DETERMINATION OF THERMAL PARAMETERS FOR PMSM

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Abstract—This paper presents determination of the thermal resistances and capacitances of the model based on the geometry of the different parts of the permanent-magnet synchronous motor. The model in state-space format has been discretized and a model-order reduction has been applied to minimize the complexity. The model has been implemented in a DSP and predicts the temperature of the different parts of the motor accurately in all operating conditions, i.e., steady-state, transient, and stall torque. The results have been compared with real measurements using temperature transducers showing very good performance of the proposed thermal model.

Index Terms—Estimation, modeling, permanent-magnet (PM) machines.

I. INTRODUCTION

MOTORS are one of the most important parts in energy conversion systems. Failure of the motor can result in failure of the whole system, and in most cases, the economical consequences are quite severe. Motors should be operated and deliver rated power within a specified range of temperature rise without any risk for demagnetization of the magnets and/or stator winding failure. In order to avoid the aforementioned failures, different kinds of thermal protection sensors are used. The most common type of protection available is the positive thermal coefficient (PTC) sensor.

A PTC is a nonlinear resistance that increases dramatically at a certain temperature. This resistance can be measured, and hence, the motor can be stopped before the temperature rise exceeds the predefined threshold level. The disadvantage of this method is the inaccuracy as it can only be used as a warning or as a shutdown signal.

A plethora of publication on thermal modeling of electrical motors can be found in the literature. Gerling and Dajaku [10] give a good overview on thermal modeling of electrical systems, and the most common equations for thermal analysis are pre-sented. In [6], a water-cooled permanent-magnet synchronous motor (PMSM) has been modeled. Two thermal models are suggested in [4]: one that consists of 107 nodes and a second that employs 7 nodes. The thermal resistances are calculated and empirical formulas for the different thermal resistances are suggested. Mellor et al. [1] developed an extensive lumped-parameter thermal model of an induction motor. As in the model suggested in [4], this model gives both a steady-state solution and a transient solution of the temperature in the motor. Staton and So [5] and Boglietti et al. [9] study the parameters’ sen Puranen [12] developed a simplified thermal model of an induction motor. This model was made in order to study the suitability and the characteristics of an induction motor in dynamically demanding drives.

Andersson [11] describes two simplified models of a PM motor. One of the models contains components based on real physical parameters and one of the models contains compo-nents based on optimized parameters. Further, Chin [19] pre-sented two different methods for thermal analysis of PMSMs employing two different software tools.

An extensive study concerning the determination of the crit-ical parameters in electrical machine thermal models is pre-sented in [13]. Fussel [3] studies the torque–speed performance of a three-phase brushless dc motor for both natural and forced convec-tions. Forced convection by means of external air cooling was considered. Marcovic et al. [14] study the thermal convection concerning a small motor when natural convection was taken into account.

One way to determine the cooling of a motor is to approxi-mate the chassis with a cylinder. Many studies have been found regarding forced, natural, and mixed convection around a cylinder [14]. These studies investigate horizontal and/or vertical flow. Nevertheless, in special applications, robot arms, etc., motors experience cooling where the flow is often a superposition of a horizontal flow and a vertical flow. No studies have been found in the literature when the
motor operates in the conditions explained before.

<table>
<thead>
<tr>
<th>Electrical Parameter</th>
<th>Thermal Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (I) in [A]</td>
<td>Losses (P) in [W]</td>
</tr>
<tr>
<td>Voltage (v) in [V]</td>
<td>Temperature (T) in [°C]</td>
</tr>
<tr>
<td>Resistance (R) in [Ω]</td>
<td>Thermal Resistance (Rₚ) in [W/K]</td>
</tr>
<tr>
<td>Capacitance (C) in [F]</td>
<td>Thermal Capacitance (Cₚ) in [J/K]</td>
</tr>
</tbody>
</table>

Electrical networks can be used in order to study the thermal behavior of a system. In Table I, the analogy between electrical and thermal parameters is illustrated. Further, Fig. 1 illustrates the analogy between the electrical and the thermal circuits.

The thermal resistance represents the thermal properties of the different materials used in the structure as well as the thermal connection between different structures. Similarly, the thermal energy stored in a structure can be modeled as a thermal capacitance.

The thermal model described in this paper is based on the geometry and the physical properties of the PMSM. Due to the general description, the model can be applied to several PM motors.

Heat transfer between two different structures can be modeled by determining the nodes and the thermal impedances of each material. Different characteristics of a specific machine part, such as temperature distribution, mechanical complexity, and material properties, were considered when the nodes and their assignments were considered. Ten nodes have been considered, i.e., the ambient, chassis, stator yoke, rotor, end winding, stator winding, shaft, ball bearings, internal air, and the mechanical structure where the motor is attached to. In the red arrows (Cond) represent the heat transport due to conduction, the green arrows (Conv) the heat flow due to convection, and the purple (Rad) due to radiation. Radiation is also present internally, but it has not been considered in this paper. The (Cond) (Conv) and (Rad) are indicated in Fig. 2(b) in the proximity of the arrows.

