Analytical Thermal Models for Small Induction Motors

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***Abstract*- Thermal analysis is an important design aspect and becoming a more important component of the electric motor design process due to the push for reduced weights and costs and increased efficiency. The accuracy of analytical thermal models depends on the accuracy of the thermal resistance computation and on the number of nodes in the equivalent thermal circuit. In this paper several thermal analytical models with different numbers of nodes are compared against with each other and with experimental data. It will be demonstrated that the more sophisticated and detailed model having a larger number of nodes can be used to calibrate the simpler but faster models with less nodes. The models are all for the same range of small TENV induction motors.**

I. INTRODUCTION

A range of small TENV induction motors, one of which is shown in Fig 1, has been modeled with analytical network thermal models having different number of nodes. The models with a small number of nodes are fast to run but can be difficult to set up accurately. The models with a large number of nodes can be programmed to give an accurate thermal prediction. This is done by dividing individual heat transfer phenomena into separate thermal resistances for which mathematical algorithms exist for their calculation, e.g. thermal resistances to represent heat transfer through composite components such as the winding and bearings, the conduction through the solid components such as the teeth and back iron and convection and radiation from the internal and external surfaces of the machine.

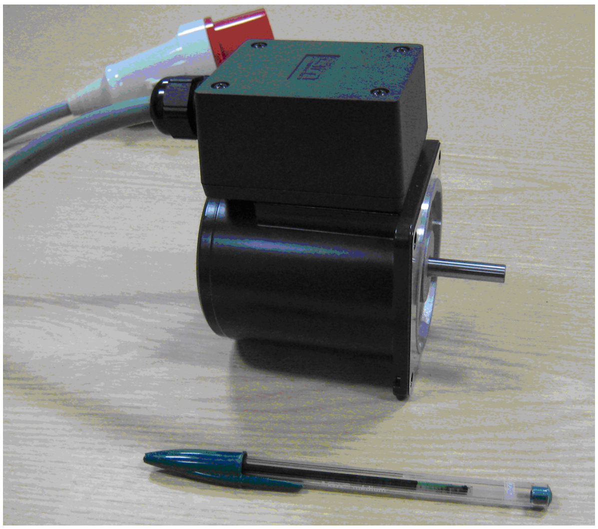


Fig. 1: TEFC induction machine modeled in the paper

The simpler thermal models described in the paper are implemented in the SPEED PC-IMD software [1] which is for simulation of induction machines. It includes analytical models for the magnetic circuit which is uses to calculate the motors equivalent circuit and so the torque/speed characteristic and performance criteria such as the winding resistance, copper losses, power factor, efficiency, etc. For many of the performance criteria such as winding resistance and copper loss it is important to know the winding and cage temperatures. The software has some simple thermal models to help predict these temperatures. However, it is important to calibrate the models as they have a limited number of nodes and do not include pre calculation of difficult to predict thermal phenomena such as heat transfer through conductor bundles, interface gaps between components, turbulent cooling around the end-windings and end-cage, convection from complex surfaces, etc. [3]. The calibration can be done using test data or using a more sophisticated thermal model set up in the Motor-CAD software [2]. Motor-CAD is an analytical network analysis software package dedicated to thermal analysis of electrical machines. It includes algorithms to automatically model complex thermal phenomena.

Automated links exist to transfer electromagnetic geometry and loss data from the PC-IMD to Motor-CAD. Additions and changes can then be made to the geometry to account for the thermal components, e.g. fins or a water jacket added to the housing etc. The steady-state or transient thermal performance can then be calculated. As many of the losses are a function of temperature an iterative process is available to pass thermal data from Motor-CAD to PC-IMD and recalculate the losses and subsequent temperatures. The simple thermal models available in PC-IMD can also be automatically calibrated based on the thermal performance calculated in Motor-CAD. This process is termed a GoTAR in PC-IMD (Go Thermal Analysis and Return). These calibrated models can then be used to give accurate predictions with PC-IMD itself, both of the steady state thermal performance and of the rapid heating of the winding under an overload condition

Details of the single thermal resistance model and the five and ten node models as implemented in PC-IMD are given in sections II and III. The more sophisticated multi-node model implemented in Motor-CAD is described in section IV. Section V gives information on the automated thermal model calibration process, while section VI compares the different thermal models with test data.

II. MODEL WITH A SINGLE THERMAL RESISTANCE

Fig. 1 shows a thermal model for a machine where the there is a single global thermal resistance between the winding and ambient (R_α). This is the simplest possible thermal model for predicting the heat dissipation of the motor and the temperature rise of the stator conductors (T_C):

$$T_C = T_{Ambient} + R_\alpha W_{Total} \quad (1)$$

W_{Total} represents the total motor losses. This model may be combined with the overall thermal capacitance to estimate the thermal time-constant of the motor. However, this model can only be used to gain an understanding of the general heating and cooling of the bulk of the machine and not for the rapid heating of the winding under overload conditions. Typically the thermal time constant of the winding is much smaller than the bulk machine thermal capacitance. This is the simplest thermal model available in PC-IMD, other than just setting the winding and cage temperatures to fixed values, and termed the DegCW model.

III. SIMPLIFIED MODELS WITH BETWEEN 5 AND 10 NODES

A more complex thermal model employs between 5 and 10 nodes to represent important features within the machine. For instance the 5 node network shown in Fig 3 has nodes to represent ambient, stator lamination, housing, winding and rotor. The internal thermal resistances between winding to stator back iron and stator back iron to housing can be calibrated from the internal temperature drops within the stator. The difference in stator and rotor temperature is defined as a temperature difference in this simple model. The convection and radiation from the housing and endcap surfaces is calculated using an effective heat transfer coefficient (h – W/m^2.K) in the model. This is used together with the frame surface area F_{Area} to calculate a frame-to-ambient thermal resistance:

$$R_{FA} = 1 / (h \times F_{Area}) \quad (2)$$

The calibration of this resistance can account for any fins on the housing by noting that F_{Area} is the effective cylindrical surface area of the frame and endcaps in equation (2).

