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# Thermal Modelling of an Alternator for Use in a Prediction System

James Graham*, Roger Dixon*, Keith Gregory*, John Pearson†

*School of Electronic, Electrical and Systems Engineering, Loughborough University,
Loughborough, Leicestershire, LE11 3TU
†BAE Systems SEIC, Holywell Park, Loughborough University,
Loughborough, Leicestershire, LE11 3TU
Contact: J.H.Graham@lboro.ac.uk

*Abstract*—**On future UAVs it is envisaged that the power requirements of all on-board electrical systems will increase. Whilst, in most flight (mission) situations the installed generation capacity will have adequate capacity to operate the systems, it is possible that during certain abnormal situations the generators on-board may be forced to operate under very high load conditions. The main failure mechanism for a generator is overheating and subsequent disintegration of windings, hence the research problem being addressed here is that of modelling the thermal dynamics of a generator in such a way that the model can be used to predict future temperatures given knowledge of the future mission requirements. The temperature predictions will be used to allow prioritising of the mission actions in order to get the most out of a generator without overheating it.**

**The research presented here shows details the modelling of the generator, and presents some initial validation results showing good correlation between data taken from the rig and the simulation output of the model.**

## I. Introduction

The current trend of increased use of electrical power to run systems on-board an aircraft [1] [2] has lead to much research being undertaken to improve system performance, reliability and maintainability. Flight critical systems previously operated by other means, such as hydraulics or pneumatics, now need to be guaranteed a constant supply of electricity to be considered safe. This aim of this study is to look at power supply within aircraft, focusing particularly on power generation, aiming to develop methods of ensuring more reliable supply of power.

The ability of a generator to supply power is based upon its thermal state, assuming there are no other faults on the system. Under normal circumstances a well designed generator will easily operate within its thermal limits, but certain abnormal situations may force very high loading of the generator which could push it near or above its thermal limits.

The main failure mechanism for a generator is overheating and subsequent disintegration of windings, hence the research problem being addressed here is that of modelling the thermal dynamics of a generator in such a way that the model can be used to predict future temperatures given knowledge of the future mission requirements. The temperature predictions will be used to allow prioratising of the mission actions in order to get the most out of a generator without overheating it.

When looking at the literature available on thermal modelling of electrical machines it became apparent that it was almost exclusively focused on their design, and there was no work using this type of model as part of a health management system. The types and use of thermal models is summarised by Boglietti et.al. [3] in their survey paper.

When choosing the modelling method, the biggest factor in the decision was the execution speed. For the model to be useful in a prediction system it would have to be able to make predictions in real-time, this eliminated computational fluid dynamics (CFD), and finite element analysis (FEA) as possible methods due to their computational intensity. Instead a lumped parameter, thermal network type model was chosen.

Literature is available detailing this type of model. Example include the work of Perrez and Kassakian [4], and the work of Mellor et. al. [5]. This works on the principle that at its most simple an electrical machine is a lump of iron/steel, with copper windings. By modelling the iron parts of the generator as cylinders, parameters can be designed to calculate the average temperature of the various components to a good degree of accuracy, but using a fraction of the computing power of other methods.

The rest of this paper details the design of the thermal model for a generator, specifically one that is part of an experimental rig available to help validate the model. Section II. talks about the experimental rig. Section III. details the model design and choices, as well as the method of simulation. Section IV. details the current results, and section V. concludes the paper.

## II. Experimental Setup

The experimental rig setup is shown in Figure 1.

The rig itself consists of a motor driving the shaft of a 3-phase, 415V, 50Hz generator with a rated power of 5kVA, allowing the shaft speed to be controlled as necessary for any experiments. Table I lists the sensor measurements currently available, although more sensors are to be added in the near future to give a larger range temperature measurements from the generator. These include the temperature of the air flow at the input, output, and in some of the air spaces where possible. Sensors which enable a mass flow reading for the airflow to be determined are also to be installed.

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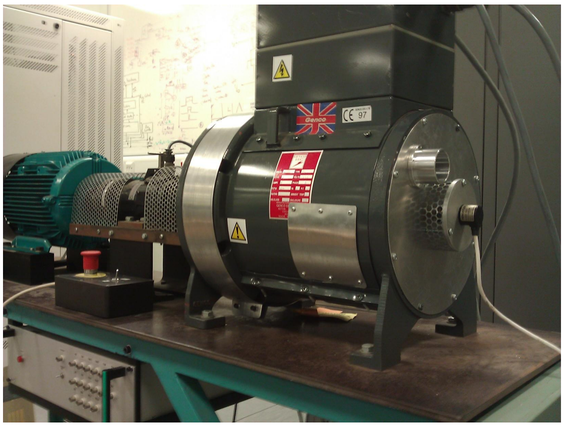

Fig. 1. Test Rig.

