Godbehere, J., Wrobel, R., Drury, D., & Mellor, P. (2016). Experimentally Calibrated Thermal Stator Modelling of AC Machines for Short-Duty Transient Operation. In 2016 XXII International Conference on Electrical Machines (ICEM 2016): Proceedings of a meeting held 4-7 September 2016, Lausanne, Switzerland. (pp. 1721-1727). Institute of Electrical and Electronics Engineers (IEEE). DOI: 10.1109/ICELMACH.2016.7732756

Experimentally Calibrated Thermal Stator Modelling of AC Machines for Short-Duty Transient Operation

J. Godbehere, R. Wrobel, D. Drury, P. H. Mellor

Abstract -- **This paper presents an approach to the thermal design of an AC machine where the application requires a low-duty transient operation. To provide accurate temperature predictions the design process has been informed with experimental data from tests on a stator-winding sector (motorette). These have been shown to be a time and cost-effective means of calibrating the thermal model of a full machine assembly, prior to manufacture of the final design. Such an approach is usually adopted in design analysis of machines with a concentrated winding topology. Here, the motorette testing has been extended to machines with distributed windings. In the interest of improving heat transfer from the winding body into the machine periphery, several alternative slot liner and impregnating materials have been compared. A total of nine stator section samples have been manufactured and evaluated. The performance trade-offs between the various combinations are discussed in detail alongside their ability to satisfy the design requirements. Based upon these experimental results three stator segment samples have been selected for transient duty analysis. A lumped parameter thermal model has been used and calibrated to match the performance of the experimental samples. This is turn has been used to predict the transient thermal performance of the full machine assembly, for the design specification. The most promising motorette variant has been selected for machine prototyping.**

Index Terms—**AC machines, thermal design, short-duty transient operation, motorette assembly.**

I. INTRODUCTION

WITH the drive to produce more power dense and efficient electrical machines, accurate thermal modelling is becoming an increasingly important aspect of the design process. The ability to predict the thermal behaviour before the machine has been manufactured is an increasingly sought after property; to reduce the overall design cycle by producing an optimised machine with the first prototype iteration.

Lumped parameter thermal models are a commonly used method of analysing and predicting machine thermal behaviour, particularly when considering a transient duty [1–4]. This is predominantly because of the fast computation time of lumped parameter circuits, which is necessary when studying extended duty cycles. However several critical components of these thermal models are difficult to predict without experimental data, for example the stator to slot liner interface, stator to housing interface, convection coefficient of the housing, and impregnation 'goodness' inside the slot [5–10]. This data can be sourced from similar machines or previous iterations of the design. However this method presents a problem if a new machine topology is to be investigated, and this data does not yet exist. In addition, manufacturing multiple full machine assemblies to investigate the thermal performance, is a costly and time consuming task.

A method which is becoming more common in this endeavour are stator segment samples, referred to as 'motorettes' [11–16]. A motorette is a representative sub-assembly of the stator and winding, manufactured using materials and processes commonly used in construction of the final electrical machine prototype. The thermal behaviour of the complete winding and stator periphery can be predicted from analysing a motorette sample, and using this data to calibrate a thermal model. The stator samples are significantly easier to build, allowing multiple batches to be produced. This provides the opportunity to trial combinations of alternative materials to be used in the construction and assembly of the winding. As has been reported in the literature, the influence of the impregnation compound [17] and slot liner [16] have a significant impact on the thermal behaviour of a machine.

The primary aim of this paper is to demonstrate the use of motorette samples for a machine case study. The specification requires a low speed, high torque and low-duty transient operation. The two most important aspects for this particular machine design are power density and compatibility with a zero-speed injection based sensorless control. The resulting design requires a distributed winding with a large number of slots, a high electrical loading at maximum torque and a large aspect ratio (stator outer diameter to machine active length) resulting in a proportionally large end winding region compared to the active length. The nature of the low speed, high torque application means that the losses in the machine are dominated by those from the winding, so the ability to effectively extract heat from the slot to the housing is the critical factor. The optimisation methodology used to generate the machine design is published in [18].

So far in literature motorette studies have focused on concentrated windings, where the inherent structure of these machine types means that a single tooth and coil can be produced [19]. Not only is this easy to manufacture, but the structure accurately represents the winding configuration in the complete machine. Replicating the correct winding layout for a stator section in a distributed wound machine is more challenging, and a completely accurate arrangement may not be possible. Therefore consideration must be given as to how to construct the motorette so that it represents the volume of

---

This work was supported in part by the EPSRC: Engineering and Physical Science Research Council.

Jonathan Godbehere, Rafal Wrobel, David Drury and Phil Mellor are with the Electrical Energy Management Group, University of Bristol, Bristol, BS8 1TR, U.K. (email: jg7560@bristol.ac.uk)

Rafal Wrobel is also affiliated with Motor Design LTD., Ellesmere, SY12 0EG, UK

winding present in the complete machine geometry as close as possible.