Fig 4 shows a thermal model that employs 10 nodes and 18 thermal resistances which is towards the top end of what would be considered as a simple thermal model. With such models all the thermal resistances can be calibrated using measurement or more sophisticated thermal models. Another option is to calculate some of the thermal resistances and capacitances based on dimensions and material properties for the particular component. A problem with calibration of such models using test data is that it can be quite problematic to isolate the individual heat transfer mechanisms, i.e. convection and radiation from the housing and endcaps, etc. The calibration process is much easier using more sophisticated multi-node network models as more detailed information is available for the different heat transfer mechanisms in the machine, i.e. we can calculate individual values for convection, radiation, conduction and interface resistances within the geometry.

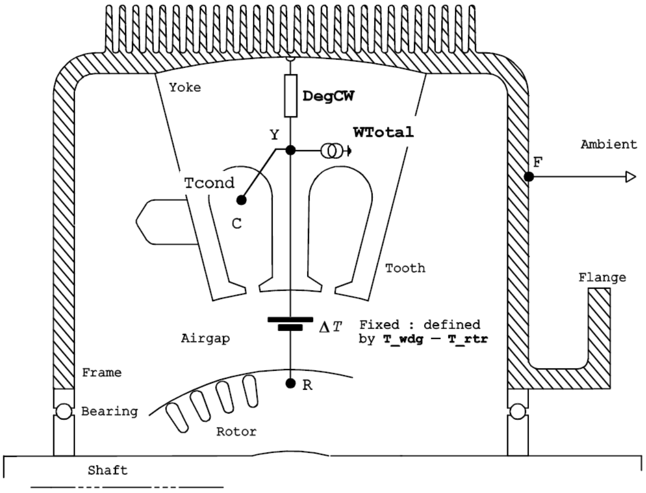


Fig. 2: Thermal model with 1 thermal resistance (DegCW model in PC-IMD)

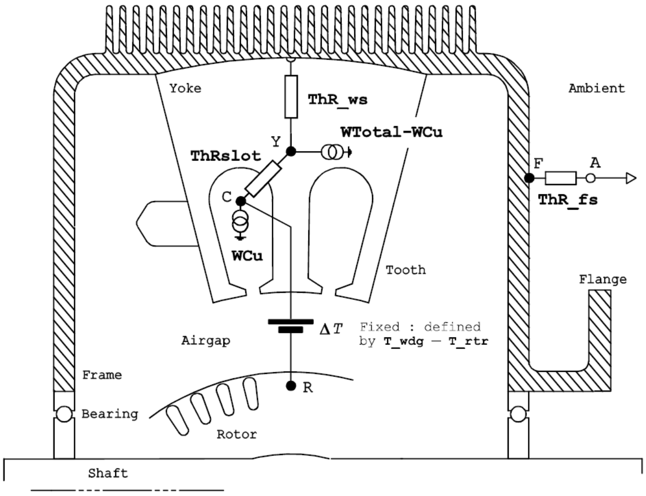


Fig. 3: Thermal model with 5 nodes (HTCoeff model in PC-IMD)

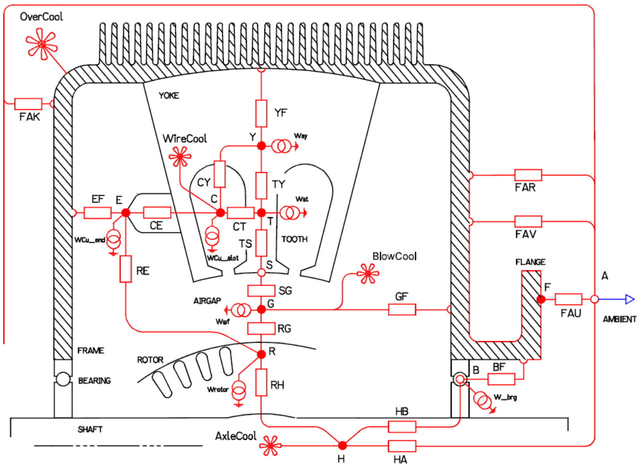


Fig. 4: Thermal model with 10 nodes (Hot10 model in PC-IMD)

IV. DETAILED MULTIPLE-NODE THERMAL MODELS

Detailed analytical thermal models tend to have 20 or more nodes to model complexities in the heat transfer path such as interface gaps between components, the composite material nature of the winding, cooling of the active and end-winding components, etc. Such detail could be modeled using numerical techniques such as finite-element analysis (FEA) and computational fluid dynamics (CFD). However, a detailed analytical model has large advantages in terms of calculation speed. The near instantaneous calculation capabilities of the analysis technique make it possible to run "what-if" scenarios in real time. It also facilitates sensitivity analysis on the main thermal unknowns to evaluate their importance on the thermal performance, i.e. effective interface gaps, impregnation goodness, etc. The main strengths of the numerical techniques are in the visualization of flow and in the development of convection formulations for use in lump-circuit analysis, rather than carrying out the thermal circuit optimization itself.

