Thermal Sensitivity Analysis for TEFC Induction Motors

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Abstract:

With the ever increasing pressures on electric motor manufactures to develop smaller and more efficient electric motors, there is a trend to carry out more thermal analysis in parallel with the traditional electromagnetic design. It has been found that attention to the thermal design can be rewarded by major improvements in the overall performance. Thus, accurate and reliable motor thermal models that can easily be incorporated into the motor designers software tools are required. In this paper one such thermal software package is described. Particular enphasis of the paper will be on using the software to fully analyse the thermal behavior of a range of Total Enclosed Fan Cooled (TEFC) induction motors. Concentration will be placed on sensitivity analysis, where the most important design parameters are varied and their effect on the temperature rise evaluated. This is useful to identify which parameters are important allowing robust designs to be developed which are insensitive to manufacturing tolerances.

Thermal Software:

The thermal software package used in this project is based on the analytical lumped circuit approach. The circuit shown in Figure 1 is a 3-dimensional representation of the main heat transfer paths within the machine. This is very similar to an electrical network, but the electrical resistances are replaced by thermal resistances and current sources by power sources (losses). Thermal resistances for the conduction heat transfer paths are calculated from the dimensions and thermal conductivity of the particular component. Radiation is calculated using the emissivity and surface area. Convection (natural and forced) is calculated using proven empirical correlations which are based on dimensional analysis [1,2]. More details of the lumped circuit model are given in references [1] and [2].

One useful feature of the software package is the implementation of ActiveX technology to allow the software to be incorporated into the designers suite of development programs. The original thermal software package was written using the Borland Delphi programming language [3]. Using ActiveX technology its is easy to treat the software as a black-box calculator. Any input parameter can be varied, the performance calculated and output parameters viewed - all from any 3rd party software package that supports the ActiveX standard, i.e. Excel, Matlab, C++, Python, etc. For instance it is very easy to write VBA scripts to run in Excel or to write Matlab routines that automate the design calculation process. This is very useful for sensitivity analysis, where the user is interested in varying a parameter value over a given range and analysing its influence on the temperature rise.

As the software is analytical in nature the speed of calculation is extremely fast such that the designer can obtain results in real time. The use of analytical routines is especially useful in this case as it is virtually impossible to reduce the problem to two dimensions as is commonly carried out with electromagnetic analysis. A three dimensional numerical solution would have a large execution time and would involve a significant amount of effort in setting up. ActiveX technology also has the advantage that the thermal software can be directly linked to other software packages such as the designers electromagnetic software. Very powerful combined packages can be developed. This is important as it is an over simplification to carry out the electromagnetic and thermal design in isolation, i.e. the temperature rise depends on the losses and the losses depend on the temperature. The thermal model can also easily be incorporated into automated optimization routines that deal with both electromagnetic and thermal design, e.g. using genetic algorithms.

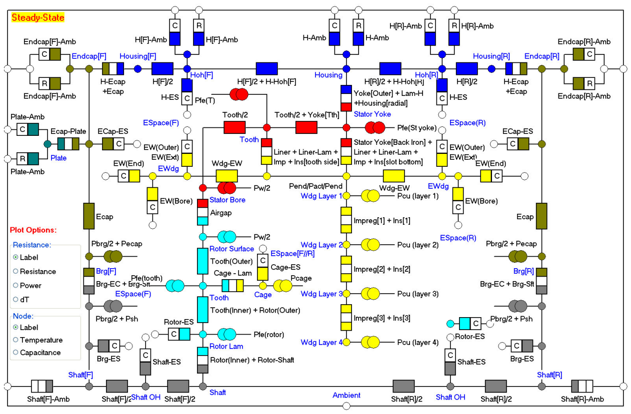

Figure 1: Lumped Circuit Model for an Induction Motor

Motor Testing and Analysis:

Thermal models have been developed for the five industrial induction motors shown in Figure 2 (rated powers of 4 kW – 7.5 kW – 15 kW – 30 kW – 55 kW, 4 poles, 380 V, 50 Hz). The models produced have been experimentally verified. In particular, for each motor a calibrated model has been set up in which certain key parameters have been varied until a good match is obtained between the measures and calculated winding, housing and stator lamination temperatures. The variables chosen in this case are the impregnation goodness (i.e. the ratio of impregnation to air for the winding), the interface gap between housing and lamination and the radiation and convection from the outer surface of the machine. The forced convection is a function of air velocity which itself depends upon the open fin channel air leakage and blockage factors due to terminal boxes and bolt lugs, etc. [1,2,4]. These design variables are difficult to identify accurately without some amount of testing. This calibration process gives us a great insight into the thermal performance of the machine as it highlights the main strengths and weaknesses of the design. The sensitivity of the temperature rise to the main design variables in the machine design can also be easily shown.

Figure 2: Induction Motors used in the analysis

DC Model:

In this model the stator copper losses are present only. For the motor testing series and parallel phase winding connections are used to supply the motor with a DC current equal to 50÷70% of the rated current. The cooling air speed is zero so a reduced current is necessary to avoid damage to the fan cooled motors. In the steady state thermal condition the adsorbed electrical power and the temperatures of the stator windings, stator core and external housing have been measured.

The required parameter values to give a calibrated model for the five motors are shown in Table I. The impregnation goodness is the ratio of impregnation volume to the volume of winding area available for the impregnation (an impregnation goodness of 0.8 means 80% impregnation with 20% air pockets). The interface gap is that between the housing and stator lamination. The h_{Adjust} factor is a multiplier used in the natural convection calculation (a value of 1 means an accurate internal correlation calculation).

Table I: DC Model Calibration

Rating	Impregnation Goodness	Interface Gap [mm]	h_{Adjust}
55kW	0.50	0.02	1.35
30kW	0.55	0.01	1.00
15kW	0.30	0.07	0.95
7.5kW	0.40	0.08	0.87
4kW	0.40	0.04	0.95

A housing emissivity of 0.8 is assumed in Table I. It is seen that the impregnation goodness is much lower than the ideal value of 1 for the range of motors. This could be an indicator that there is a significant amount of air in the impregnation. Alternatively, it could be that the impregnation material has a lower thermal conductivity or the slot liner material properties are worse than those assumed. The winding is a very complex composite of copper and insulation in which often accurate insulation material data is not available. Calibration of one of the winding input parameter values is usually sufficient as all the winding thermal resistances associated with the different complex issues are in series. Trying to calibrate more than one of these (i.e. calibrate the impregnation goodness, the impregnation thermal conductivity and the interface gap between liner and lamination) is usually not necessary and often requires more effort than can be justified by the marginally a more accurate model.

The effective interface gaps between the housing and lamination shown in Table I are much larger than a value of around 0.005 – 0.01mm that could practically be achieved between two smooth solid surfaces with a relatively high pressure and the metallic materials used here (aluminum housing used in the smallest three motors and cast iron housing in the two largest motors) [1]. The reason why this interface is usually much larger in electrical machines is that the stator has a laminated surface that could be less then perfectly smooth. It may have features stamped on the outside surface of the lamination that result in a larger effective gap and there are manufacturing difficulties in fitting the housing onto the stator lamination. Also, in the case of an aluminum housing its higher temperature expansion rate leads to a less tight fit at higher temperatures. This often totally negates the advantage that aluminum is a softer material than cast iron and leads to a smaller effective interface gaps at ambient temperatures [1].