The nodes of interest and the thermal resistances between the nodes are clearly shown. Additionally, in Fig. 3, the power losses in the different parts of the PMSM, such as iron losses, stator winding, and end winding losses, are represented as current sources. The thermal impedances due to conduction and convection have been considered. It must be noted that no finite-element (FEM) calculations have been required to obtain the thermal model described in the following paragraphs.

Conduction occurs when heat is transferred from one element to another due to a temperature gradient between the two elements. The energy is transferred from a warmer region to a colder region and is described by Fourier’s law

\[
q = -\lambda A \frac{\partial T}{\partial x} \quad (1)
\]

where \(q\) is the heat transfer rate, \(\frac{\partial T}{\partial x}\) is the temperature gradient in the direction of the heat flow, \(A\) is the cross-section area, and \(\lambda\) is a positive constant called the thermal conductivity of the material. The thermal conductivity indicates the ability of the material to conduct heat. The thermal resistance for conduction is defined as

\[
R_{th} = \frac{t}{A\lambda} \quad (2)
\]

where \(t\) is the thickness of the element [20].

Similarly, convection occurs when heat is transferred to or from an element by a moving fluid. The heat transfer rate is described by
where $T_w$ is the temperature of the element, $T_\infty$ is the temperature of the fluid, $A$ is the surface area, and $h$ is a coefficient called the convection heat transfer coefficient [2].

The thermal resistance for convection [20] is defined as

$$R_{th} = \frac{1}{Ah}, \quad (4)$$

Two different kinds of convection can be defined: the natural convection and the forced convection. Forced convection occurs when an external source, for example, a pump or a fan, is used to move the fluid. Natural convection, on the other hand, occurs in the absence of an external source, and the driving sources for natural convection are buoyancy and gravity [19].

The stored thermal energy in the different nodes is modeled by thermal capacitance $C_{th}$ (in joules per kelvin) [20], which is

$$C_{th} = mC_p \quad (5)$$

where $m$ is the mass of the structure and $C_p$ is the specific heat capacity. Some of the convection heat transfer coefficients have to be determined experimentally and several proposals have been found in the literature [4], [6], [8], [12]. In this paper, the equation defined experimentally by Kylander [4] has been used since this equation can be used for a wide range of peripheral velocity of the rotor. The convection heat transfer coefficient in the air gap depends on the characteristics of the flow. A turbulent flow gives a higher heat transfer coefficient compared to a laminar flow. The modified Taylor number $Ta_m$ is used in order to determine the value of Nusselt number $Nu$, as given in [1], [4], and [12], which is the factor in the heat transfer coefficient and depends on the flow.

$$Ta_m = \frac{\omega^2 d_{stator} \text{Bore} \delta^3}{2 \cdot \nu^2} \quad (6)$$

where $\omega$ is the angular velocity and $\nu$ is the kinematic viscosity of the air. $Nu$ is calculated from

$$Nu = \begin{cases} 2, & Ta_m < 1740 \\ 0.409 Ta_m^{0.241} - 1377 Ta_m^{-0.75}, & Ta_m > 1740 \end{cases} \quad (7)$$

The $Nu$ used in order to calculate the heat transfer coefficient of the shaft is

$$Nu = \left( \frac{0.825 + \frac{0.387 \cdot d_{stator}^{4/3}}{1 + (0.492/Pr)^{0.75}}}{1} \right)^2$$
The thermal resistances and capacitances of the motor are calculated according to (2), (4), and (5), respectively. Nevertheless, a number of thermal resistances are nonlinear, i.e., they are speed dependent or are dependent on the temperature of the component. The thermal resistance used to model the ball bearings is speed dependent. The resistance modeling the convention between the rotor and the stator yoke depends on the temperature of the two parts. The power losses in a PMSM will cause a temperature rise in the different parts of the motor. Power losses consist of winding losses, iron losses, friction losses in the ball bearings, and friction losses due to turbulence caused by the internal air flow.

The resistive losses of the stator winding can be defined as

\[ P_{\text{resistive}} = R_i i^2 \]

where \( R_i \) is the winding resistance at a certain temperature and \( i \) is the rms value of the current in each phase.