A secondary objective of this paper is to conduct a material selection study for the target machine specification. A total of nine motorettes have been produced to the same geometry. Three different impregnation materials have been compared, including a solvent based varnish, a non-solvent based varnish, and an epoxy resin potting compound. Also compared are three different types of slot liner, producing nine different combinations of impregnation material and slot liner type. The properties of these compounds vary, however the interaction of the impregnation material with the slot liner will also effect the resultant thermal properties [16], and is difficult to predict without experimental data. The insight gained from this study has been used to downselect the insulation system for the final machine prototype.

II. MACHINE SPECIFICATION

The machine design considered in this paper uses a V-shape interior permanent magnet (V-IPM) machine, utilising parallel slots and cooled by natural convection. The requirements for the operating envelope are shown in Table I.

TABLE I

MACHINE OPERATING ENVELOPE SPECIFICATIONS

Peak Power (kW)	**Peak Torque (Nm)**	**Maximum Speed (RPM)**	**DC link voltage (V)**
1.5	47	420	28

The fundamental parameters describing the configuration and geometry of the design are shown in Table II. Active materials to be used in the machine construction include round aluminium conductors, 42 MGOe NdFeB permanent magnets and 0.2mm laminated silicon iron. Due to the low-duty transient operation a high electrical loading can be used, in order to minimise the weight of the machine. For the same reason a large aspect ratio (stator bore to the machine active length) has been used to meet the required torque demand.

TABLE II

BASIC MACHINE DESIGN DATA

No. Poles (p)	**No. Slots (q)**	**Stator Bore (D) (mm)**	**Active Length (L) (mm)**	**Air gap (g) (mm)**	**RMS phase current (I_{prms}) (A_{rms})**	**Magnetic Loading (T)**	**Electrical Loading (A/m^2)**
16	72	112	35	1	64	0.8	105000

Based upon the low speed requirements of the machine and the choice of the number of poles, the resulting electrical frequency is relatively low. Because of this the majority of losses generated in the machine are attributed to the winding region. Therefore the choice of conductor, impregnation material and slot liner have a great impact on the overall thermal performance of the machine.

Due to the low electrical frequency the AC losses in the winding can be assumed to be negligible. This means that the best course of action to minimise conductor losses is to increase the slot fill factor. Several trials using rapid-prototyped stator segments and different combinations of wire diameters were conducted and it was found that using a single round aluminium conductor was an effective solution. Aluminium is more pliable compared with the equivalent sized copper conductor and thus easier to bend and manoeuvre. This facilitated a larger conductor size to be used compared to copper, however care must be taken as Aluminium conductors can suffer from fatigue. Configurations of both material types were investigated, and the best configurations for each are presented in Table III. Although aluminium has a higher electrical resistivity compared to copper, achieving a higher slot fill factor mitigates this penalty to some extent while still providing a lighter overall solution. The parameters describing the aluminium conductor configuration are presented in Table IV. A diagram representing the slot shape and conductor arrangement is shown in Fig. 1.

TABLE III

WINDING CONFIGURATION PARAMETERS

Material	**Bare round conductor diameter (mm)**	**Number strands in hand**	**Slot fill (%)**	**Estimated phase resistance (Ω) (20°C)**	**Estimated total conductor weight (kg)**
Copper	0.53	8	37	0.1428	0.678
Aluminium	1.70	1	47	0.1686	0.272

TABLE IV

WINDING CONFIGURATION PARAMETERS

Type	**Turns per slot side (N_s)**	**Throw**	**Parallel Paths**	**Path Type**	**Conductor current density at peak torque (A/mm$^{2)}$**
Double layer	4	4	1	Upper/Lower	27

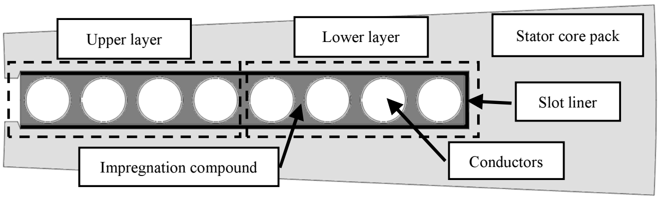

Fig. 1. Machine slot shape and approximate conductor placement.

III. MOTORETTE SAMPLE CONSTRUCTION

The impregnation materials selected for this investigation are shown in Table V. An epoxy potting compound is chosen for its superior thermal conductivity, superior impregnation goodness within the slot and full encapsulation of the end-winding region, allowing for better heat extraction. This type of potting material is expected to perform the best, but introduces a more complex impregnation process to the machine manufacture. To balance this two different types of varnish impregnation compounds have been included also. The solvent based varnish represents a standard potting material type. The non-solvent varnish is a newer impregnation type and brings the bonus of a significantly shorter curing time compared to the solvent type.

A selection of three different slot liners for the investigation are shown in Table VI. They are all different classes of slot liner material and as such have varying material properties. The Peek film is a new type of slot liner material that is being trialed in this investigation. As can be seen in Table VI it offers the highest thermal conductivity and dielectric breakdown voltage, showing good potential as a slot liner material. Due to the relatively small slot size of the machine it was desirable to use a thin slot liner material to maximise the slot fill factor. In the initial winding experiments it was found that a 0.18 mm thick liner offered a balance between liner reduction and mechanical rigidity. A 0.18 mm thickness was not available for the PEEK material and such the closest thickness to this was chosen instead (0.15 mm).