The motor housings shown in Figure 2 are not optimized for natural convection. However, an accurate prediction is required to be able to predict thermal performance when such shaft mounted fan motors operate at or close to stall. The modeling of natural convection over such surfaces is extremely difficult as the ingress of air into the deep fin channels is quite limited. The software used to model the motors recognizes this limitation and automatically accounts for this by limiting the effective convection area of any fin channels on the side of the motor to a depth equal to the fin spacing [2]. This seems to give acceptable results as shown in Figure 3. Here we see the computed and measured thermal resistance from winding to ambient at stall for the five motors (default setting of all parameters). This is further confirmed by the fact that the required adjustment factor for natural convection (h_{Adjust}) in Table I is close to 1 for all the motors. Any deviation from 1 may not necessarily be due to an error in the natural convection formulation, but could be an inaccurate estimate of the housing surface emissivity (assumed to be 0.8 in this case), drafts in the test bay area, extra cooling via conduction to the test bed, etc. This last term is taken account in the calculation by attaching the motor model to a model of a flat plate that has its own convection and radiation. The accuracy of this model is however a function of the interface gaps between housing to feet and feet to base-plate and the size and surface finish of the plate. If accurate test data is required an insulted base-plate is recommended. However, this is not always practical and in many cased the base-plate (or flange mounted plate) is sized to represent the extra cooling achievable by conduction in practice, i.e. represents the cooling effects of the load.

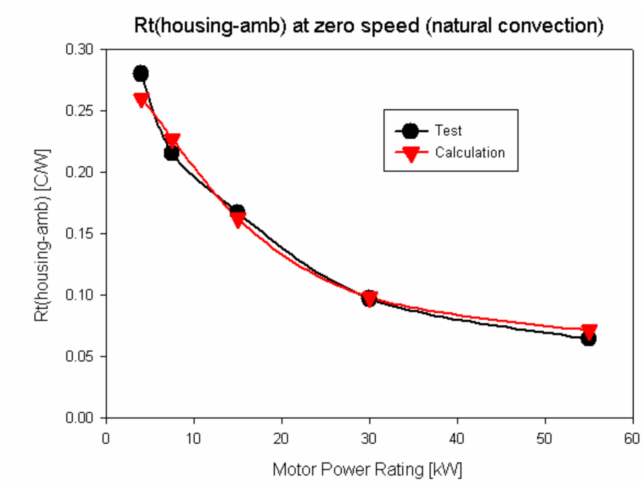

Figure 3: Natural convection resistance between frame and ambient air

The above discussion highlights the problems that can be faced when trying to put together an accurate thermal model of the motor. The designer often has limited information on such things as the achievable impregnation goodness and effective interface gap and may have to assume certain material thermal properties. This is where sensitivity analysis can be most useful. The designer can gain a though understanding of which are the most important design variables in his machine.

Figure 4 to Figure 8 show the dc model sensitivity analysis results performed. In this case for each motor we plot the variation in winding temperature about the calibrated model values for varying values of the following parameters:

- average housing natural convection heat transfer coefficient [h_{Adjust}]
- impregnation thermal conductivity
- housing emissivity
- impregnation goodness
- interface gap between housing and stator lamination

We vary each parameter between -80% to + 100% of the calibrated model values – unless the hard limit is reached first, i.e. the maximum theoretical impregnation goodness factor is 1, as is the maximum emissivity.

It is seen that the design is more sensitive to some parameters than others. In this case the most sensitive parameters are at the top of the list. This data is useful to give an understanding of what the most important parameters for the design are and to make sure that expected manufacturing tolerances do not lead to unexpected results and sub-standard designs. Some of the design variables we cannot do much about in this case. For instance we cannot improve the natural convection without increasing the useful surface area of the housing which may not be practical. The emissivity of the housing can be increased slightly, but we are close to the practical limit of around 0.95 in any case. We could decrease the effective interface gap between housing and stator lamination but the sensitivity analysis seems to suggest that this will not give a vast improvement in performance. The best things to concentrate on are to improve the impregnation material (higher thermal conductivity) and/or increase the impregnation goodness factor (improved impregnation techniques with less trapped air).

