Power Engineering Briefing Note Series
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Thermal Analysis of Electrical Machines : Limits and Heat Transfer Principles

PEBN #3 (10 May 2008)

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Abstract – this brief gives an overview of the thermal analysis of electrical machines. The key thermal limitations in electrical machines are often winding insulation life and demagnetisation of the permanent magnets. The three key heat transfer principles (conduction, convection and radiation) are introduced drawing largely from Ref [2].

I. THERMAL LIMITING FACTORS

A. Winding Insulation

The temperature capability of insulation materials used in electrical machines is grouped in classes as shown in Table 1.

TABLE 1. COMMON INSULATION CLASSES [1]

Class	Maximum Operating Temperature
Class A	105°C
Class B	130°C
Class F	155°C
Class H	180°C

The insulation on copper windings is very sensitive to over temperature operation. The Arrhenius law states that insulation life expectancy roughly halves for every 10°C rise in temperature. For example consider a class F insulation (155°C) with an expected life of 20,000 hrs. If this is operated at 175°C temperature, which is 20°C above its design value, then its expected life is one quarter of its design value, that is 5,000 hrs. Note if the material is operated at 135°C, that is 20°C below design value, its expected life will be 80,000 hrs.

B. Permanent Magnets

The magnetic properties of permanent magnets (PM) are temperature dependent and limit their allowable operating temperature range.

TABLE 2. SINTERED PERMANENT MAGNET PROPERTIES [2]

Property	Ferrite	NdFeB	SmCo
Curie Temperature	450°C	310-350°C	700-800°C
Max. Working Temp.	250°C	80-200°C	250-350°C
Temp. Co-efficient of B_R	-0.2%/°C	-0.08%/°C to -0.15%/°C	-0.045%/°C to -0.08%/°C

The Curie temperature is the temperature at which the PM irreversibly loses magnetization and represents the ultimate temperature limit. A more practical limit is the maximum working temperature shown.

The remanent flux density B_R for PM materials falls as the temperature increases. This means that for PM machines designed for high temperature operation, there can be a significant difference between the back-emf at room temperature and operating temperature. This decrease in the remanent flux density also makes the machine more prone to demagnetisation when high stator winding currents are present and so this needs to be checked at the maximum expected operating temperature.

II. HEAT TRANSFER BY CONDUCTION

A. Conduction Principles

In AC electrical machines, heat transfer by conduction is the main method by which power losses from the conductors are transferred to the outside of the machine. The heat flux ϕ is given by [2] :

$$\phi = k\frac{dT}{dx} \approx k\frac{\Delta T}{t} \quad \text{W/m}^2 \tag{1}$$

where dT/dx is the rate of change of temperature with position, ΔT is the temperature difference across the material, t is the thickness of the material and k is the thermal conductivity of material in W/(m.K). Typical values for the thermal conductivity of common materials is given in Table 3.

TABLE 3. TYPICAL THERMAL CONDUCTIVITY VALUES [1,4]

Material	Thermal Conductivity
air @ 25°C	0.025 W/(m.K)
stator coils (typical)	0.06 – 0.09 [3]
Nomex slot liner	0.13
epoxy (unfilled)	0.19
insulation (typ)	0.2
epoxy (silica filled)	0.3
thermal epoxy	1 – 4
lamination material	20 – 46
steel	50
copper	385

B. Conduction Analysis Example : Slot Temperature Rise

What is an acceptable current density J (A/mm^2) for electrical machines? Consider a "deep" parallel-sided slot as shown in Fig. 1, so that the heat flow can be assumed to be one-dimensional in a horizontal direction.

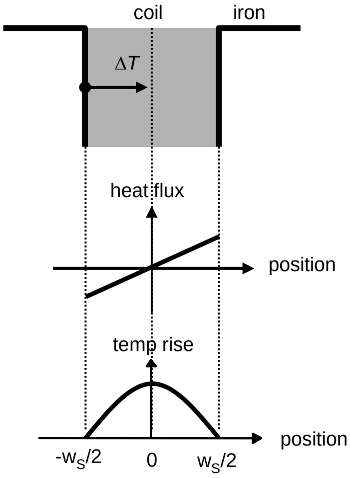

Fig. 1. Simplified thermal analysis of heat conduction through a deep, parallel-sided slot showing the parabolic temperature distribution.

The heat flux increases linearly with the distance from the centre of the slot. This results in a parabolic temperature distribution with a peak value :

$$\Delta T_m = \frac{pf \times \rho \times J^2 \times w_s^2}{8k} \quad \text{K} \tag{2}$$

where :

pf : fraction of slot area which is copper (typically 30%)

ρ : resistivity of conductor, for instance 2.36×10^{-8} Ω.m at 120°C for copper

J : is the current density in A/m^2

k : thermal conductivity of the composite of the conductor, air, insulation and varnish in the slot;

w_S : is the width of the slot

Fig. 2 assumes a slot conductivity of 0.075 W/(mK) which is typical for commercial induction machines [3]. The allowable current density falls inversely with coil width. For wide slots the allowable current density is very low. Hence for large machines (e.g. power station generators) it is necessary to pass coolant directly through the conductors to achieve reasonable values of current density.