TABLE V
POTTING COMPOUND PROPERTIES

Property	**Elan-tron W 4260 (Epoxylite)**	**Elmotherm 073-1010 (Elantas)**	**Elan-protect up 142 (Elantas)**
Potting material	Epoxy	Varnish (solvent)	Varnish (non-solvent)
Thermal conductivity (W/m·K)	0.6	0.13	0.13
Specific heat capacity (J/kg·K)	1700	1700	1700
Density (kg/m^3)	1730	980	980

TABLE VI
SLOT LINER PROPERTIES

Property	**Nomex 410 (Dupont)**	**ThermaVolt (3M)**	**PEEK film (VICTREX)**
Thickness (mm)	0.18	0.18	0.15
Basis weight (Kg/m^2)	0.174	0.274	?
Dielectric breakdown voltage (kV)	6.12	3.3	18
Tensile strength (kN/m)	22.7/11.6	7.2/3.9	?
Thermal conductivity @ 180°C (W/m·K)	0.143	0.18	0.25
Insulation class	R (220 °C)	R (220 °C)	R (220 °C)

It is not possible to completely replicate the distributed winding configuration in a single tooth motorette. This is because the throw is greater than one slot. However for a DC motorette thermal test the volume of conductor present, and associated equivalent power loss is the important component. This means an alternative winding configuration to that of the final machine assembly can be used, as long as the number of conductors in the slot are the same, and the end winding conductor length between slots, is equivalent to that for the complete machine assembly.

Motorette with four slots were constructed for the experiments. This was decided as a compromise between minimising the size of the motorette assembly while ensuring that an end-winding arrangement representative of the final machine assembly could be achieved. A winding pattern using a single phase was derived and is demonstrated in Fig. 2. This is repeated until a total of eight conductors are present in each slot. Fig. 3 shows a comparison between a motorette, and a rapid prototyped stator section of the same shape. The rapid-prototyped stator section has eighteen slots and the central slots of it are wound with three phases in the correct winding pattern required for the complete machine. The motorettes were wound with end-windings approximately equivalent in length to the example shown, in order to approximate the end winding region to be expected in the complete machine assembly.

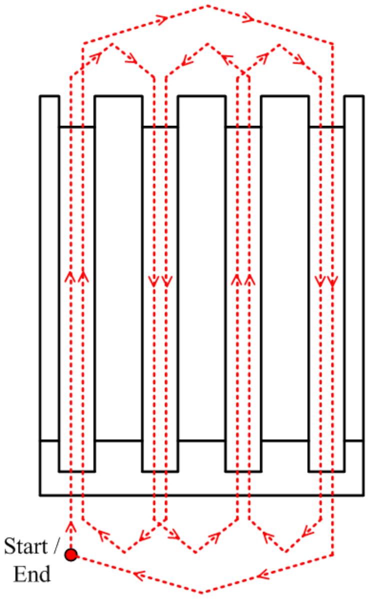

Fig. 2. Motorette winding pattern for two conductor turns. To be repeated four times.

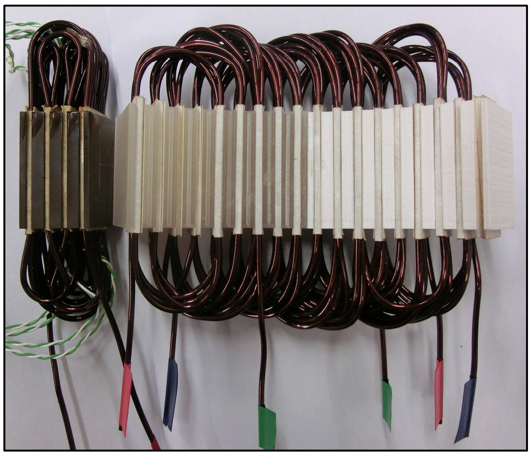

Fig. 3. Motorette (left) with rapid-prototyped stator section model (right)

Nine motorette samples were constructed, these include three for each impregnation type, each with one of the three slot liners. The winding coil and stator were instrumented with a number of type-K thermocouples located at strategic locations. These include the centre of the slot, end-winding region, centre of the stator tooth, centre of the stator yoke, cold-plate and ambient temperature in the insulated chamber. Two thermocouples were used for each location to introduce a level of redundancy, and also to improve the temperature measurement accuracy by taking an average of the temperature data. Small holes were drilled for the tooth and yoke thermocouples on either side of the motorette as shown in fig. 4. A high temperature superglue was used to secure the thermocouples in place where necessary.