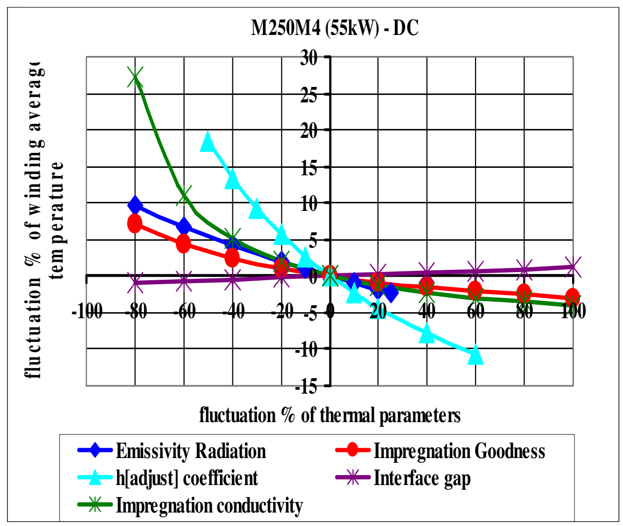

Figure 4: DC model sensitivity analysis (55kW)

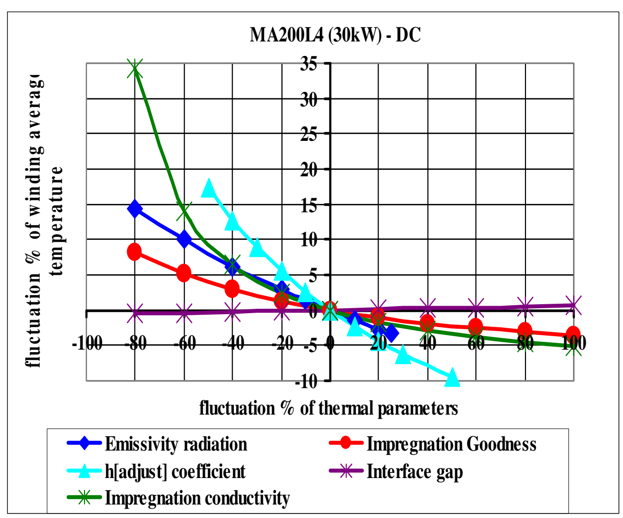

Figure 5: DC model sensitivity analysis (30kW)

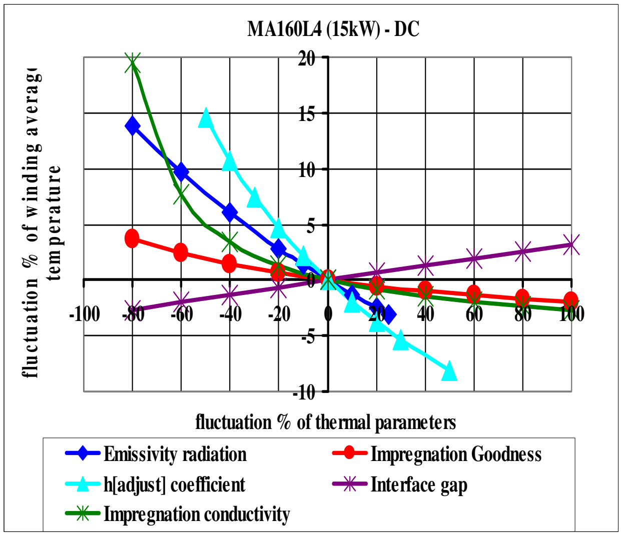

Figure 6: DC sensitivity analysis (15kW)

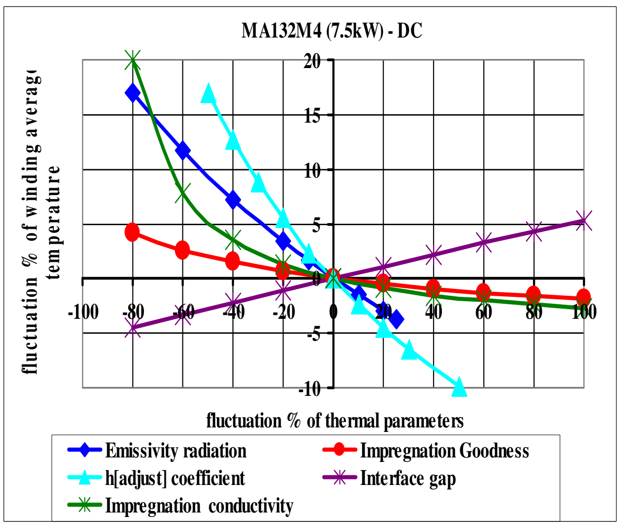

Figure 7: DC model sensitivity analysis (7.5kW)