The thermal network as implemented in Motor-CAD for an induction machine with TENV cooling is shown in Fig 5. The circuit consists of thermal resistances and heat sources connected between motor component nodes. The geometry is defined by a set of geometric parameters such as Housing Type (cylindrical, square, radial fins, axial fins, etc.), Tooth Width, Slot Depth, etc. Some of the parameters are made from a selection of choices (Housing Type, Slot Type, etc) and some are numerical values (Slot Number, Poles Number, Slot Depth, etc.). The user can select from a wide range of cooling types. From the geometry, cooling types and materials selected a thermal resistance network (with losses and thermal capacitances) is automatically constructed so that both the steady-state and transient thermal calculations can be made. The temperatures of important nodes within the machine geometry (such as the housing, tooth, back iron, winding hot-spot, etc) are predicted using the analysis. All thermal resistances and thermal capacitances in the network are calculated automatically from the geometry, cooling type and materials used using standard analytical heat transfer theory [3-6]. Motor-CAD does contain some specially developed mathematical algorithms to allow accurate thermal calculations for more difficult to analyze parts, e.g. the winding, which is a complex composite part consisting of randomly placed strands of wire surrounded by a mixture of enamel, impregnation and air and the slot liner [3]. Much effort has been made to set realistic default parameters for more difficult to estimate quantities such as the effective interface gap between the stator lamination and housing [3].

This type of pre-parameterized model approach is possible as the general geometric form of radial gap electric motors and generators are very similar. There may be some geometric differences, such as housing fin shapes (no fins, radial fins and axial fins of various shapes, etc.), different rotor bar shapes, (single and double cage with round and rectangular, bars etc), and slot shape (parallel tooth, parallel slot, etc.) but in general all machines are very similar. The different geometric shapes are accounted for in Motor-CAD by allowing the user to select different component types (Housing Type, Bar Type, Slot Type, etc.).

V. SIMPLE MODEL CALIBRATION USING MULTI-NODE DETAILED THERMAL MODELS

Various automated data links and been developed between SPEED and Motor-CAD software. The two packages form a perfect combination for designing electric motors and generators. The thermal capabilities of Motor-CAD ideally complement the electromagnetic capabilities of the SPEED software. To obtain a true optimum design it is essential to take account of both the electromagnetic and thermal design aspects. In fact there should be strong interaction between the two disciplines as it is impossible to accurately analysis one without the other, i.e. the losses are critically dependent upon the temperature and vice versa.

In this section of the paper we will demonstrate features to automatically calibrate the simplified PC-IMD thermal models using the sophisticated thermal model set up in Motor-CAD (referred to as a GoTAR – Go Thermal Analysis and Return). This allows the user to make best use of the detailed thermal modeling features in Motor-CAD and fast combined loss/thermal calculations in PC-IMD. Motor-CAD is used to optimize the cooling by dealing with features such as the cooling method used (TENV, TEFC, water jackets, wet rotor, etc.), the size of the thermal components (fin, channel dimension, etc), manufacturing issues (impregnations goodness, interfaces between components, etc.) and the materials used (slot liner, impregnation, etc).

After the data has been transferred from PC-IMD to Motor-CAD the user may adjust some geometric quantities, e.g. details such as the bearing dimensions which are not available in PC-IMD. Intelligent geometry scaling is used to make sure that geometric parameters that are not available in PC-IMD are given reasonable values for the size of machine under consideration, e.g. bearing that fir the machine, etc.

A typical example of the geometry for an induction machine in PC-IMD being automatically transferred to Motor-CAD is shown in Fig 6.

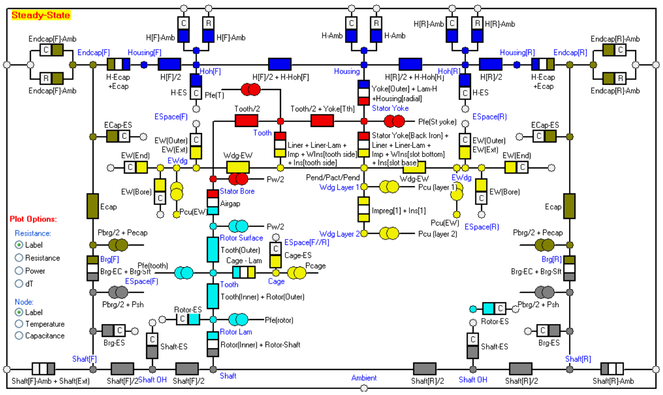


Fig. 5: Detailed multi-node thermal network

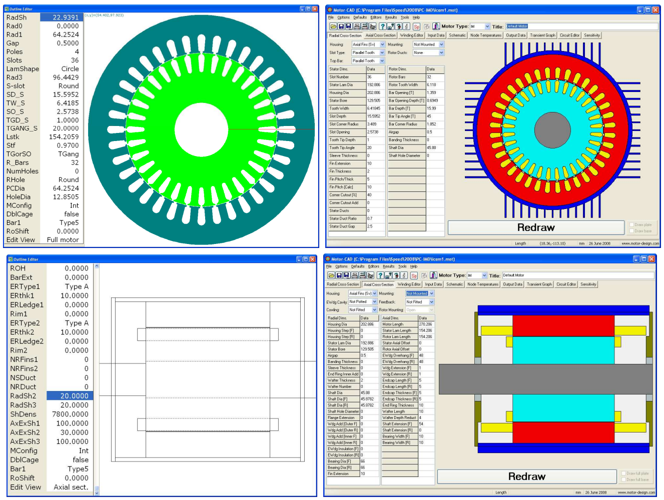


Fig. 6: Automatic transfer of geometry from PC-IMD to Motor-CAD

The geometry in Fig 6 is not one of the machines being studied in this paper in this case. It is the geometry for a much larger machine where axial fins and a shaft mounted fan are used to improve the cooling compared to a TENV machine. The predicted torque/speed characteristic is shown in Fig 7 for one of the TENV machines being studied here. The performance at any point on the torque/speed characteristic can be calculated such as the losses and efficiency. The losses are automatically transferred to the Motor-CAD model.

