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Characterising the ‘in situ’ Thermal Behaviour of Selected Electrical Machine Insulation and Impregnation Materials

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Abstract— This paper presents results from an analysis of thermal behaviour for alternative slot liner insulation and varnish impregnation materials used in the construction of electrical machines. These materials are typically characterised by the individual material properties altered to suit a particular application. However, the manufacturer provided material data is usually inadequate when comparing the complete insulation systems. This research is focused on the conductive heat transfer from the winding body into the machine periphery in context of the complete insulation system. An experimental approach using the stator-winding segment subassembly has been adopted here, for the representative ‘in situ’ heat transfer measurements. The effects of impregnation ‘goodness’, in volume manufacture repeatability and individual versus ‘in situ’ material physical properties on the stator-winding thermal behaviour are discussed in detail. The results suggest that the use of a particular slot liner insulation and varnish impregnation has a prominent impact on the winding heat transfer as well as appropriate manufacture and assembly processes used. The experimental work has been supplemented with theoretical analysis to provide a more comprehensive insight into the winding heat transfer phenomena, in particular the winding-to-slot contact thermal resistance.

Keywords—low-voltage electrical insulation system, slot liner material, impregnation material, manufacture repeatability, heat transfer;

I. INTRODUCTION

The continuous drive towards compact high-performance electrical machine solutions has resulted in an increasing need for a more comprehensive thermal design-analysis approach, where various design, manufacture and assembly parameters are accounted for. These factors have a significant impact on a machine’s thermal behaviour and usually require experimental methods to validate the initial design assumptions. The stator-winding assembly is particularly challenging in this context as it consists of various material types and uses several manufacturing processes. Also, the power loss generated within the winding body is one of the main heat sources in an electrical machine. Therefore, providing a design solution with ‘low’ power loss and ‘good’ dissipative heat transfer capability is very desirable. There is a wide body of work focusing on both design aspects including various winding

constructions with ‘low’ power loss generation, e.g. high-speed/high-frequency applications [1]-[9] and winding impregnation and cooling mechanisms to provide ‘good’ heat extraction from the winding body, e.g. automotive and aerospace applications [10]-[18], [26].

In this paper, the latter design aspect is investigated, in particular the use of various electrical insulation materials for the winding assembly. The electrical insulation system used in construction of the stator-winding assembly has an important role of separating the winding conductors/turns from each other and winding body from the stator core pack. Simultaneously, it should provide ‘good’ heat transfer from the winding into the machine periphery, typically. The separation between the winding and stator core is usually assured by the suitable slot liner material together with winding impregnation. The available slot liners are usually in the form of film or paper-like sheets, which are formed to size and fitted together with the winding within slots of the stator assembly. In some applications the slot lining is realised by an appropriate powder coating of the complete stator core pack. The slot liner and impregnation materials interact during the winding impregnation process altering the thermal properties for the complete stator-winding assembly. For example, impregnation material may penetrate and fill cavities within the stator-winding assembly and/or the slot liner material can absorb some of the impregnation. The impregnation material is usually varnish- or resin-based with the winding impregnated using dipping, trickling or vacuum impregnation techniques. The overall heat transfer from the winding body into the stator core and machine periphery is strongly affected by the insulating/impregnating materials as well as the manufacture and assembly processes used. Assuring a reliable process, where the stator-winding performance measures are repeatable in volume manufacture is an other important aspect in the design-development of electrical machines.

These design issues are usually treated during the ‘design for manufacture’ and ‘design for performance’ stages of the development process. In this paper, the use of various slot lining and impregnation materials, and repeatability of the manufacture and assembly of the stator-winding assembly is investigated. The experimental approach adopted in this