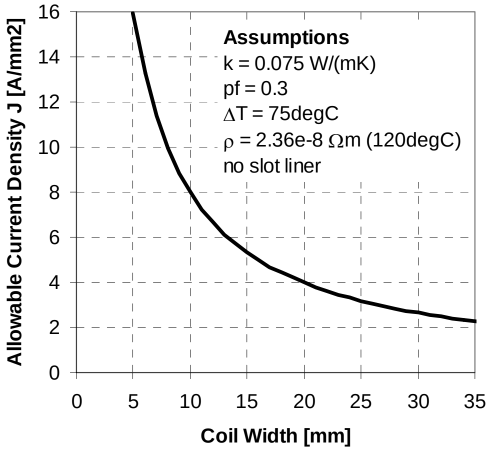

Fig. 2. Maximum allowable conductor current density as a function of coil width for a typical range of assumptions listed in the figure.

III. CONVECTION

The heat transfer by convection is given by *Newton's Law of Cooling* [2] :

$$\phi = h \times \Delta T \quad \text{W/m}^2 \tag{3}$$

where ΔT is the difference in temperature between the cooling medium and the hot surface and h is the heat transfer co-efficient which depends on the properties of the fluid and it's velocity. There are two types of convection : natural convection where fluid circulation is purely due to natural movement of the fluid associated with thermal gradients while forced convection is where the fluid circulation is driven by an external fan, blower or pump.

A. Natural Convection

The heat transfer co-efficient for natural convection around an un-finned cylindrical motor of diameter D which is mounted horizontally is approximately given by [2] :

$$h \approx 1.324 \times \left(\frac{\Delta T}{D}\right)^{0.25} \quad \text{W/m}^2/\text{K} \tag{4}$$

For instance for a 0.1 m diameter motor with a temperature rise of 40°C, then $h \approx 5.9$ W/m^2/K and so from (3) the heat flux is $\phi = 237$ W/m^2.

Ref. [5] gives typical values of heat transfer co-efficient for natural convection as 2 – 25 W/m^2/K for gases and 50 – 1000 W/m^2/K for liquids.

B. Forced Convection

Blowing air over the motor increases the heat transfer co-efficient by the square root of the air velocity and typical values are about five times the natural convection co-efficient. It can be roughly estimated as [2] :

$$h \approx 3.95\sqrt{\frac{v}{L}} \quad \text{W/m}^2/\text{K} \tag{5}$$

For instance for an air velocity of 4 m/s blowing over a motor which is 0.1 m long (5) gives a value of $h \approx 25$ W/m^2/K which is roughly four times that for natural convection. For a 40°C temperature difference this gives a heat flux of ϕ = 1000 W/m^2.

Ref. [5] gives typical values of heat transfer co-efficient for forced convection as 25 – 250 W/m^2/K for gases and 50 – 20,000 W/m^2/K for liquids.

IV. RADIATION

The heat flux associated with electromagnetic radiation is given by [2] :

$$\phi = \varepsilon\sigma\left(T_h^4 - T_a^4\right) \quad \text{W/m}^2 \tag{6}$$

ε is emissivity (1 for an ideal black body), a value of 0.9 is more reasonable for a black-painted surface

σ = Stefan-Boltzmann's constant 5.67 x 10^{-8} W/(m^{2}K^4)

T_h = temperature of hot object (K)

T_a = temperature of surroundings (K)

For example consider a temperature rise of 40°C above an ambient of 20°C and a 0.9 value for emissivity, then the heat flux is :

$$\phi = 0.9 \times 5.67 \times 10^{-8}\left(\left[60+273\right]^4 - \left[20+273\right]^4\right) = 251 \text{ W/m}^2$$

which is comparable to that obtained by natural convection.

V. ROUGH RULES OF THUMB

Ref. [2] gives some rough rules of thumb as follows for the maximum heat flux obtainable with a 40°C rise as roughly :

- 800 W/m^2 for natural convection and radiation;
- 3,000 W/m^2 for forced convection;
- 6,000 W/m^2 for direct liquid cooling.

VI. REFERENCES

[1] E.S. Hamdi, "Design of Small Electrical Machines," Wiley, 1994.

[2] J.R. Hendershot and T.J.E. Miller, "Design of Brushless Permanent-Magnet Motors", Magna Physics Publishing and Clarendon Press, 1994.

[3] D. Staton, A. Boglietti and A. Cavagnino, "Solving the More Difficult Aspects of Electric Motor Thermal Analysis in Small and Medium Size Industrial Induction Motors," IEEE Transaction on Energy Conversion, Vol. 20, Issue 3, Sept. 2005, pp. 620 – 628.

[4] http://en.wikipedia.org/wiki/Thermal_conductivity (accessed 10 May, 2008)

[5] F.P. Incropera and D.P. DeWitt, "Introduction to Heat Transfer," Wiley, 1990.

A WORD FOR TODAY

> *These are the words of the Amen, the faithful and true witness, the ruler of God's creation. "I know your deeds, that you are neither cold nor hot. I wish you were either one or the other! So, because you are lukewarm—neither hot nor cold—I am about to spit you out of my mouth."*
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> Revelation 3:14-16 (NIV)