TABLE I
SENSOR ON THE RIG

| Variable | Signal Label | Transducer Range |
|---|---|---|
| Stator Phase U Current | Ua1 | $\pm 230A$ |
| Stator Phase U Current | Ua2 | $\pm 15A$ |
| Stator Phase V Current | Va1 | $\pm 230A$ |
| Stator Phase V Current | Va2 | $\pm 15A$ |
| Stator Phase W Current | Wa1 | $\pm 230A$ |
| Stator Phase W Current | Wa2 | $\pm 15A$ |
| Stator Phase U - Neutral Voltage | Uv | $\pm 500V$ |
| Stator Phase V - Neutral Voltage | Vv | $\pm 500V$ |
| Stator Phase W - Neutral Voltage | Wv | $\pm 500V$ |
| Exciter Winding Current | Ea | $\pm 5A$ |
| Exciter Winding Voltage | Ev | $\pm 125V$ |
| Auxiliary Winding Current | Xa | $\pm 2.5A$ |
| Auxiliary Winding Voltage | Xv | $\pm 500V$ |
| Stator Phase U Temperature | Ut | $-50$ to $300°C$ |
| Stator Phase V Temperature | Vt | $-50$ to $300°C$ |
| Stator Phase W Temperature | Wt | $-50$ to $300°C$ |

## III. Model Design

The first stage in designing a lumped parameter model is to subdivide the generator into the various section, with each section then being modeled, as a subset of the full model. The subdivisions need to model the generator in sufficient detail that the temperature states of various parts of the generator can be found. This is balanced by the most important requirement, that the model is able to simulate the thermal state in real time so the number of nodes needs to be kept to the minimum possible.

Many authors have made different choices in how they subdivide their model Yangsoo et.al [6] divided the stator and rotor into multiple nodes in order to obtain the best possible accuracy, but this also lead to increased computation time. Kylander [7] showed that a thermal network model can still obtain high accuracy even when subdividing the machine in a modest number of areas. This was also applied by Okoro [8] giving steady state temperatures within $\pm 5°C$.

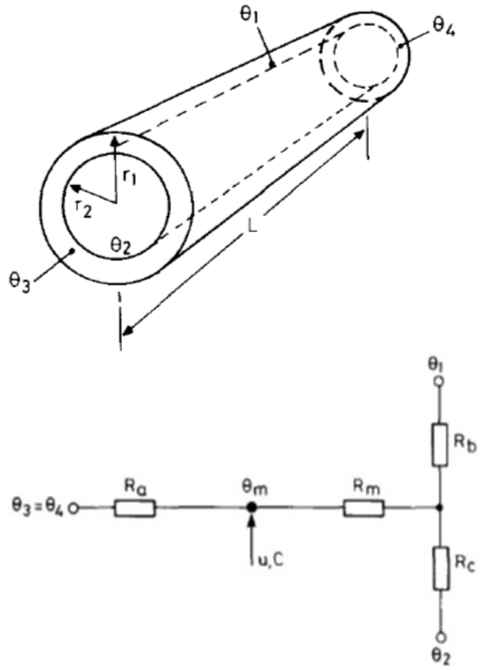


Fig. 2. Standard Cylinder and Thermal Network [5].

### A. Subdivisions within the Model

In the model the generator was broken down into 5 main areas, some of which were further subdivided. The 5 areas were the frame, stator, rotor, shaft and the air within the generator.

Unlike most current literature where the whole motor is considered in the same amount of detail, whether that be high or low, for this model the most important heat paths were identified and modeled in the most detail. These were: the stator, due to the fact that the stator winding will be the hottest part of the motor; and the air in the generator, the high airflow through the machine means that the forced convection created by it needs to be modeled carefully to get the best accuracy.

Two types of heat transfer considered in the model: conduction; and convection. The conductive heat transfer was modeled using a node at the centre representing the average temperature of the section, where any heat input, and the heat storage of the section are introduced, thermal resistance then describe the heat conduction over the component. The general model used to represent a cylinder is shown in Figure 2.