Stator iron losses can be divided into losses due to hysteresis in the yoke \( P_h \) and losses due to the eddy currents flowing in the laminations of the yoke \( P_e \). The total stator iron losses as well as the hysteresis and eddy current losses are defined as
The model has been implemented in a DSP, and the thermal parameters of the PMSM are calculated in real time. This implies that the model has to be described in the discrete form. Thus,

\[
x[k + 1] = A_d x[k] + B_d u[k]
\]

\[
y[k] = C_d x[k] + D_d u[k]
\]

Where

\[
A_d = e^{AT_{\text{sample}}}
\]

\[
B_d = \int_0^{T_{\text{sample}}} e^{A\sigma} B d\sigma
\]

\[
C_d = C\quad \text{and} \quad D_d = D.
\]

In Fig. 4, the RTTM of the PMSM studied in this paper is illustrated.

Electrical measurements such as the speed of the motor \(\omega\) and the output instantaneous torque \(T\) are used in order to estimate the losses in the different parts of the PMSM. Additionally, and with knowledge of the operating condition of the motor, vital decisions can be taken concerning the thermal behavior of the motor. Standstill operation and/or acceleration of the motor under certain loaded conditions can be identified.

A. Model-Order Reduction

Model-order reduction (MOR) is a branch of systems and control theory, which studies properties of dynamical systems in application for reducing their complexity while preserving (to a certain extent) their input–output behavior. MOR replaces the original large-scale system with a reduced order i.e., much smaller system, yet still retains the original behavior under investigation to high accuracy.

As already mentioned, the model is used in order to estimate the temperature of different parts in real time. Consequently, the execution time of the model is limited. The execution time depends on the model complexity. By reducing the model, the execution time is comparably decreased. Model reduction has been reported in [36] and [37]. In the present paper, the balance truncation algorithm [38] has been used but is not discussed, although experimental results and simulations are shown.

In Fig. 5, the results obtained by the reduced model are shown. The deviations at three selected points A, B, and C where random perturbations have been added to the speed and torque signals are highlighted. These are summarized in Table III.

As shown in the table, the deviations obtained by comparing the results obtained by the full-order model and the reduced model are negligible.
THEORETICAL AND EXPERIMENTAL RESULTS

A number of simulations have been performed by employing a MATLAB/SIMULINK software in order to verify the thermal behavior of the device under test (DUT). The representation of the discrete-time thermal model is shown in Fig. 6. The calculation of the losses is based on two lookup tables with analytical and experimental data for the motor.

In Fig. 7, the inputs of the model are clearly shown, i.e., the torque reference and the speed of the motor. The torque reference and the speed of the motor fully described the operating conditions of the PMSM in combination with the operating temperature. The operating temperature of the motor is introduced to the model as a feedback loop and is shown in Fig. 7. In Fig. 8, the drive cycle used is shown. The motor operates at constant speed and torque for 3800 s. Then, the speed is varied from 1000 to 1500 r/min, as shown in the figure, for 4000 s. Further, with the motor operating at constant speed, the torque is varied. In Fig. 9, a comparison between the simulation results obtained by the MATLAB/Simulink model and experimental results is shown. As shown in the figure, excellent agreement has been achieved. In Fig. 9, the warm-up and the cooldown periods are shown. When the motor is stopped, the model is still in operation and estimates the temperature of different parts considering that the losses fed into the motor are zero. This feature is quite important since the estimated temperature during cooldown can be used when the motor is restarted. The measured values were obtained with one PT100 sensor located at the end winding of the motor as well as one PT100 located on the housing. The model has been tested when the motor is operating under stall torque. During stall torque, the current is distributed unevenly in the winding of the motor. In Fig. 10, the current through the phase winding is shown. The vertical lines indicate different stall torque cases. When the motor operates, as indicated by the second vertical line (green), the current through phase U is zero and 0.9 p.u. and -0.9 p.u. through phases V and W, respectively. This implies that phases V and W are thermally stressed and phase U is cooled down. In Fig. 11, the results obtained by simulations and experiments are plotted. The results correspond to phase W. As shown in the figure, the agreement is excellent considering the measured and the simulated temperatures of the chassis. On the other hand, the results obtained for the phase end winding temperature is fairly acceptable. The deviation is up to 8°C. As shown in the figures, good agreement between simulation and experimental results has been obtained when the motor is operating at steady state and during transient operating conditions.

On the other hand, during stall torque operation, the agreement is fairly good since at this working point, only one phase carries the full current, which makes it difficult to obtain an accurate estimation. However, the results obtained could still be used to protect the motor effectively.

V. IMPLEMENTATION OF THE RTTM AND EXPERIMENTAL RESULTS

The RTTM has been implemented in the DSP of the inverter of the motor. As already mentioned and due to the execution time limitations, a reduced model has been considered. Different drive cycles have been considered in
order to prove the feasibility of the model.