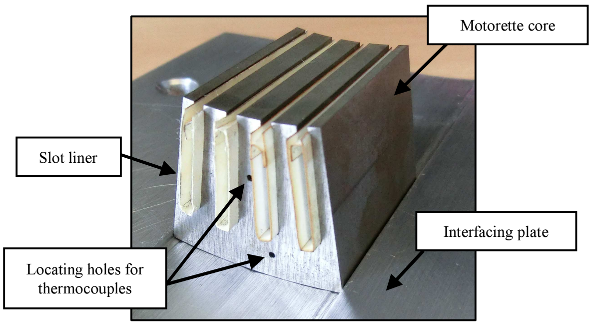

Fig. 4. Motorette before thermocouple instrumentation and impregnation

Once the motorettes were wound and instrumented with thermocouples they were impregnated with the selected insulation compounds as per the manufacturer instructions. The epoxy resin compound necessitated a mould to allow the end winding region to be fully encapsulated. The varnish based compounds were dipped and baked to cure. A vacuum chamber was used for all motorettes to help remove pockets of air within the sample. Fig. 5 shows all nine motorette samples.

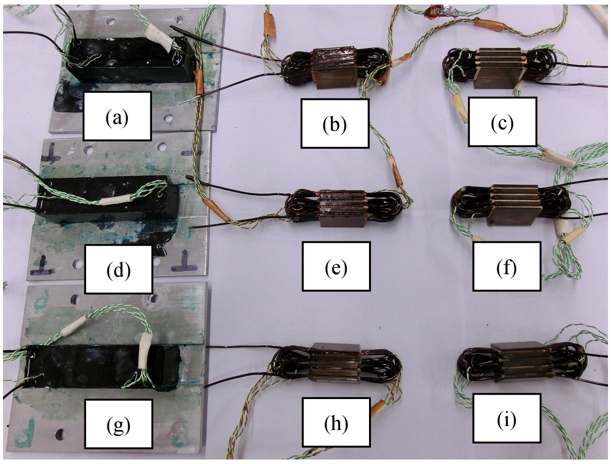

Fig. 5. Motorette samples: epoxy with Nomex liner (a), solvent varnish with Nomex (b), non-solvent varnish with Nomex (c), epoxy with ThermaVolt (d), solvent varnish with ThermaVolt (e), non-solvent varnish with ThermaVolt (f), epoxy with Peek (g), solvent varnish with Peek (h) and non-solvent varnish with Peek (i).

IV. EXPERIMENTAL SETUP AND TESTING PROCEDURE

The experimental setup consists of a thermally insulated chamber, liquid-cooled temperature-controlled cold plate, data acquisition system and dc power supply, Fig. 6. To promote a good contact between the motorette and cold plate an interface plate to match the outer stator surface is used. The interface plate is bolted to the water-cooled cold plate and thermal paste is applied to promote a good interface contact. Similarly thermal paste is applied between the varnish impregnated motorette samples and an interface plate. In addition some external pressure is applied to the top of the varnish impregnated samples to help ensure a good contact between the motorette sample and interface plate. The epoxy impregnated samples however are potted to individual interface plates, and so this additional pressure is not required.

A consideration when using aluminium conductors is the oxidation of the material when exposed to the environment. Unlike copper, simply stripping off the enamel and adding a crimp will not guarantee reliable electrical conductivity. One way to overcome this problem is to cold-weld the aluminium conductor to an equivalent sized copper conductor. This copper conductor is then crimped and connected to a power supply in the normal fashion. This cold-weld was achieved using a Pressure Welding Machines M30 hand cold weld tool. This tool achieves the weld by forcing the two ends of the conductor together with very high pressure. The resulting cold-weld is mechanically strong and ensures good electrical conductivity.

Each motorette sample was tested with a range of current values. For each current step the sample was left until a thermal steady state was achieved. This was gauged by monitoring the temperature change for the end-winding region, and a steady state was deemed to be met when the temperature change was less than 1°C over a ten minute period. The current and temperature data for each thermocouple was recorded every ten seconds, and the voltage drop across the motorette sample at each steady state condition.

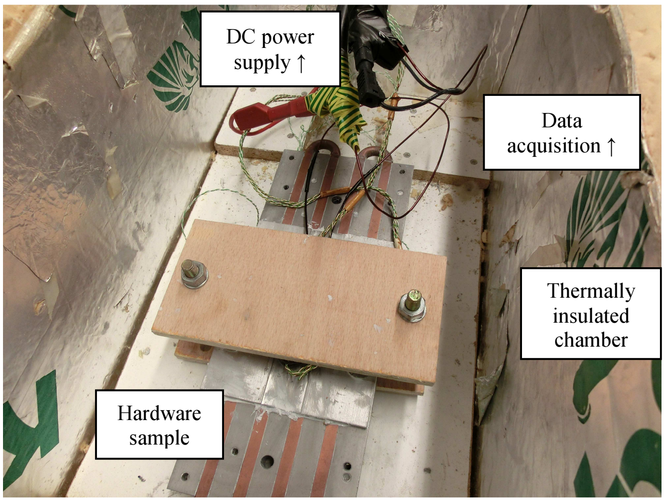

Fig. 6. Experimental setup for DC motorette thermal tests

V. HARDWARE RESULTS

The experimental data provides an insight into the power loss handling abilities of the various stator winding sample variants. By evaluating the winding slot temperature rise above the stator back iron the heat transfer capability of the slot region can be deduced. This information for all nine motorette samples has been plotted in Fig. 8. To aid with comparison of the various samples a line is drawn across the graph. This demonstrates the amount of heat dissipation in the winding needed to generate a 50°C temperature rise between stator back iron and winding slot.