Due to the fact that the stator in the machine is only 54mm long, it was assumed that the axial temperature in the components of the model is constant, this is shown in figure 2 as a single thermal resistance $R_a$ representing the flow of heat from the mean temperature to the ends of the cylinder. Unlike many authors using this approximation though the decision was taken to model the whole length of the machine, not just half. This was due to considerations with the coolant network that are described later. The equations for the network from Mellor et. al. are shown below [5].

$$R_a = \frac{L}{6\pi k_a(r_1^2 - r_2^2)} \quad (1)$$

$$R_b = \frac{1}{2\pi k_r Ls}\left(1 - \frac{2r_2^2 log(\frac{r_1}{r_2})}{r_1^2 - r_2^2}\right) \quad (2)$$

$$R_c = \frac{1}{2\pi k_r Ls}\left(\frac{2r_1^2 log(\frac{r_1}{r_2})}{r_1^2 - r_2^2}\right) \quad (3)$$

$$R_m = \frac{1}{4\pi k_r Ls(r_1^2 - r_2^2)}\left(r_1^2 + r_2^2 - \frac{4r_1^2 r_2^2 log(\frac{r_1}{r_2})}{r_1^2 - r_2^2}\right) \quad (4)$$

Where $R_{a,b,c,m}$ are the resistance shown in Fig. 2, $L$ is the cylinder length, $r_1$ and $r2$ are the outer and inner radius respectively, $k_r$ and $k_a$ are the axial and radial thermal conductances, and $s$ is the stacking factor.

*1) Stator:* As stated earlier the stator is one of the two important areas in the model, and getting the necessary detail to model the winding temperature as well as the iron temperature was necessary. The stator was split into three areas, the stator back iron, stator teeth and stator winding. The stator iron and teeth were modeled as cylinders shown above, with the addition for the stator teeth of a resistance which gave the temperature of the inside of the slot touching the winding.

The stator winding was modeled by using the network for a rod (i.e. inner radius = 0) to represent a single slot, then multiplying this by the number slots on the stator.

*2) Rotor:* The rotor was modeled as a single cylinder, this choice was made because it was less important to have the same detail in the model that the stator has, as it would be much cooler during operation and not liable to overheat. It would also be extremely difficulty to measure the temperature of the rotor during operation making it hard to validate the results accurately, and the extra computation time required to simulate the nodes is unnecessary in this application.

*3) Shaft and Frame:* Both the shaft and frame were modeled as simple two resistance networks, which are more than adequate for this application.

### *B. Coolant Network*

The generator that the model is based upon (Fig. 1) has a large fan attached to the shaft designed to provide a large amount of airflow through the generator. This means that within this model it is not appropriate to assume that most heat transfers from the stator to rotor, or vice versa.

Yangsoo and Kauth [6] researched the modelling of an induction motor with forced cooling, using a two-network solution, one for the motor, one for the cooling. In this case both parts are modeled as a single network in order to maintain greater simplicity. The major difference between radial and axial heat flow is in how the resistance for axial heat flow is defined. Figure 3 shows a diagram of the thermal network for the air gap in the machine.

The thermal resistances $R_{con1}$ and $R_{con2}$ are calculated using the equation for convective heat transfer

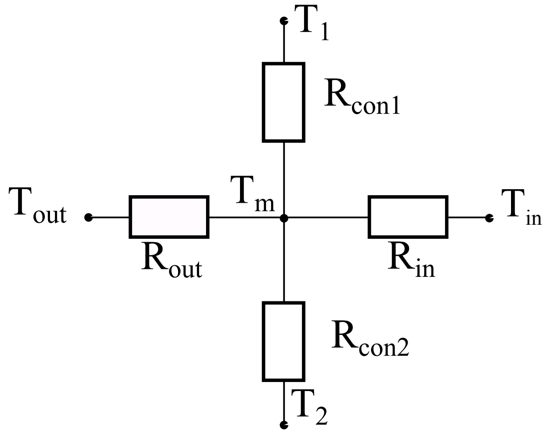


Fig. 3. Network for airflow.

$$R = \frac{1}{h_C A} \quad (5)$$

Where $h_C$ is the convective heat transfer co-efficient, and $A$ is the surface area.

The thermal resistance for $R_{in}$ and $R_{out}$ are based upon the mass flow rate through the air section

$$R = \frac{1}{\dot{m}C_p} \quad (6)$$

Where $\dot{m}$ is the mass flow rate, and $C_p$ is the thermal conductivity. As expected this leads to very low resistance values for axial heat flow through the air sections as expected with forced convection.