In Motor-CAD we can compare temperatures at its equivalent nodes to those in the various simple thermal models in PC-IMD. For instance for the DegCW model set up in PC-IMD with default parameters we obtain the results shown in Fig 8.

In this case we are quite lucky that the default thermal resistance is set at 3C/W which is close to the measured value for this small machine. This means that the predicted winding temperature is close to that calculated by Motor-CAD in this case. For larger machines the 3C/W would be far too large and a much worse comparison would result. Details are also given of the comparison between losses and thermal resistances for the two models in Figs 9 and 10 respectively. Both models have the same losses as Motor-CAD obtains its loss values directly from PC-IMD. The Motor-CAD prediction of the equivalent thermal resistance from winding to ambient is 2.74C/W in this case which is close to the 3C/W assumed in PC-IMD. The Motor-CAD equivalent thermal resistance from winding to ambient is calculated from the total loss and the predicted average winding temperature taken from the full multi-node temperature prediction.

The user can select values to be calibrated using the checkboxes and then perform an iterative calibration automatically passing temperatures, losses and relevant calibrated parameters between to PC-IMD and Motor-CAD. The calibrated winding to ambient thermal resistance and resulting temperatures are now shown in Fig 11 for the DegCW model. The calibrated losses are shown in Fig 12.

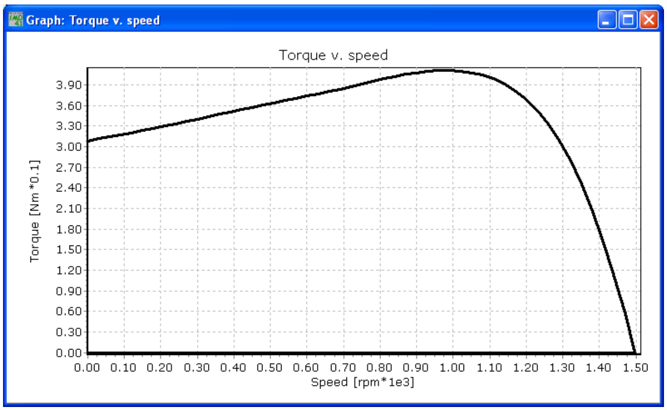
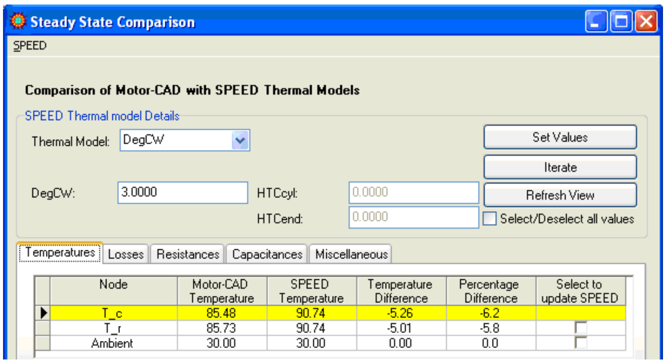


Fig. 7: Torque/Speed characteristic calculated in PC-IMD



Steady State Comparison

SPEED

Comparison of Motor-CAD with SPEED Thermal Models

SPEED Thermal model Details

Thermal Model: DegCW

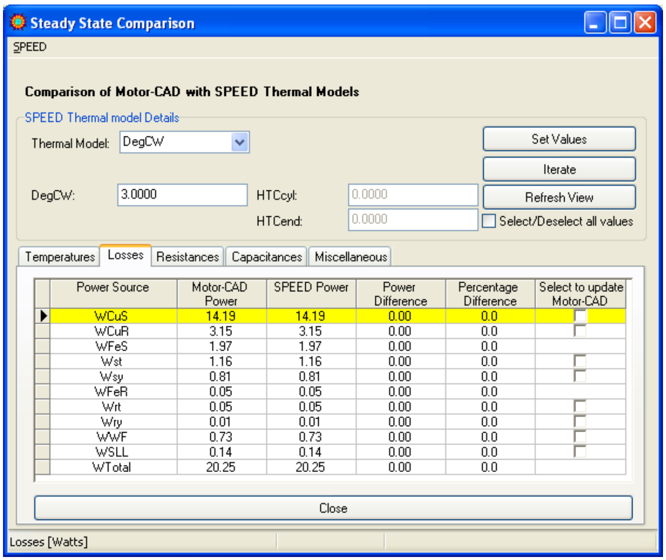
DegCW: 3.0000

HTCcyl: 0.0000

HTCend: 0.0000

Node	Motor-CAD Temperature	SPEED Temperature	Temperature Difference	Percentage Difference	Select to update SPEED
T_c	85.48	90.74	-5.26	-6.2	
T_r	85.73	90.74	-5.01	-5.8	☐
Ambient	30.00	30.00	0.00	0.0	☐

