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A criterion for determining the relative importance of the fluctuating component of a periodic heat source

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ABSTRACT

Devices such as rotating electrical machines, transformers, and microprocessors experience thermal loading during operation. This is caused by device losses which manifest themselves as heat sources. Whether operated continuously or on a duty cycle these heat sources are often periodic in nature, exhibiting both mean and fluctuating components. This paper proposes a criterion which can be used to estimate the relative importance of the fluctuating component of a periodic heat source on the temperature response of a device, or a component within a device. It may be used by the heat transfer analyst to determine whether a periodic heat source can be modeled accurately by its mean value or whether it must be modeled as a function of time. During thermometric tests it enables the experimentalist to determine whether the measured temperature rise rate represents an instantaneous or a mean value of heat generation rate. The criterion is derived by considering a sinusoidal heat source acting on a thermal network element. A case study is presented where the criterion is used to estimate the relative importance of the fluctuating component of a range periodic heat sources present in a rotating electrical machine. Results are compared with numerical predictions and agreement is found to be fit for purpose.

1. Introduction

Losses in devices such as rotating electrical machines, linear actuators, transformers, and microprocessors cause thermal loading which can age components, limit performance, and cause failure. Device losses manifest themselves as heat sources which are often periodic in nature [1–3]. For example Fig. 1 shows the computed instantaneous iron loss in a permanent magnet synchronous machine (PMSM).

When thermometric experiments are performed on these devices, as in [4–6], the experimentalist must decide whether the measured temperature response represents a mean or an instantaneous value of heat generation rate. When numerically modeling the thermal performance of these devices the analyst must decide whether the heat source can be accurately represented by its equivalent mean value, or whether its variation over time must be modeled explicitly. It may be possible to make a computational saving when the source is represented by its equivalent mean value as, when compared with the time varying heat source, a larger time step may be used during the simulation. Although thermal models of these devices are common [7–14] discussions regarding the level of detail to which the heat source must be modeled are rare. Often the experience of the analyst or empirical evidence is relied upon to justify modeling decisions a posteriori.

Fig. 2, which is a similar to the work of [3], shows a typical application where a periodic heat source is present in an integrated circuit application. Presented with this data an experimentalist would have to make a judgement about whether the mean or instantaneous heat generation rate was being measured. It may also be unclear whether the measured response is due to an instantaneous heat generation rate, or whether it is noise in the temperature sensor measurement and can be filtered out without loss of fidelity. Similarly, given the heat source profile in Fig. 2 the analyst must decide whether to model the transient nature of the heat source, or whether to use its mean value and make a computational saving by increasing the simulation time step.

In lieu of the above, this paper presents the derivation and application of a criterion which can be used to estimate the relative importance of the fluctuating component of a periodic heat source on the temperature response of a device or component. It may be used by the heat transfer analyst to determine whether a periodic heat source can be modeled accurately by its mean value, or

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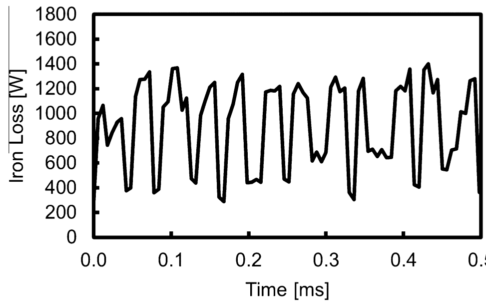

Fig. 1. Computed instantaneous iron loss in a PMSM.

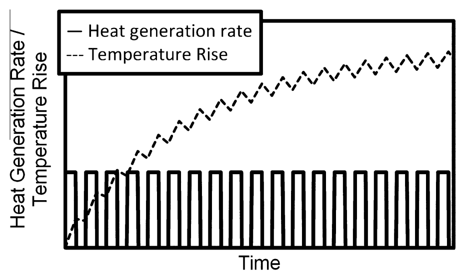

Fig. 2. Temperature response of an integrated circuit to a periodic heat source.