This thermal network is used to model the four air sections in the generator, the air gap, the two end air sections, and finally the air in the gap between the stator and the frame. The air flows into the end air at one side, splits between the air gap and top air, then re-combines on the other side. The size of the gap between stator and the frame is much larger than the stator/rotor air gap meaning the large proportion of the air flows through it cooling the stator and transferring some heat to the frame.

### *C. Solving the Thermal Network*

Figure 4 shows the complete thermal network of the generator, with Table II showing what each number in the diagram represents. From this a heat balance equation can be obtained for each node in the model, the equation for the central node of the stator iron is shown below

$$C_{si}\frac{d\theta_{sim}}{dt} = \frac{1}{R_{sia}}(\theta_{sia} - \theta_{sim}) + \frac{1}{R_{sir3}}(\theta_{sim'} - \theta_{sim}) + U_{si} \quad (7)$$

Where the subscript $si$ denotes that the value is from the stator back iron, with the letters $a$ and $r$, denoting axial and radial directions respectively, $R_{sia}$ for example is the stator iron axial resistance. $C_{si}$ is the heat storage for the stator back iron, $\theta_{sim}$ is the average temperature of the part, $U_{si}$ is the heat

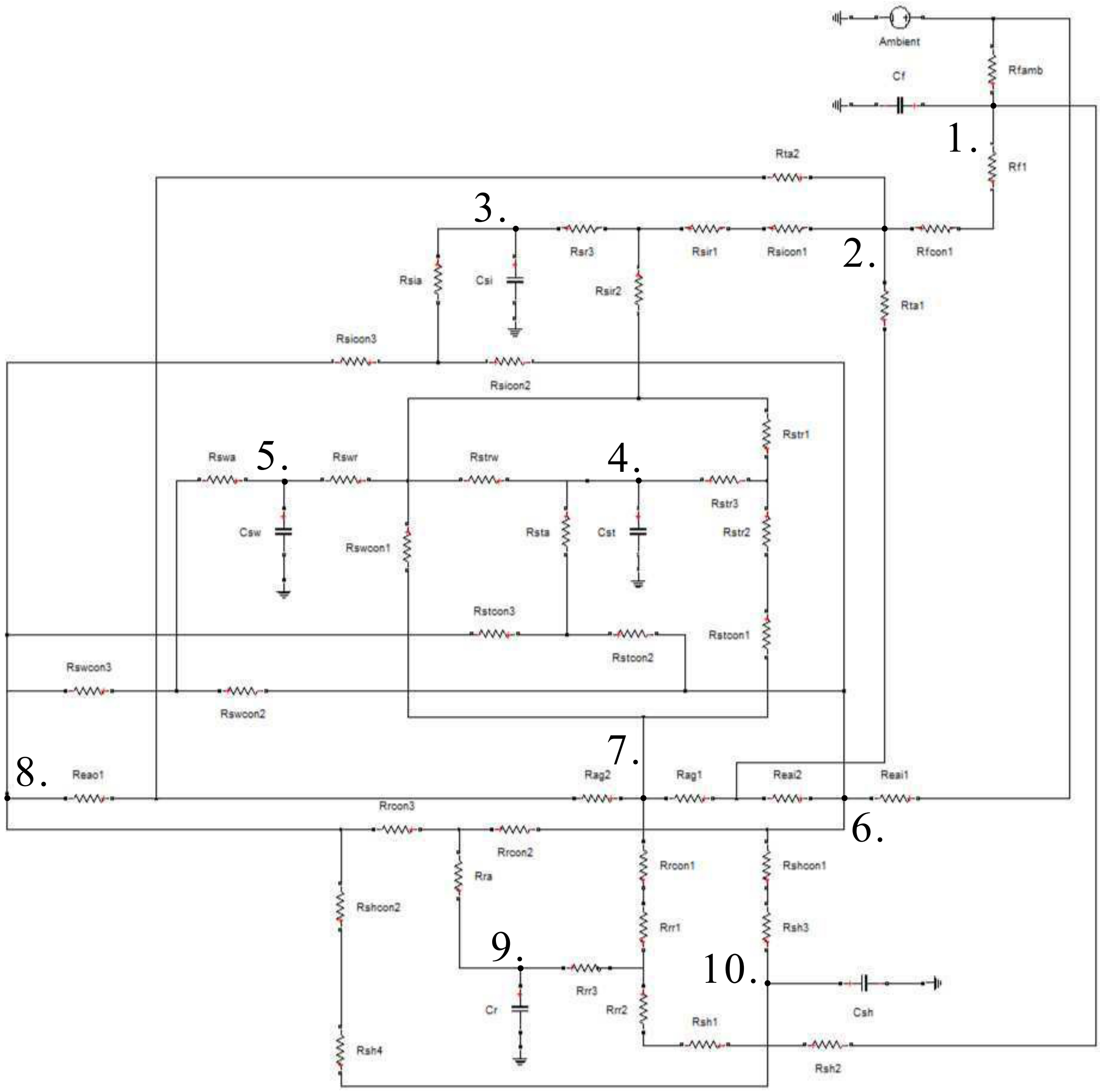


Fig. 4. Complete thermal network.