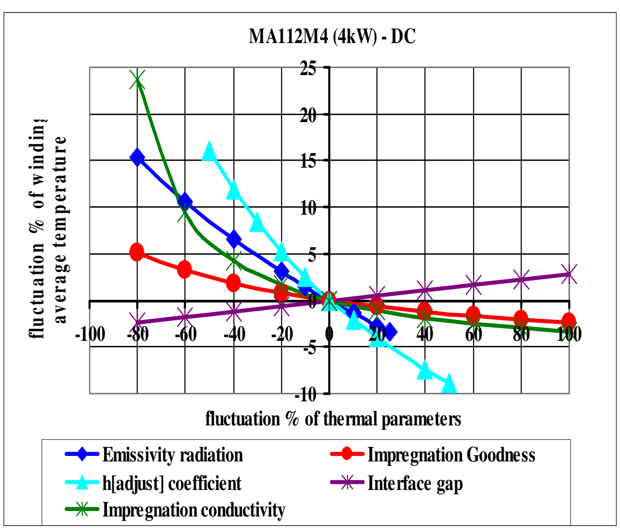

Figure 8: DC model sensitivity analysis (4kW)

Variable Frequency Model:

Steady state on-load thermal tests have been performed for supply frequency in the range 10 to 50 Hz. Measurements were made of the adsorbed electrical power, the mechanical power at the shaft and the temperatures of the stator windings, stator core and external housing. Tests have also been made of the air speed flowing in the open fin channels on the outside of the housing. The air speed variation along the channels (due to leakage), around the periphery and with speed has been measured. More deatils of the air speed measurements are given in references [1] and [3]. Figure 9 and Figure 10 show some of the cooling air speed data produced.

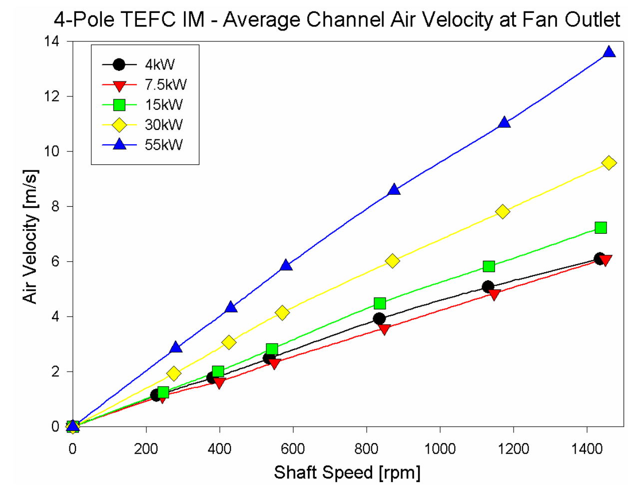

Figure 9: Variation in fin channel air velocity (average at fan outlet) with rotational speed for the motors in Figure 2

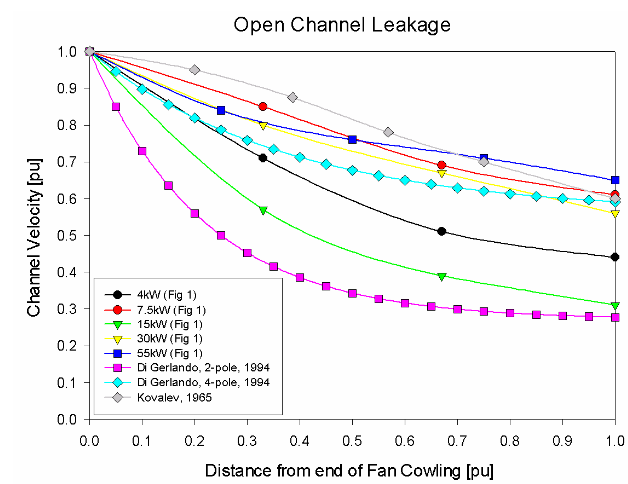

Figure 10: Typical form reduction in local fin channel air velocity with distance from the fan