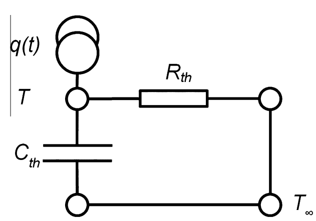

Fig. 3. Thermal network element used to derive the criterion.

whether it must be modeled as a function of time. It allows the experimentalist to determine whether a measured temperature rise over time corresponds to a mean or an instantaneous heat generation rate. It also enables the experimentalist to determine which frequencies can be filtered out of a transient temperature measurement without loss of fidelity.

2. Criterion derivation

A thermal network element (Fig. 3) is used to derive the criterion. The thermal network consists of a thermal resistance R_{th} (Eq. (1)) and a thermal capacitance C_{th} (Eq. (2)).

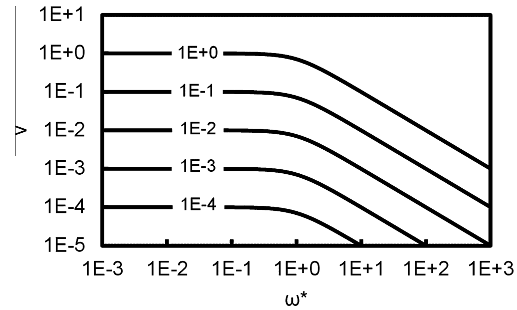

Fig. 5. Criterion values plotted over a range of ω^*, each plot line represents a different value of q^*.

$$R_{th} = \frac{l}{kA} + \frac{1}{hA} \tag{1}$$

$$C_{th} = \rho C_p V \tag{2}$$

where k is the thermal conductivity (W/m K), A is the surface area (m^2), h is the coefficient of convective heat transfer (W/m^2 K), l is the length scale (m) V/A where V is the volume of the element, ρ is the density (kg/m^3), and C_p is the heat capacity (J/kg K).

A temperature difference θ is defined as T–T_∞. A sinusoidally varying heat source acts as a forcing function on the element and is considered to be composed of mean and fluctuating components $\bar{q}$ and q' respectively. Fig. 4 shows the response of the thermal element to such a heat source. By assuming temperature independent material properties the temperature response can also be decomposed into mean and fluctuating components $\bar{\theta}$ and θ' respectively. The steady state mean component is given by Eq. (3).

$$\bar{\theta} = \bar{q} R_{th} \tag{3}$$

where $\bar{\theta}$ is the mean value of the temperature rise (K), and $\bar{q}$ is the mean value of the heat source (W).

The steady state fluctuating component is given by Eq. (4).

$$C_{th}\frac{d\theta'}{dt} + \frac{1}{R_{th}}\theta' = q' \sin \omega t \tag{4}$$

where θ' is the fluctuating component of the temperature rise (K), t is the time (s), q' is the fluctuating component of the heat source (W), and ω is the angular velocity (rad/s).

The solution of Eq. (4) is seen to be:

$$\theta' = \frac{q'}{C_{th}\left(\frac{1^2}{\tau} + \omega^2\right)}\left(\frac{1}{\tau}\sin \omega t + \omega \cos \omega t\right) \tag{5}$$

where $\tau = R_{th}C_{th}$ is the thermal time constant (s).

Eq. (5) is at a maximum when:

$$\frac{d}{dt}\left(\frac{1}{\tau}\sin \omega t + \omega \cos \omega t\right) = 0 \tag{6}$$

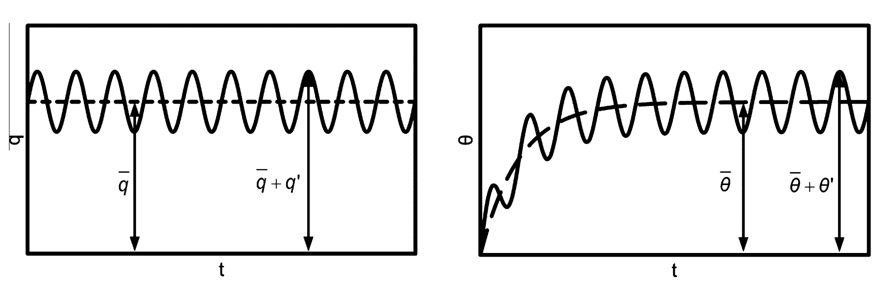

Fig. 4. Definition of a periodic heat source and response of the thermal network element to the source.