TABLE II
MODEL SUBDIVISIONS

| Fig. 4 No. | Generator Part |
|---|---|
| 1 | Frame |
| 2 | Top Air |
| 3 | Stator Back iron |
| 4 | Stator Teeth |
| 5 | Stator Winding |
| 6 | End Air In |
| 7 | Air Gap |
| 8 | End Air Out |
| 9 | Rotor |
| 10 | Shaft |

input to the stator iron. $\theta_{sia}$ and $\theta_{sim'}$ are the temperatures at the adjacent nodes, with $R_{sia}$ and $R_{sir3}$ being the thermal resistance between them.

Each node can be expressed in a similar manner to Eq. 7, these equations can then be expressed in matrix form

$$[C]\frac{d[\theta]}{dt} = [G][\theta] + [u] \tag{8}$$

where $[C]$ is a square matrix of thermal heat storage values, $[G]$ is a square matrix of thermal conductance between nodes, $[\theta]$ is the node temperature states, and $[u]$ is a column matrix of heat sources. The above differential equations allow the network to be solved for transient conditions.

TABLE III
SIMSCAPE EQUIVALENT COMPONENTS

| Electrical Component | Thermal Equivalent |
|---|---|
| Resistor | Thermal Resistance |
| Capacitor | Heat Storage |
| Current Source | Heat Input |
| Voltage Source | Constant Temp |

### D. Simulation in Simscape

When the initial work was undertaken to create this model, the first iterations were kept simple with few nodes to test the concept, complexity was then increased through iterations, with the addition of nodes. It was found that while it was easy to update the various resistances within the model using a simple Matlab script, the addition of nodes meant that often equations completely changed, as well as new ones added, and this meant that the system of equations would have to constantly be re-written, and then condensed, taking a lot of time.

In order to speed up the process, to avoid having to re-calculate the the matrices for Eq. 8 every time changes to the number of nodes are made, the Simscape package in the Matlab Simulink environment was used. Specifically the electrical component libraries. The electrical library was used instead of the thermal library due to the fact the thermal library doesn't have the flexibility required to simulate the cylindrical components used, nor can some of the interactions be modeled sufficiently between certain sub-divisions within the model.

The electrical components within the model are easily related to the equivalent thermal ones, Table III list the components and what they represent.

## IV. VALIDATION

Some initial data was collected from the alternator rig and was used to show that the model performed as expected. Currently it was only possible to extract temperature data for stator windings, as more temperature sensors are yet to be installed, but the results still give a good indication of the accuracy of the model until full validation is finished.

The temperatures were measured using PT 100 type platinum resistance thermometers (PRT) placed within each of the stator windings. The PRTs conform to the class B specification in BS 1904 : 1984 [9], the probes are 35mm long, and 4.8mm diameter, with a thin film core. The three measurements taken were then combined to give an average temperature of the stator windings as a whole.

Figure 5 shows a comparison of the measured stator winding temperature to the simulated one. The results show that the model simulates the final steady state temperature with good accuracy, but as is seen in work by others [8] the time constant of the model is faster than the actual system, while this doesn't lead to huge inaccuracy matching the time constant more accurately will provide better performance during rapid load transitions. Further data needs to be collected, giving

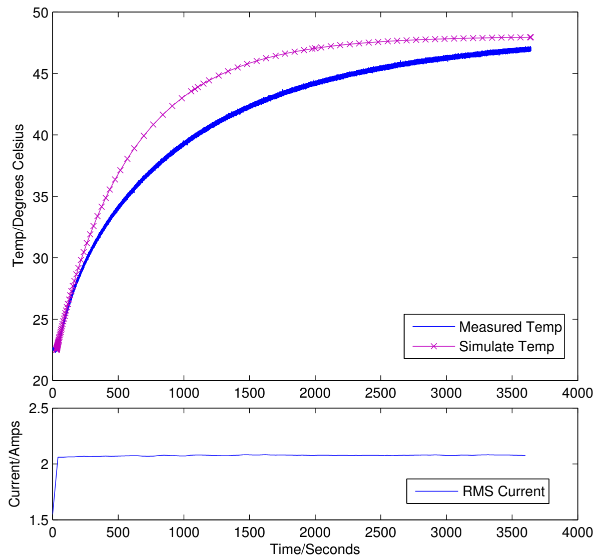


Fig. 5. Initial comparison of model to stator winding temperature.