Figure 11 to Figure 15 show a comparison of calculated and measured winding temperatures at different frequencies (dc to 50Hz). The dc model is that used to calibrate the model. For the ac model the only other parameter that has to be estimated is the average channel air velocity at the fan outlet. In this case the test data shown in Figure 9 has been used. Motor manufactures often have such curves (or the variation in volume flow rate with motor size and speed). Average leakage data from that shown in Figure 10 is also used. It is seen that there is a generally good correspondence between calculated and measured winding temperatures over the frequency range. In most cases the predictions are within the ±5°C band shown on the test data (in all cases it is hoped to predict the temperature to ±5°C). Any errors are most likely due to imperfections in the velocity measurements. It has been shown that not only does the air velocity vary down the axial length of the machine but around the periphery and over the cross-sectional area of the channel [1,3]. This makes it very difficult to obtain a figure for the average velocity using velocity sensors. It would have been more accurate to measure the volume flow rate of air and the average velocity could then have been estimated from the known cross-sectional area between housing and fan cowling.

As expected, the air speed has a major impact on the cooling performance of the design. Figure 16 to Figure 19 show sensitivity anlaysis for the 55kW and 4kW motors with the lowest and highest frequency supplies. The outlet air velocity of the fan and the air leakage factor for the active section of the machine are the main parameters that influence the cooling. The air leakage actor for the active section of the machine has a larger influence than that for the overhanging frame sections at the drive and non-drive ends of the machine. This is because the active section accounts for a significantly larger proportion of the housing surface area. It is surprising that the low speed (10Hz) models show that the variation in air velocity around the calibrated values has as significant impact on the cooling as in the high speed (40 and 50Hz) models. Even at these low shaft speeds the air output from the fan is sufficient to make the forced convection heat transfer coefficient [W/m^2/C] around 3 times greater than that for natural convection (the factor is around 6 to 7 times at the highest shaft speeds). Typically the convection terms add with a to the power three coefficient [5] so forced convection dominates even at low rotational speeds in this case:

$$h_{Mixed}^3 = h_{Forced}^3 \pm h_{Natural}^3 \qquad (1)$$

A plus term is used if the natural convection is aiding or at right angles to the forced convection flow.

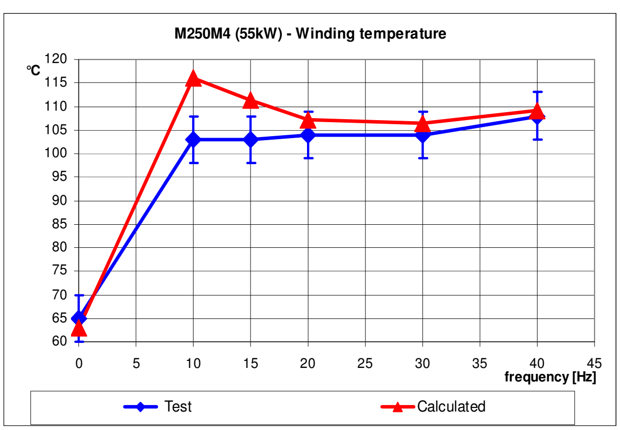

Figure 11: Calibarted model error with supply freq. (55kW)