It can be seen that all epoxy potted motorettes have performed better than the varnish potted samples. This is to be expected given the higher thermal conductivity and better impregnation 'goodness' into the slot with this type of impregnation material. Looking at the slot liner variants with epoxy resin it can be seen that the Peek plastic has performed the best, next ThermaVolt and last Nomex. This reflects the differences in thermal conductivity between the different slot liner types, with Peek performing the best as it has the highest thermal conductivity. The varnish potted motorettes however do not follow this trend. Comparing the two varnish compounds with the same slot liner it can be seen that with Nomex and ThermaVolt the non-solvent varnish provides better thermal conductivity. However they perform identically with the Peek slot liner material. The ability of the slot liner to absorb the impregnation material improves heat extraction in the slot when combined with varnish based potting compounds. The data suggests that the Peek plastic has poor porous properties. However it can be concluded that for both varnish types ThermaVolt was the superior slot liner material.

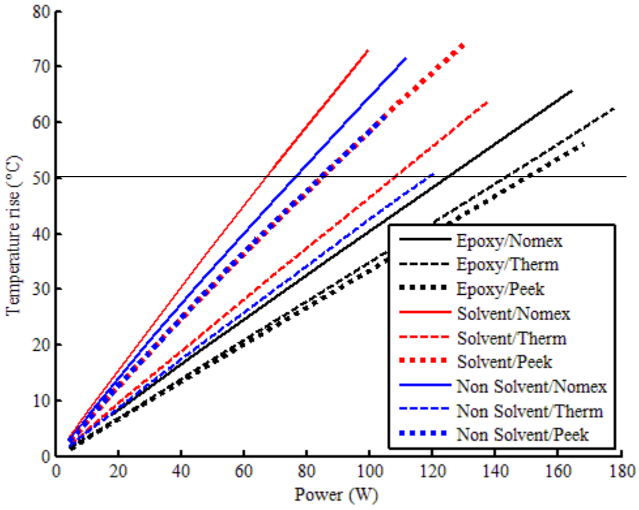

Fig. 8. Slot temperature rise above yoke vs. winding dc power loss for motorette variants

VI. THERMAL MODEL CALIBRATION FOR TRANSIENT DUTY ANALYSIS

The results shown in Fig. 8 give an initial idea of the thermal conductivity within the slot for the motorette variants. However the machine specification is for a transient duty cycle. Although the epoxy based potting compound provides the best heat extraction from the winding body, it may not be necessary if the machine design stays cool enough for the duration of the duty cycle. The critical factor is the winding hotspot, likely to be located in the end-winding region. A varnish based assembly may provide adequate heat extraction for the target specification, and would be preferable due to ease of manufacture with this potting compound method.

A method was developed to use the experimental data to calibrate a thermal model of the complete machine. The desired duty cycle could then be tested and predictions made on the temperature performance of the complete machine assembly. A lumped parameter thermal model based on the geometry of the machine, and properties of the materials defined is used [20]. The slot region uses a cuboidal element approach, where the winding and impregnation compound are combined into a single component with separate thermal conductivities in three dimensions [21]. The contact between slot liner to stator, and stator to housing is modelled with a layer of air between the two materials. The lumped parameter circuit model is demonstrated in Fig. 9, with the portion isolated for the motorette calibration shown. The water cooled housing (cold plate) and ambient temperature are set to the values recorded from the experimental data.

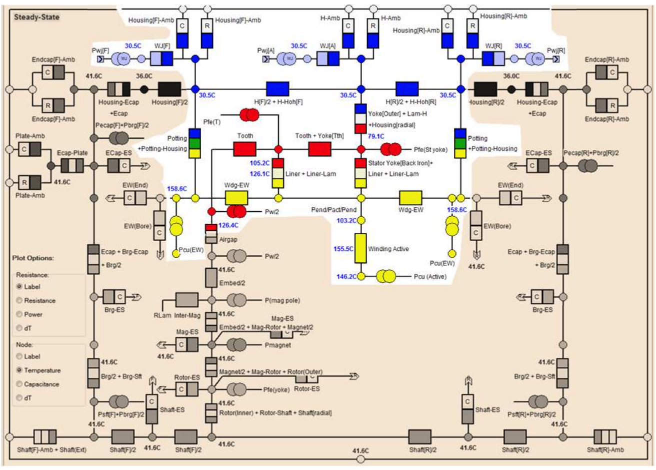

Fig. 8. Lumped parameter thermal model circuit, with stator, slot, end-windings and active section of the housing isolated [20]

The most promising motorette samples were chosen for thermal model calibration: epoxy with Peek, epoxy with ThermaVolt and non-solvent varnish with ThermaVolt. These three examples provide a good comparison of performance between the two different types of potting compound and slot liner.