information on other areas of the generator. Tests need to be undertaken which show the model simulating multiple steps for increasing power output, and finally tests which show the model performance during a cooling cycle.

Also included are graphs showing the simulated temperatures for the rest of the generator (Figures 6 and 7). Looking at the graph it can be seen that the simulation results meet some basic expectation. The stator winding and teeth are the hottest parts of the generator as expected, followed by the stator iron. It also shows that the heat flow in the air is modeled correctly, with the input air temperature much lower than the output air temperature.

## V. FURTHER WORK

The work described here covers just the initial modelling of the generator, with some initial validation work completed. The next stage is to complete the validation process, with the expectation of increasing the accuracy of the model further, especially refining the most important heat paths in the model around the stator and its winding, as well as the airflow through the generator.

There is also the second stage of the study to complete using the model as a prognostic tool to predict the generator's thermal state over time. This will include designing a system to set the initial model states as accurately as possible before prediction, a method of creating estimated load profiles, and the designing of scenarios to test the system at its limits.

## VI. CONCLUSION

This paper has presented the thermal model for a 3-phase generator. The execution is very fast, simulating 3614 seconds of operation in 2.59 seconds, therefore easily fulfilling the

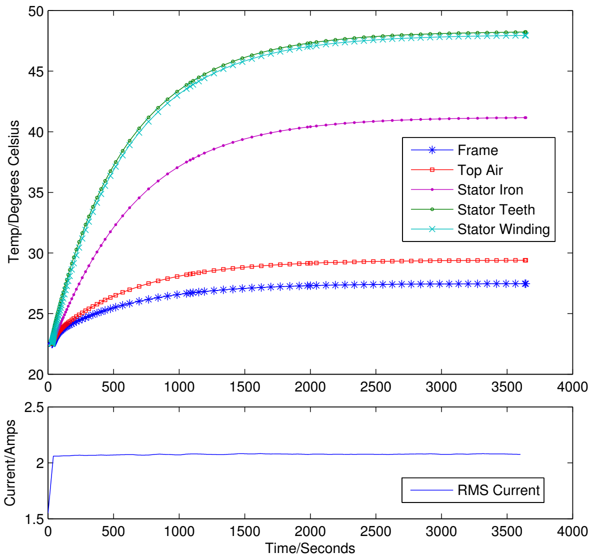


Fig. 6. Stator, Frame and Top Air temperatures with current over time.

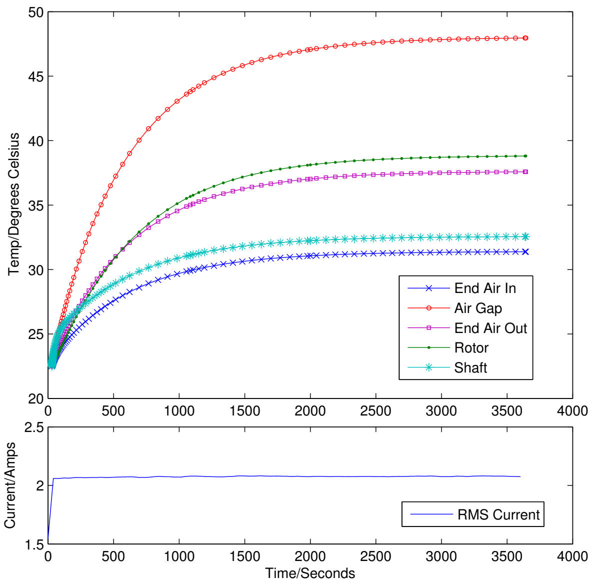


Fig. 7. Air and Rotor temperatures with current over time.

most important requirement of the model, to operate in real-time or faster.

Initial validation results show that the model is able to achieve a good degree of accuracy as well, simulating transient operation. Although there is still more testing to be undertaken with extra sensors added to test if this accuracy is maintained across all temperature states of the model.

## VII. Acknowledgments

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