analysis makes use of the stator-winding segment samples, which allow for various build combinations to be evaluated in a time and cost effective manner, prior to prototyping of the complete machine. It is important to note that the method commonly used when evaluating thermal behaviour of electrical machines relies on tests with the complete machine assembly [15], [16], [27], [28]. Such an approach, however, is usually limited due to available hardware. Here, a number of representative stator-winding exemplars have been manufactured and tested. This includes more absorbent slot liner materials, which potentially provide an improved heat transfer from the winding body into the machine periphery. However, as this type of slot liner material has usually lower ratings in terms of dielectric breakdown voltage and tensile strength, careful consideration must be given to selecting the material to satisfy the application and manufacture/assembly requirements. The experimental data from the manufacture repeatability tests indicates that a degree of discrepancy in performance measures between theoretically identical formed samples exists. Consequently, for in volume manufacturing, appropriate manufacture quality check needs to be in place to ensure final product conformance measures within the manufacture and/or performance tolerances or limits.

The experimental work presented in the paper has been complemented with theoretical analysis. This provides a more comprehensive insight into the heat transfer phenomena from the winding body into the machine periphery. In particular, the interface thermal resistance between the winding body, slot liner and laminated core pack has been investigated. This is especially important as the application of ‘better’ materials, e.g. slot liner and/or impregnation materials with improved thermal conductivity, might not yield expected performance gains if is not supplemented with appropriate manufacturing and assembly processes. Also, in the analysed case the theoretical predictions have confirmed that the winding-to-slot interface thermal resistance has a significant impact on the heat transfer from the winding body. This issue has also been reported by other authors [15], [16], [19], [26]-[29]. As the slot interface thermal resistance is notoriously difficult to predict theoretically, the thermal design of a machine without any experimental data or previous experience might be challenging and ultimately inaccurate. A detailed discussion regarding the outcomes of experimental and theoretical work has been provided in the latter section of the paper.

II. HARDWARE CONSTRUCTION AND MATERIALS

A. Stator-Winding Segment – Test Samples

To evaluate the use of alternative slot liner materials and repeatability of the manufacture processes used in the construction of the stator-winding assembly, a number of representative hardware exemplars have been produced. Such an approach allows for time and cost effective evaluation of ‘in situ’ thermal behaviour for alternative insulation systems prior to prototyping complete machine assembly. An individual hardware exemplar (motorette) consists of an open-slot solid steel stator core, a single-layer concentrated wound preformed coil, slot liner and slot closure/wedge, Fig. 1. The preformed coil is manufactured using compacted Type-8 Litz wire providing a high conductor fill factor. The motorette’s slot

geometry is identical to that of a brushless PM machine, which is currently in the prototyping stage of the development cycle. Some of the machine characteristics include: radial-flux topology, surface mounted PM rotor assembly, forced air-cooled housing and high torque-density with targeted continuous specific torque capability of the machine exceeding 20Nm/kg, based on the weight of the active stator and rotor elements. A more detailed machine specification is provided in [23]. The relatively ‘high’ transient overload capability requirement for the machine with air-cooled housing imposes the use of particular insulating and impregnating materials. The selected materials should enable the machine target transient thermal envelope while operating at the materials overload thermal limits.