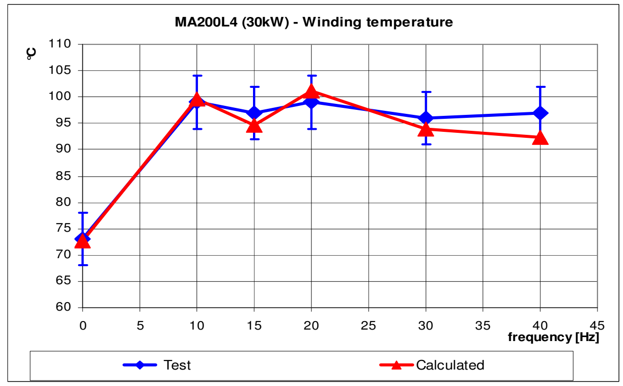

Figure 12: Calibarted model error with supply freq. (30kW)

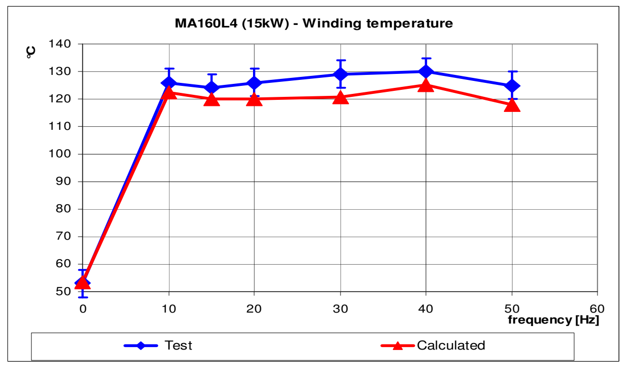

Figure 13: Calibarted model error with supply freq. (15kW)

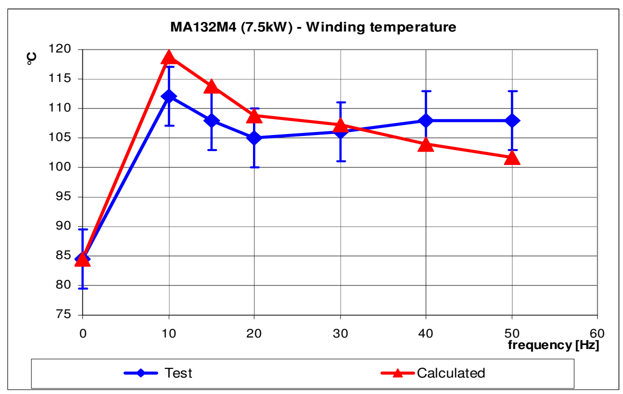

Figure 14: Calibarted model error with supply freq. (7.5kW)

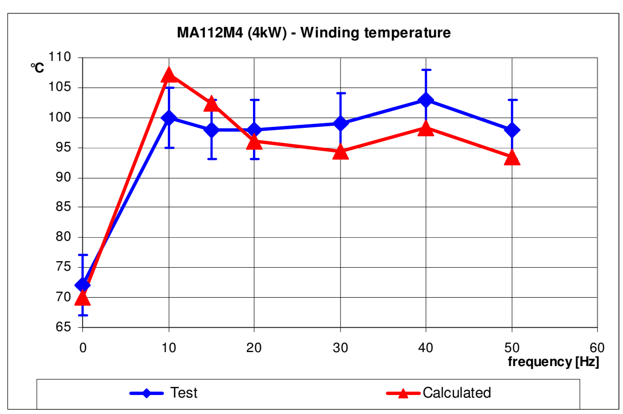

Figure 15: Calibarted model error with supply freq. (4kW)