Fig. 8: Comparison of Motor-CAD and PC-IMD DegCW model temperatures



Steady State Comparison

SPEED

Comparison of Motor-CAD with SPEED Thermal Models

SPEED Thermal model Details

Thermal Model: DegCW

DegCW: 3.0000

HTCcyl: 0.0000

HTCend: 0.0000

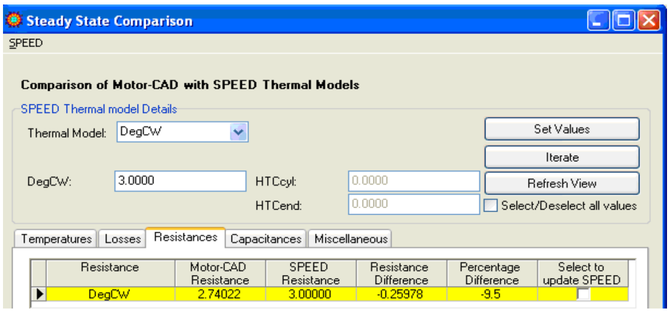
Power Source	Motor-CAD Power	SPEED Power	Power Difference	Percentage Difference	Select to update Motor-CAD
WCuS	14.19	14.19	0.00	0.0	☐
WCuR	3.15	3.15	0.00	0.0	☐
WFeS	1.97	1.97	0.00	0.0	
Wst	1.16	1.16	0.00	0.0	☐
Wsy	0.81	0.81	0.00	0.0	☐
WFeR	0.05	0.05	0.00	0.0	
Wrt	0.05	0.05	0.00	0.0	☐
Wry	0.01	0.01	0.00	0.0	☐
WWF	0.73	0.73	0.00	0.0	☐
WSLL	0.14	0.14	0.00	0.0	☐
WTotal	20.25	20.25	0.00	0.0	

Losses [Watts]

Fig. 9: Comparison of Motor-CAD and PC-IMD DegCW model losses

More details of the temperatures within the machine can be studied using the thermal resistance network solved in Motor-CAD (Fig 13) or by viewing the temperatures of nodes on the cross-section, the axial cross-section being shown in Fig 14.

A similar method as described above is used to calibrate the 5 and 10 node models in PC-IMD, but with more parameters calibrated in such cases. For instance the calibrated 10 node model is shown in Figs 15 to 17.



Steady State Comparison

SPEED

Comparison of Motor-CAD with SPEED Thermal Models

SPEED Thermal model Details

Thermal Model: DegCW

DegCW: 3.0000

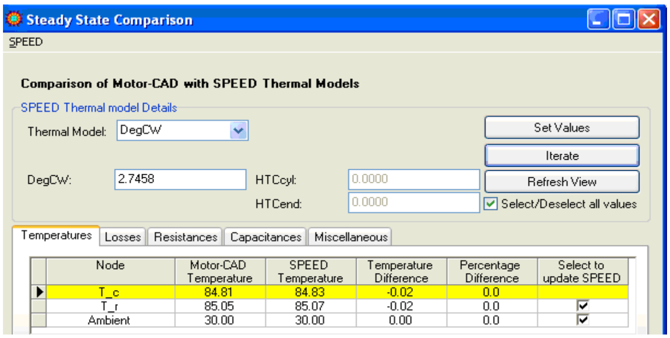
HTCcyl: 0.0000

HTCend: 0.0000

☐ Select/Deselect all values

Resistance	Motor-CAD Resistance	SPEED Resistance	Resistance Difference	Percentage Difference	Select to update SPEED
DegCW	2.74022	3.00000	-0.25978	-9.5	☐

Fig. 10: Comparison of Motor-CAD and PC-IMD DegCW model thermal resistance values



Steady State Comparison

SPEED

Comparison of Motor-CAD with SPEED Thermal Models

SPEED Thermal model Details

Thermal Model: DegCW

DegCW: 2.7458

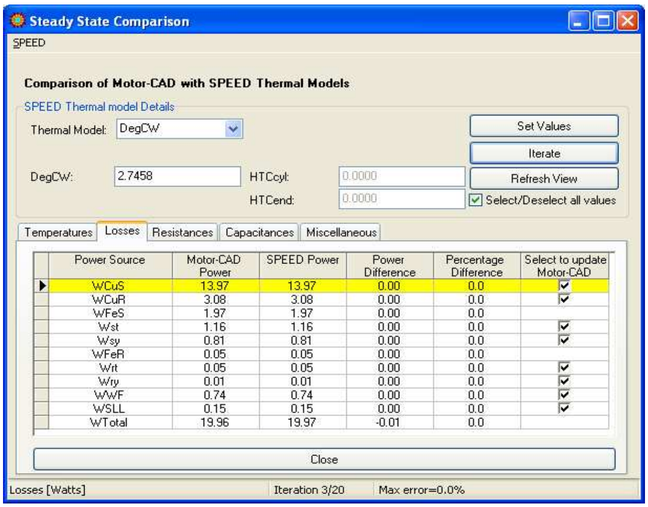
HTCcyl: 0.0000

HTCend: 0.0000

☑ Select/Deselect all values

Node	Motor-CAD Temperature	SPEED Temperature	Temperature Difference	Percentage Difference	Select to update SPEED
T_c	84.81	84.83	-0.02	0.0	
T_r	85.05	85.07	-0.02	0.0	☑
Ambient	30.00	30.00	0.00	0.0	☑

Fig. 11: Calibrated PC-IMD DegCW model. Comparison of nodal temperature thermal resistance values.



Steady State Comparison

SPEED

Comparison of Motor-CAD with SPEED Thermal Models

SPEED Thermal model Details

Thermal Model: DegCW

DegCW: 2.7458

HTCcyl: 0.0000

HTCend: 0.0000

☑ Select/Deselect all values

Power Source	Motor-CAD Power	SPEED Power	Power Difference	Percentage Difference	Select to update Motor-CAD
WCuS	13.97	13.97	0.00	0.0	☑
WCuR	3.08	3.08	0.00	0.0	☑
WFeS	1.97	1.97	0.00	0.0	
Wst	1.16	1.16	0.00	0.0	☑
Wsy	0.81	0.81	0.00	0.0	☑
WFeR	0.05	0.05	0.00	0.0	
Wrt	0.05	0.05	0.00	0.0	☑
Wry	0.01	0.01	0.00	0.0	☑
WWF	0.74	0.74	0.00	0.0	☑
WSLL	0.15	0.15	0.00	0.0	☑
WTotal	19.96	19.97	-0.01	0.0	

Losses [Watts] Iteration 3/20 Max error=0.0%

Fig. 12: Calibrated PC-IMD DegCW model. Comparison of loss data used in the two models.