A particle swarm optimisation routine [22] and fitness function (1) was developed to calibrate the thermal model for the three chosen motorette variants. The fitness functions aims to minimise the difference between the temperatures within the model to that of the recorded data (2). To aid this process and prevent unrealistic calibration solutions, material test data from [23] is used. In this paper the author experimentally measures the thermal conductivity of impregnation and winding cuboidal samples. One of the samples tested uses round aluminium conductors 1.6 mm in diameter, the exact same epoxy resin potting compound and to a packing factor of 55%. The sample has a thermal conductivity of 2.4 W/m/°C. This cuboidal sample is close in specification to the motorette samples produced in this paper, and is used to define the parameter ranges for the equivalent thermal conductivity. The main calibration values, and the temperature fitness at the maximum power dissipation recorded for each motorette variant are shown in table VII and Fig. 9.

$$Fitness = \sum_{i=1}^{4} F_i \tag{1}$$

$$F_i = 1 - \frac{abs(T_{motorette,i} - T_{model,i})}{T_{motorette,i}} \tag{2}$$

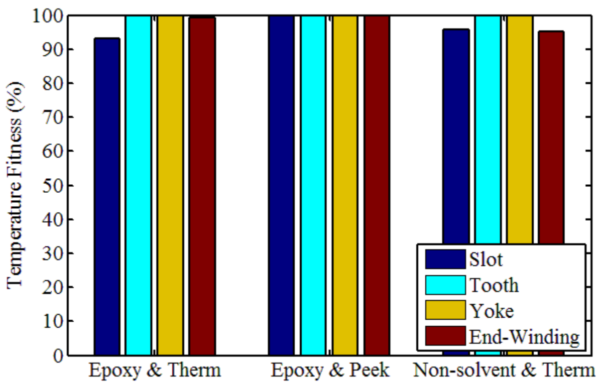

Fig. 9. Temperature fitness between calibrated lumped parameter model and motorette experimental data, at maximum current recorded for each motorette variant.

TABLE VII
MAIN CALIBRATED MOTORETTE THERMAL MODEL PROPERTIES

Motorette	Slot liner to stator interface air gap (mm)	Stator to housing interface gap (mm)	Effective slot material thermal conductivity (W/m/C)	
			Radial	Tangential
Epoxy & ThermaVolt	0.005	0.007	2.96	2.43
Epoxy & Peek	0.009	0.015	2.71	2.46
NS varnish & ThermaVolt	0.000	0.010	1.65	1.29

VII. TRANSIENT DUTY SIMULATION

The calibration of the slot region is applied to a complete model of the machine assembly for each motorette variant. The stator to housing interface air gap is set to the same value of 0.03 mm for all three material variations. This represents an average interface gap for a shrink fit machine and housing [9]. A simple, naturally cooled, radial casing, 15 mm thick is used. Fig. 10 shows radial and axial views of the complete machine assembly. The duty cycle to be applied to each machine is detailed in table VIII. The transient simulation is shown in Fig. 12, to aid with comparison, only the winding hotspot and stator yoke are included.

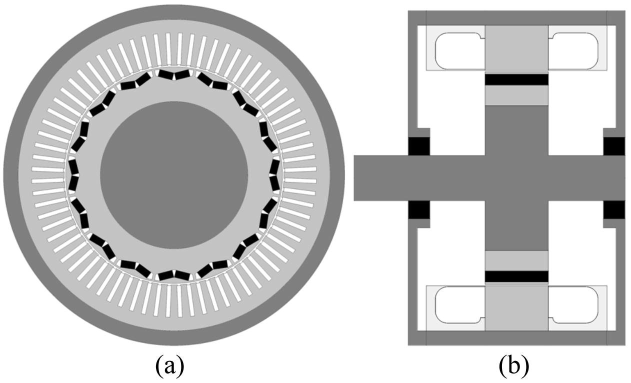

Fig. 10. Radial (a) and axial (b) view of the complete machine assembly

TABLE VIII
TRANSIENT DUTY CYCLE SPECIFICATION

Period	Time (secs)	Current (A_{rms})	Speed (RPM)	Ambient Temp. (°C)	Times repeated
A	15	64	100	32	12
B	50	5	100	32	

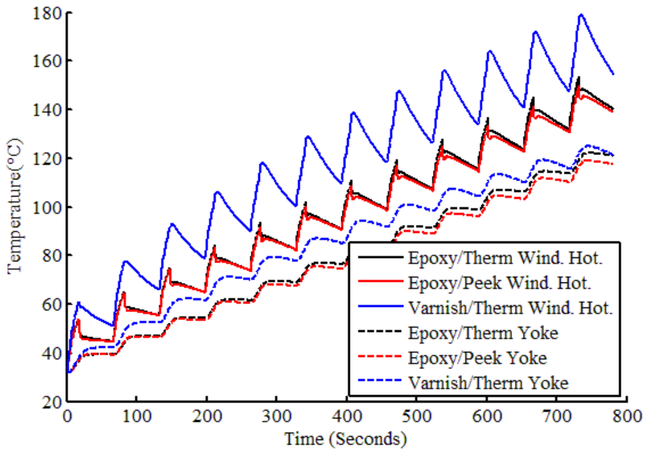

Fig. 12. Transient thermal performance for complete machine assembly for selected epoxy and non-solvent varnish configurations.

