this speed is determined by the bearing that is suitable upto a certain speed. For brushed motors the maximum speed is usually limited by contact loss of the brushes as a result of unroundness of the collector, which is accompanied by severe formation of sparks.
3) Maximum power; for brushed motors this is usually limited by the commutation-boundary.
4) Maximum torque; when a reduction or gearbox is mounted to the motor this reduction will be able to allow through a maximum peak torque. Larger torques will lead to mechanical damage of the reduction.
5) 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 prof.dr.ir. John Compter, an authority in the field of electric motor-design, and employed by Philips Applied Technology.

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