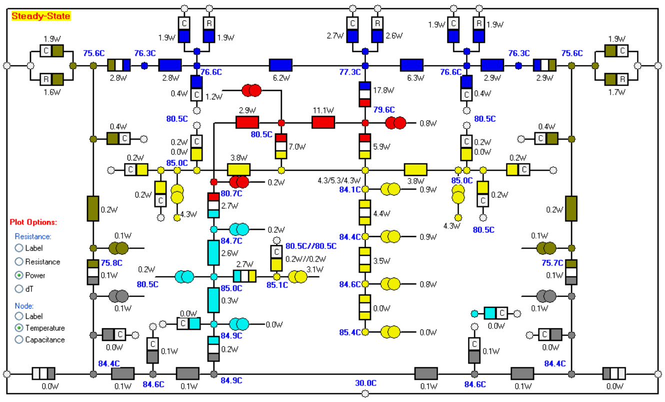


Fig. 13: Calibrated PC-IMD DegCW model. Full Motor-CAD nodal network.

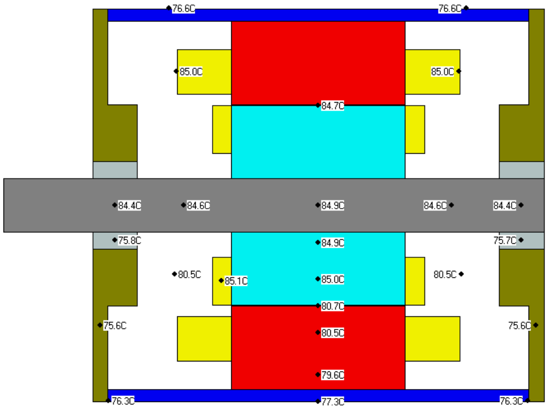


Fig. 14: Calibrated PC-IMD DegCW model. Axial cross-section temperatures.

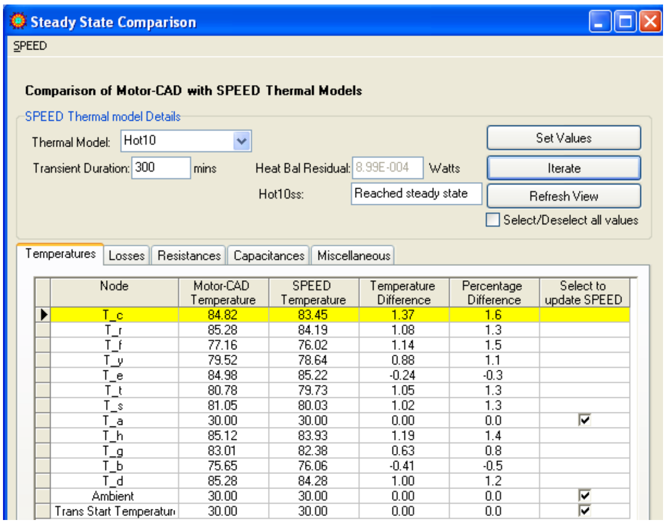
Much more data has been set in PC-IMD in this case, the calibrated data being shown in red in Fig 17. It would be very difficult to perform the calibration without an automated iterative process for such models. When calibrating the 10 node model we must set a sufficiently long simulation time to reach steady-state as PC-IMD always carries out a thermal transient calculation for such a model. A comparison of the Motor-CAD thermal transient and the PC-IMD Hot10 thermal transient is shown in Fig 18. As expected they are similar as the Hot10 model has been calibrated by the Motor-CAD model in this case.

VI. RESULTS DISCUSSION

Two small TENV induction motors have been modeled. Both motors operate at 50Hz and have 4-pole. Motor A has 3-phases, while Motor B is a permanent-split capacitor motor. Rated torque is 0.2Nm for both motors. Fig. 1 illustrates one of the analyzed motors. Table I shows the results for the steady-state temperature rise for the stator winding. Model 1 is based on the DegCW equivalent thermal circuit shown in Fig. 2 with thermal resistance from Motor-CAD calibration. Model 2 is based on the Hot10 equivalent thermal circuit model shown in Fig. 4. Again, the parameters within the model are set up according to the automated Motor-CAD calibration process. Model 3 is the original Motor-CAD model. As expected all three models give very similar results as they are calibrated using the same Motor-CAD model.

VII. CONCLUSIONS

Simplified and/or detailed analytical thermal models can be successfully used in predicting the temperature rise in small induction motors. The level of detail and accuracy of these models strongly depends on the number of nodes and how the thermal resistances are set up. The calibration process for various reduced nodal model has been successfully described. Once calibrated the reduced node thermal models give both satisfactory accuracy and allow very fast and robust thermal calculations.