Studying Fig. 12 it can be seen that the epoxy with Peek and ThermaVolt variants performed very similarly, as was suggested from the initial analysis in Fig. 8. For an epoxy resin based solution the optimum slot liner should be chosen based on cost and ease of manufacture. The most important information to be gained from the simulation is the maximum hotspot temperature reached in the end-winding. It can be observed that a maximum temperature difference of approximately 35 °C between the varnish based version and epoxy based version is seen. Although significant, the maximum temperature reached is still within the limits of the conductor insulation class, therefore the non-solvent varnish with ThermaVolt slot liner has been chosen for the machine prototyping.

VIII. CONCLUSIONS

This paper presents an experimental approach to establish a thermal model for use in the design of a distributed wound machine for a low-duty transient application. Stator segment experiments (motorettes) have been used to provide experimental data to inform and calibrate a lumped parameter circuit model of a machine.

Used solely for concentrated wound machines so far, a method to develop motorettes for a distributed wound machine has been developed. Based on rapid-prototyped models of the design, estimations of the end-winding length between slots has been found, and a winding layout for a four slot stator segment has been created which mimics the volume of winding in the true machine layout.

Initial experimental analysis of nine motorette samples demonstrates the performance of the various impregnation compound and slot liner types chosen. The three best variants were selected for transient thermal analysis.

Replicating the test conditions for the motorette samples, critical parameters to the design thermal model were calibrated using a particle swarm optimisation algorithm. The calibrated thermal models show good agreement over the full range of current to the motorette experimental data.

Based upon the transient model simulation results it has been decided that a non-solvent varnish potting compound should be used with ThermaVolt slot liner for the final machine assembly. Although a superior performance is observed with an epoxy compound, the additional manufacturing steps required to produce this are undesirable. In addition, the possibility of increasing the electrical loading to further reduce the size of the machine is limited by the requirement for sensorless control capability, where heavy saturation of the magnetic circuit needs to be avoided.

The aim in the future is to manufacture the machine presented in this paper and validate this analysis with experimental data of the full machine assembly.

IX. ACKNOWLEDGEMENT

The authors wish to thank DICAMIT slr and Victrex for providing technical advice and material samples for the research.

X. REFERENCES

[1] A. Boglietti, E. Carpando, M. Cossale, A. Lucco Borlera, D. Staton, and M. Popescu, "Electrical machine first order short-time thermal transients model: Measurements and parameters evaluation," in *Industrial Electronics Society, IECON 2014 - 40th Annual Conference of the IEEE*, 2014, pp. 555–561.

[2] Y. K. Chin and D. A. Staton, "Transient thermal analysis using both lumped-circuit approach and finite element method of a permanent magnet traction motor," in *AFRICON, 2004. 7th AFRICON Conference in Africa*, 2004, vol. 2, pp. 1027–1035 Vol.2.

[3] J. Fan, C. Zhang, Z. Wang, Y. Dong, C. E. Nino, A. R. Tariq, and E. G. Strangas, "Thermal Analysis of Permanent Magnet Motor for the Electric Vehicle Application Considering Driving Duty Cycle," *Magnetics, IEEE Transactions on*, vol. 46, pp. 2493–2496, Jun. 2010.

[4] T. Sawata and D. Staton, "Thermal modeling of a short-duty motor," in *IECON 2011 - 37th Annual Conference on IEEE Industrial Electronics Society*, 2011, pp. 2054–2059.

[5] A. Boglietti, A. Cavagnino, and D. Staton, "Determination of Critical Parameters in Electrical Machine Thermal Models," *Industry Applications, IEEE Transactions on*, vol. 44, pp. 1150–1159, 2008.

[6] A. Boglietti, A. Cavagnino, and D. A. Staton, "TEFC induction motors thermal models: a parameter sensitivity analysis," *Industry Applications, IEEE Transactions on*, vol. 41, pp. 756–763, May 2005.

[7] R. Camilleri, D. A. Howey, and M. D. McCulloch, "Experimental investigation of the thermal contact resistance in shrink fit assemblies with relevance to electrical machines," in *Power Electronics, Machines and Drives (PEMD 2014), 7th IET International Conference on*, 2014, pp. 1–9.

[8] G. G. Guemo, P. Chantrenne, and J. Jac, "Parameter identification of a lumped parameter thermal model for a permanent magnet synchronous machine," in *Electric Machines Drives Conference (IEMDC), 2013 IEEE International*, 2013, pp. 1316–1320.

[9] D. Staton, A. Boglietti, and A. Cavagnino, "Solving the More Difficult Aspects of Electric Motor Thermal Analysis in Small and Medium Size Industrial Induction Motors," *Energy Conversion, IEEE Transactions on*, vol. 20, pp. 620–628, 2005.

[10] D. A. Staton and A. Cavagnino, "Convection Heat Transfer and Flow Calculations Suitable for Electric Machines Thermal Models," *Industrial Electronics, IEEE Transactions on*, vol. 55, pp. 3509–3516, Oct. 2008.

[11] J. L. Baker, R. Wrobel, D. Drury, and P. H. Mellor, "A methodology for predicting the thermal behaviour of modular-wound electrical machines," in *Energy Conversion Congress and Exposition (ECCE), 2014 IEEE*, 2014, pp. 5176–5183.