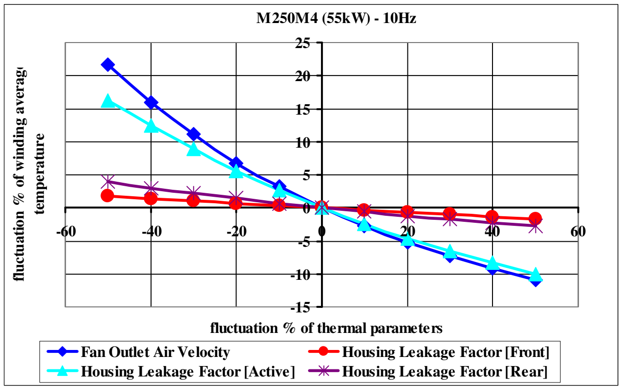

Figure 16: AC model sensitvity analysis (55kW) – 10Hz

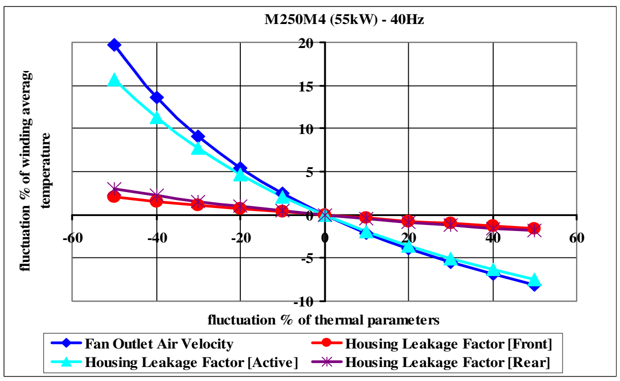

Figure 17: AC model sensitvity analysis (55kW) – 40Hz

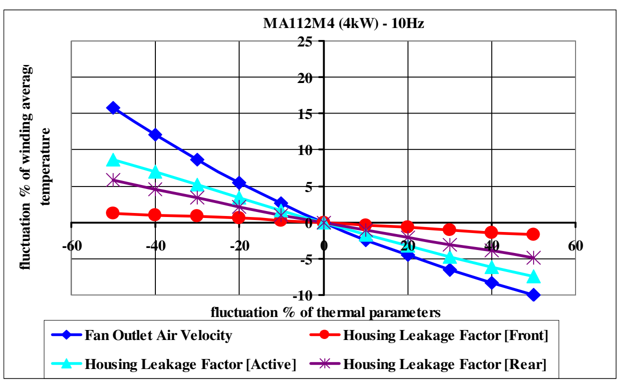

Figure 18: AC model sensitvity analysis (4kW) – 10Hz

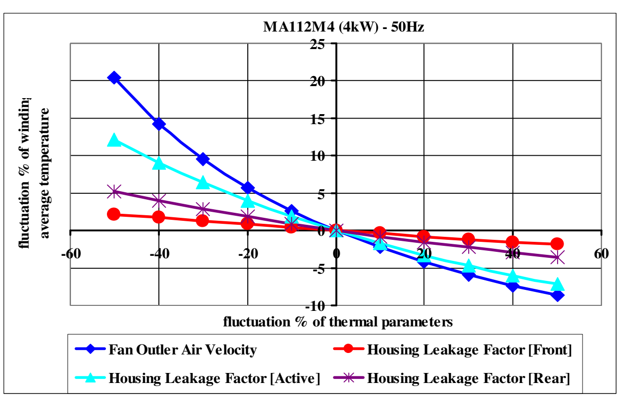

Figure 19: AC model sensitvity analysis (4kW) – 50Hz

Conclusions:

It is seen that some calibration is usually required to obtain accurate thermal models in terms of absolute temperature prediction. However, even with an un-calibrated model sensitivity analysis is useful to highlight the design variables to which the design is most dependent upon and to investigate the possible magnitude of variation in performance for any change in such variables. This can be useful for investigating the build up of manufacturing tolerances or to see if it is worth investing in new materials or manufacturing techniques that may improve certain aspects of the design.

Some of the design variables the user can have little influence upon, i.e. the amount of natural convection. Other variables the designer may be able to influence and give an improved design, i.e. use of a different paint to increase the emissivity, use of improved impregnation materials or techniques to reduce the temperature build up in the winding or a better fit of the housing and stator lamination to reduce the temperature differential at this interface. Sensitivity analysis will help identify the areas of the design where the designer should concentrate such effort and which areas that any effort will be a waist of valuable manpower resources and increase design expenses.

References:

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Acknowledgment:

The authors thank Dr Roberto Lamberti for Laurea Thesis at Politecnoico di Torino, and FIMET Motori & Riduttori for the technological support to this research.