Comparison of Motor-CAD with SPEED Thermal Models

SPEED Thermal model Details

Thermal Model: Hot10

Transient Duration: 300 mins

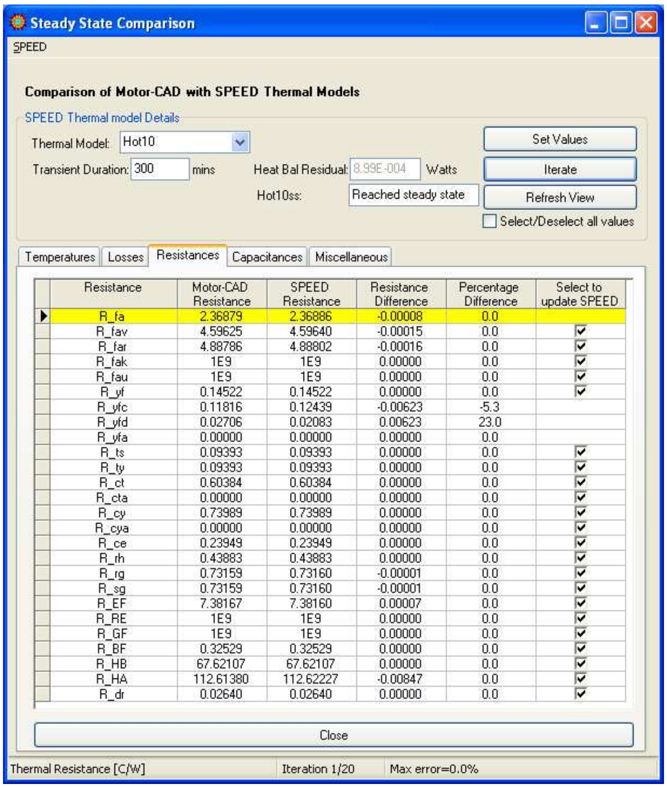
Heat Bal Residual: 8.99E-004 Watts

Hot10ss: Reached steady state

☐ Select/Deselect all values

Node	Motor-CAD Temperature	SPEED Temperature	Temperature Difference	Percentage Difference	Select to update SPEED
T_c	84.82	83.45	1.37	1.6	
T_r	85.28	84.19	1.08	1.3	
T_f	77.16	76.02	1.14	1.5	
T_y	79.52	78.64	0.88	1.1	
T_e	84.98	85.22	-0.24	-0.3	
T_t	80.78	79.73	1.05	1.3	
T_s	81.05	80.03	1.02	1.3	
T_a	30.00	30.00	0.00	0.0	☑
T_h	85.12	83.93	1.19	1.4	
T_g	83.01	82.38	0.63	0.8	
T_b	75.65	76.06	-0.41	-0.5	
T_d	85.28	84.28	1.00	1.2	
Ambient	30.00	30.00	0.00	0.0	☑
Trans Start Temperatur	30.00	30.00	0.00	0.0	☑

Fig. 15: Calibrated PC-IMD Hot10 model. Comparison of nodal temperatures.



Comparison of Motor-CAD with SPEED Thermal Models

SPEED Thermal model Details

Thermal Model: Hot10

Transient Duration: 300 mins

Heat Bal Residual: 8.99E-004 Watts

Hot10ss: Reached steady state

☐ Select/Deselect all values

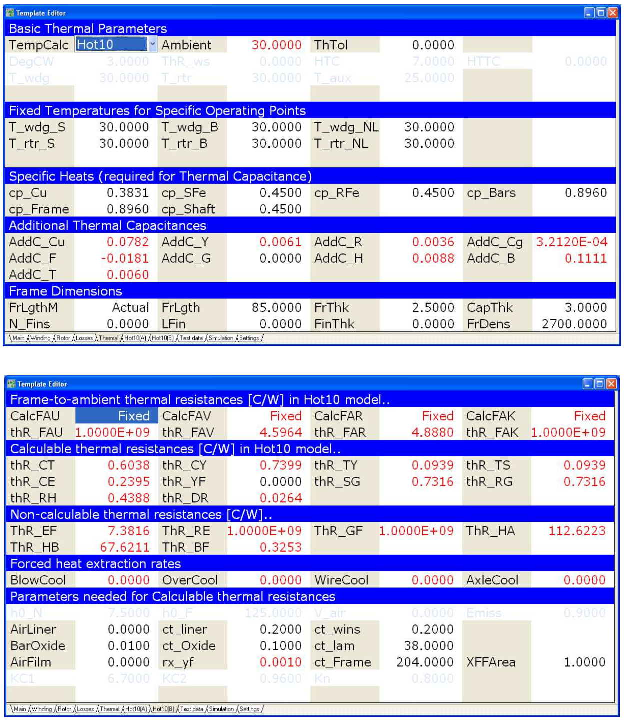
Resistance	Motor-CAD Resistance	SPEED Resistance	Resistance Difference	Percentage Difference	Select to update SPEED
R_fa	2.36879	2.36886	-0.00008	0.0	
R_fav	4.59625	4.59640	-0.00015	0.0	☑
R_far	4.88786	4.88802	-0.00016	0.0	☑
R_fak	1E9	1E9	0.00000	0.0	☑
R_fau	1E9	1E9	0.00000	0.0	☑
R_yf	0.14522	0.14522	0.00000	0.0	☑
R_yfc	0.11816	0.12439	-0.00623	-5.3	
R_yfd	0.02706	0.02083	0.00623	23.0	
R_yfa	0.00000	0.00000	0.00000	0.0	
R_ts	0.09393	0.09393	0.00000	0.0	☑
R_ty	0.09393	0.09393	0.00000	0.0	☑
R_ct	0.60384	0.60384	0.00000	0.0	☑
R_cta	0.00000	0.00000	0.00000	0.0	☑
R_cy	0.73989	0.73989	0.00000	0.0	☑
R_cya	0.00000	0.00000	0.00000	0.0	☑
R_ce	0.23949	0.23949	0.00000	0.0	☑
R_rh	0.43883	0.43883	0.00000	0.0	☑
R_rg	0.73159	0.73160	-0.00001	0.0	☑
R_sg	0.73159	0.73160	-0.00001	0.0	☑
R_EF	7.38167	7.38160	0.00007	0.0	☑
R_RE	1E9	1E9	0.00000	0.0	☑
R_GF	1E9	1E9	0.00000	0.0	☑
R_BF	0.32529	0.32529	0.00000	0.0	☑
R_HB	67.62107	67.62107	0.00000	0.0	☑
R_HA	112.61380	112.62227	-0.00847	0.0	☑
R_dr	0.02640	0.02640	0.00000	0.0	☑