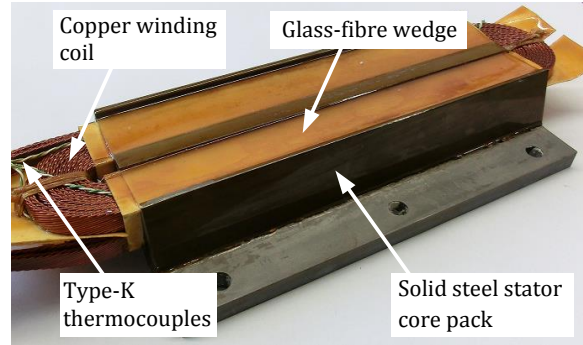


Fig. 1. Test sample (motorette) prior to impregnation

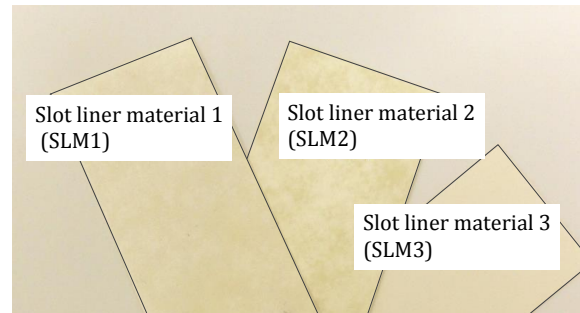


Fig. 2. Samples of the slot liner materials used in the analysis

TABLE I. BASIC SLOT LINER MATERIAL DATA

Property	SLM1	SLM2	SLM3
Thickness [mm]	0.25	0.25	0.25
Basis weight [kg/m ²]	0.249	0.366	0.270
Dielectric breakdown voltage ¹⁾ [kV]	8.25	5.0	1.8
Tensile strength ²⁾ [kN/m]	29.6/16.1	9.3/6.0	2.1/0.7
Thermal conductivity @ 180°C [W/m·K]	0.139	0.230	0.195
Insulation class	R (220°C)	R (220°C)	R (220°C)

Slot liner material 1 (SLM1) – Nomex 410 by Dupont

Slot liner material 2 (SLM2) – ThermaVolt by 3M

Slot liner material 3 (SLM3) – CeQUIN I by 3M

¹⁾ ASTM D-149 standard test method;

²⁾ Fibre machine direction of paper/across fibre direction of paper.

The analysis is limited to the selected slot liner insulation and varnish impregnation materials appropriate for this machine design.

Both the winding coil and stator core are instrumented with several Type-K thermocouples. In total there are 14 thermocouples located in the winding and stator core allowing for the heat transfer/thermal resistance across various paths to be determined.

B. Slot Liner Insulation Materials

Three alternative slot liner materials have been considered here, which are characterised by different thermal conductivity and their ability to absorb the impregnation medium, amongst other requirements. The ability to absorb the impregnation material is particularly relevant to the quality of the heat transfer from the winding body into the stator core pack. It is expected that a material with a ‘good’ absorption factor will provide reduced thermal resistance across the stator-winding interface as compared with more commonly used slot liner materials. Samples of the materials used are shown in Fig. 2, and basic material data is listed in Table I. The complete set of material physical properties is available on the manufactures’ online material data repository [21], [22].

When analysing the basic material data, it is evident that SLM2 has the highest thermal conductivity among the analysed materials, which is also reflected in its higher density. SLM3 is a highly absorbent material, which requires impregnation to achieve its full physical properties. Although the stated thermal conductivity of SLM3 is lower than SLM2, the total insulation system thermal conductivity may be higher for SLM3 due to improved penetration of the impregnation material. SLM1 has the highest dielectric breakdown voltage and tensile strength for the set of analysed materials. Both SLM2 and SLM3 are categorised as inorganic liners, whereas SLM1 belongs to the group of organic linear materials. SLM3 has the highest inorganic-content for the analysed material samples and is primarily composed of glass fibres and microfibers, inorganic fillers, and less than 10% organic binders. Due to a high glass fibre content it is recommended to handle the material with gloves to prevent skin irritation. The inorganic liner materials have low moisture absorption and high long-term dielectric strength. However, they suffer from reduced mechanical strength, which is particularly important in the manufacture and assembly processes. Throughout the assembly of a number of motorettes, it has been found that SLM3 is the most ‘fragile’ from the group of liner materials considered. As a result of the reduced mechanical strength, both SLM3 and SLM2 are well suited for a ‘single stage assembly’, where repeated mechanical stress associated with winding or conductors insertion is limited, e.g. placement of the preformed winding coil analysed in this research. Conversely, SLM1 has been found to be very robust allowing for repeatable conductor insertion, e.g. ‘winding in situ’ where the winding is wound on the stator core pack. Due its organic composition SLM1 should be stored in a sealed container to prevent moisture absorption.