[12] R. Wrobel, P. H. Mellor, and D. Holliday, "Thermal Modeling of a Segmented Stator Winding Design," *Industry Applications, IEEE Transactions on*, vol. 47, pp. 2023–2030, 2011.

[13] R. Wrobel, A. Mlot, and P. H. Mellor, "Investigation of end-winding proximity losses in electromagnetic devices," in *Electrical Machines (ICEM), 2010 XIX International Conference on*, 2010, pp. 1–6.

[14] R. Wrobel, D. Salt, N. Simpson, and P. H. Mellor, "Comparative study of copper and aluminium conductors - Future cost effective PM machines," in *Power Electronics, Machines and Drives (PEMD 2014), 7th IET International Conference on*, 2014, pp. 1–6.

[15] R. Wrobel, D. Staton, R. Lock, J. Booker, and D. Drury, "Winding Design for Minimum Power Loss and Low-Cost Manufacture in Application to Fixed-Speed PM Generator," *Industry Applications, IEEE Transactions on*, vol. 51, pp. 3773–3782, 2015.

[16] R. Wrobel, S. J. Williamson, J. D. Booker, and P. H. Mellor, "Characterising the performance of selected electrical machine insulation systems," in *Energy Conversion Congress and Exposition (ECCE), 2015 IEEE*, 2015, pp. 4857–4864.

[17] J. Richnow, P. Stenzel, A. Renner, D. Gerling, and C. Endisch, "Influence of different impregnation methods and resins on thermal behavior and lifetime of electrical stators," in *Electric Drives Production Conference (EDPC), 2014 4th International*, 2014, pp. 1–7.

[18] J. Godbehere, R. Wrobel, D. Drury, and P. H. Mellor, "Design methodology of a brushless IPM machine for a zero-speed injection based sensorless control," in *Energy Conversion Congress and Exposition (ECCE), 2015 IEEE*, 2015, pp. 5601–5608.

[19] S. Ayat, R. Wrobel, J. Goss, and D. Drury, "Experiment Informed Methodology for Thermal Design of PM Machines," in *Ecological Vehicles and Renewable Energies (EVER), 2016 Eleventh International Conference on*, 2016.

[20] Motor-CAD, "http://www.motor-design.com."

[21] R. Wrobel and P. H. Mellor, "A General Cuboidal Element for Three-Dimensional Thermal Modelling," *Magnetics, IEEE Transactions on*, vol. 46, pp. 3197–3200, 2010.

[22] J. Robinson and Y. Rahmat-Samii, "Particle swarm optimization in electromagnetics," *Antennas and Propagation, IEEE Transactions on*, vol. 52, pp. 397–407, Feb. 2004.

[23] N. Simpson, R. Wrobel, and P. H. Mellor, "Estimation of Equivalent Thermal Parameters of Impregnated Electrical Windings," *Industry Applications, IEEE Transactions on*, vol. 49, pp. 2505–2515, Nov. 2013.

XI. BIOGRAPHIES

Jonathan Godbehere received the M.Eng degree in Electrical and Electronic Engineering from the University of Bristol, Bristol, U.K., in 2012. He is currently working toward the Ph.D. degree with the Electrical Energy Management Group, Faculty of Engineering, University of Bristol.

His Ph.D. research is on permanent magnet machine design for sensorless control.

Rafal Wrobel (SM'13) received the M.Sc.Eng. degree from the Technical University of Opole, Opole, Poland, in 1998, the Ph.D. degree from the Technical University of Lodz, Lodz, Poland, in 2000 and the Habilitation degree from the Technical University of Opole, Opole, Poland, in 2013. (2000-2002), he was an Assistant Professor with the Technical University of Opole. (2002-2011) he was a Research Fellow with the Electrical Energy Management Group (EEMG) at the University of Bristol, Bristol, U.K. Since 2011, he has been a Senior Research Fellow with the EEMG, and his research interests include multi-physics and multi-disciplinary design-analysis of electrical machines and wound passive components.

David Drury received the M.Eng. degree in mechanical engineering and the Ph.D. degree in control engineering from the University of Bristol, Bristol, U.K.

He is a Senior Lecturer in electrical engineering with the Department of Electrical and Electronic Engineering, Faculty of Engineering, University of Bristol, where he specialises in the manufacture, test, and modelling of electrical drive systems with a particular interest in more electric transport systems (automotive and aerospace) as part of the Electrical Energy Management Group. His research interests include extending dynamic testing methods to include virtual testing methods for full system drive testing (electric machines, converters, and/or energy storage media) using a combination of experimental equipment and real-time systems.

Phil H. Mellor received the B.Eng. and Ph.D. degrees in electrical engineering from the Department of Electrical Engineering, University of Liverpool, Liverpool, U.K., in 1978 and 1981, respectively.

He is currently a Professor of electrical engineering with the Department of Electrical and Electronic Engineering, University of Bristol, Bristol, U.K. Prior to this, he held academic posts at the University of Liverpool (1986-1990) and the University of Sheffield, Sheffield, U.K. (1990-2000). His research activities include high-efficiency electric drives, and actuation and generation systems for application in more electric aircraft and hybrid electric vehicle