Thermal Resistance [C/W] Iteration 1/20 Max error=0.0%

Fig. 16: Calibrated PC-IMD Hot10 model (calibrated thermal resistances).

TABLE I
CALIBRATED MODELS FOR WINDING TEMPERATURE RISE

	Model 1	Model 2	Model 3
Motor A	55°C	53°C	55°C
Motor B	66°C	64°C	66°C



Basic Thermal Parameters

TempCalc	Hot10	Ambient	30.0000	ThTol	0.0000		
DegCW	3.0000	ThR_ws	0.0000	HTC	7.0000	HTTC	0.0000
T_wdg	30.0000	T_rtr	30.0000	T_aux	25.0000		

Fixed Temperatures for Specific Operating Points

T_wdg_S	30.0000	T_wdg_B	30.0000	T_wdg_NL	30.0000
T_rtr_S	30.0000	T_rtr_B	30.0000	T_rtr_NL	30.0000

Specific Heats (required for Thermal Capacitance)

cp_Cu	0.3831	cp_SFe	0.4500	cp_RFe	0.4500	cp_Bars	0.8960
cp_Frame	0.8960	cp_Shaft	0.4500				

Additional Thermal Capacitances

AddC_Cu	0.0782	AddC_Y	0.0061	AddC_R	0.0036	AddC_Cg	3.2120E-04
AddC_F	-0.0181	AddC_G	0.0000	AddC_H	0.0088	AddC_B	0.1111
AddC_T	0.0060						

Frame Dimensions

FrLgthM	Actual	FrLgth	85.0000	FrThk	2.5000	CapThk	3.0000
N_Fins	0.0000	LFin	0.0000	FinThk	0.0000	FrDens	2700.0000

Frame-to-ambient thermal resistances [C/W] in Hot10 model..

CalcFAU	Fixed	CalcFAV	Fixed	CalcFAR	Fixed	CalcFAK	Fixed
thR_FAU	1.0000E+09	thR_FAV	4.5964	thR_FAR	4.8880	thR_FAK	1.0000E+09

Calculable thermal resistances [C/W] in Hot10 model..

thR_CT	0.6038	thR_CY	0.7399	thR_TY	0.0939	thR_TS	0.0939
thR_CE	0.2395	thR_YF	0.0000	thR_SG	0.7316	thR_RG	0.7316
thR_RH	0.4388	thR_DR	0.0264				

Non-calculable thermal resistances [C/W]..

ThR_EF	7.3816	ThR_RE	1.0000E+09	ThR_GF	1.0000E+09	ThR_HA	112.6223
ThR_HB	67.6211	ThR_BF	0.3253				

Forced heat extraction rates

BlowCool	0.0000	OverCool	0.0000	WireCool	0.0000	AxleCool	0.0000

Parameters needed for Calculable thermal resistances

h0_N	7.5000	h0_F	125.0000	V_air	0.0000	Emiss	0.9000
AirLiner	0.0000	ct_liner	0.2000	ct_wins	0.2000		
BarOxide	0.0100	ct_Oxide	0.1000	ct_lam	38.0000		
AirFilm	0.0000	rx_yf	0.0010	ct_Frame	204.0000	XFFArea	1.0000
KC1	6.7000	KC2	0.9600	Kn	0.8000		

Fig. 17: Calibrated PC-IMD Hot10 model (calibrated Hot10 data in PC-IMD).

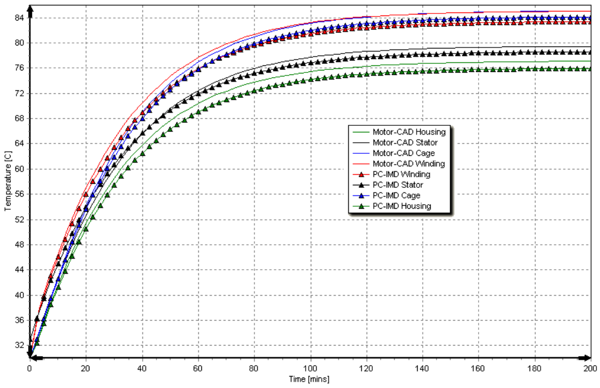


Fig. 18: Calibrated PC-IMD Hot10 model (Hot10 and Motor-CAD transients)

REFERENCES

[1] SPEED PC-IMD software manual, University of Glasgow, UK

[2] Motor-CAD software manual, Motor Design Ltd, UK

[3] D.A. Staton, A. Boglietti, 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, n.3 pp.620-628.

[4] A. Cavagnino, D. Staton, “Convection Heat Transfer and Flow Calculations Suitable for Analytical Modelling of Electric Machines”, CD Conf. Rec. IECON06, 6-10 November 2006, Paris, France, pp. 4841-4846.

[5] J.P. Holman, Heat Transfer, McGraw-Hill, 1997.

[6] A.F. Mills, Heat Transfer, Prentice Hall, 1999.