The experimental setup is shown in Fig. 12, where it is shown that the speed of the motor is controlled by an inverter and the torque by the load machine. PT100 elements have been used in order to measure the temperature of the different parts of the motor that are of interest, i.e., the end and stator winding temperature, the stator yoke temperature, and the shaft and chassis temperature.

square of the current, as given by (9). As shown in the figure, the results are in good agreement, though the deviations are not constant. A summary of the results is given in Table IV. The presented values correspond to the maximum deviation at steady state. Similarly, the plus sign indicates that the temperature is overestimated by the RTTM.

In Fig. 13, the examined drive cycle and a comparison between the estimated and the measured temperatures are shown.

The examined cycle is a high-speed, high-torque drive cycle. Therefore, the motor losses are comparably high. Observe that the iron losses are proportional to the square of the speed, as defined in (10). Similarly, the winding losses are proportional to the

In Fig. 14, the examined drive cycle and a comparison between the estimated and the measured temperatures are shown. The specific drive cycle is a mixture of stall torque, transient, and steady-state operations. The speed of the motor is not very high compared with the drive cycle presented in Fig. 13(a). On the other hand, the motor experience intermittent high peak

![Results obtained by the reduced model (three selected points A, B, and C are shown for comparison).](image)

<table>
<thead>
<tr>
<th>( \Delta \theta ) in (^{\circ}{\text{C}} ) at A</th>
<th>( \Delta \theta ) in (^{\circ}{\text{C}} ) at B</th>
<th>( \Delta \theta ) in (^{\circ}{\text{C}} ) at C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.012</td>
<td>0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Table II**

*Deviations comparing the full-order model with the results obtained by the reduced model.*
**Fig. 6** Real-time thermal model

**Fig. 7** Drive cycle

### TABLE III
**SUMMARY OF THE RESULTS AT STEADY STATE**

<table>
<thead>
<tr>
<th></th>
<th>EndWinding</th>
<th>Chassis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>103</td>
<td>82</td>
</tr>
<tr>
<td>Simulated</td>
<td>106</td>
<td>88</td>
</tr>
<tr>
<td>$T$</td>
<td>+3</td>
<td>+6</td>
</tr>
</tbody>
</table>

The plus sign indicates that RTTM overestimates the temperature.
Fig. 8 Comparison between measured and simulated results

Fig. 9 Stall torque operation. Observe that the vertical lines are determining the current through the windings of the motor.

**TABLE IV Motor Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of poles</td>
<td>$n$</td>
</tr>
<tr>
<td>Low speed torque</td>
<td>$T_0$</td>
</tr>
<tr>
<td>RMS Torque</td>
<td>$T_{rms}$</td>
</tr>
<tr>
<td>Rated Speed</td>
<td>$N_0$</td>
</tr>
<tr>
<td>Speed at RMS Torque</td>
<td>$N_{rms}$</td>
</tr>
<tr>
<td>Current at $T_0$</td>
<td>$I_0$</td>
</tr>
<tr>
<td>Resistance at $20^\circ$C per phase</td>
<td>$R_{20}$</td>
</tr>
<tr>
<td>Nominal winding inductance per phase</td>
<td>$L$</td>
</tr>
<tr>
<td>Value of $T_0$</td>
<td>40 [Nm]</td>
</tr>
<tr>
<td>Value of $T_{rms}$</td>
<td>32 [Nm]</td>
</tr>
<tr>
<td>Value of $N_0$</td>
<td>3560 [rpm]</td>
</tr>
<tr>
<td>Value of $N_{rms}$</td>
<td>1460 [rpm]</td>
</tr>
<tr>
<td>Value of $I_0$</td>
<td>26.8 [A]</td>
</tr>
<tr>
<td>Value of $R_{20}$</td>
<td>0.123 [Ω]</td>
</tr>
<tr>
<td>Value of $L$</td>
<td>1.49 [mH]</td>
</tr>
</tbody>
</table>
torque. This implies that the winding losses might be the dominant power loss mechanism. As shown in the figure, the results are in good agreement. The current through the warm winding, phase U, and the current through phase V are comparable with each other. Observe that the RTTM estimates the highest temperature of the motor that is critical in order to avoid motor failure due to high thermal stresses.

VI. CONCLUSION

In this paper, an RTTM concerning a PMSM has been presented. The modeling procedure was briefly presented. The thermal resistances and capacitances of the model are calculated based on the geometry of the different parts of the motor. The model is then expressed in a matrix form, represents a state-space model, and is discretized. Since the model is expressed in state space, conventional control theory techniques, e.g., MOR, have been applied in order to reduce the complexity of the model. Simulation results have been compared with experimental results in order to study the performance and the feasibility of the concept. Additionally, the RTTM has been implemented in a DSP, and the estimated results have been compared with experimental results. An overall good agreement has been achieved between estimated and experimental results. The deviations obtained can be due to discretization of the model, though it is evident that the model discretization can cause minor problems.

REFERENCES