C. Varnish Impregnation Materials

Two types of winding impregnation varnish have been evaluated in the analysis. An initial body of work was focused

TABLE II. BASIC VARNISH MATERIAL DATA

Property	VM1	VM2
Temperature Index	200°C	200°C
Curing temperature/time	160°C/4 hrs	160°C/1 hr
Electrical strength @ 155°C ¹⁾	>80 kV/mm	235 kV/mm
Resistivity @ 155°C ²⁾	> 10 ¹¹ Ω/cm	> 10 ¹¹ Ω/cm

Varnish material 1 (VM1) – Elmothorm 073-1010 by Elantas

Varnish material 2 (VM2) – ELAN-protect UP142 by Elantas

¹⁾ Electrical strength at elevated temperature, following IEC 60464 part 2

²⁾ Volume resistivity at elevated temperature, following IEC 60464 part 2

on the motorette samples impregnated using solvent based varnish VM1. Based on the initial findings, a further set of motorette has been manufactured and tested. Here, a non-solvent based varnish VM2 has been used to impregnate the winding. In both cases vacuum impregnation technique has been employed. Selected properties for the varnish materials are listed in Table II, with complete data provided by the manufacturer [22]. The material data suggests that VM2 has shorter curing time as compared with VM1, which is of importance when considering in volume manufacture. The shorter curing time results from low solvent varnish composition, reducing the operator discomfort associated with varnish vapour/fumes present during impregnation. For the solvent based varnishes, such as VM1, the solvent is baked off during curing process, resulting in cavities within the heat transfer paths and increased equivalent thermal resistance. In contrast, VM2 has a gelling property allowing for better quality impregnation. Here, the winding sample is heated up to 120°C during the impregnation process, which initiates setting of the varnish within 7 minutes.

D. Motorette Fabrication

Each of the stator-winding exemplars used in the analysis followed identical fabrication procedure. Initially, an individual winding coil instrumented with thermocouples is preformed on an appropriate mandrel. The coil is then slotted into the representative stator core segment with selected slot liner material in place. The coil insertion stage requires particular attention due to tight tolerance between the stator and winding assemblies. This has been chosen to provide ‘good’ heat transfer from the winding body into the machine periphery, fully utilising the attributes of the open-slot machine topology [23]. Finally, the coil is mechanically secured within the stator slots using suitable glass-fibre based wedges.

During the impregnation process, the complete stator-winding assembly is submerged in a selected impregnating material in a vacuum environment. This provides improved penetration of the impregnation. It is important to note that the mounting surface of the stator core assembly used, to interface the motorette with test rig, is protected during the impregnation process. The impregnated material sample is transferred into a preheated oven and cured. The curing temperature and duration is chosen following the material manufacturer guidelines, table II.

III. EXPERIMENTAL SETUP AND TESTING PROCEDURE

An experimental approach has been used to assess the influence of various slot linear and varnish materials on the conductive heat transfer across the stator-winding interface. The experimental set-up consists of a thermally insulated chamber, liquid-cooled temperature-controlled cold plate, data acquisition system and dc power supply, Fig. 3.

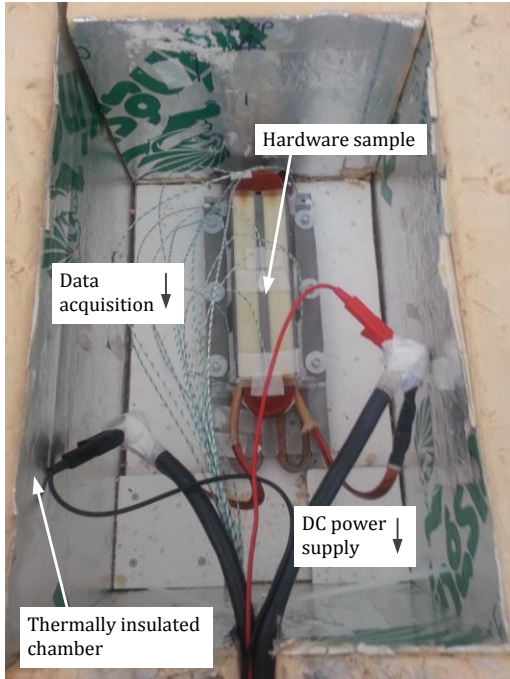


Fig. 3. Experimental setup for dc thermal tests

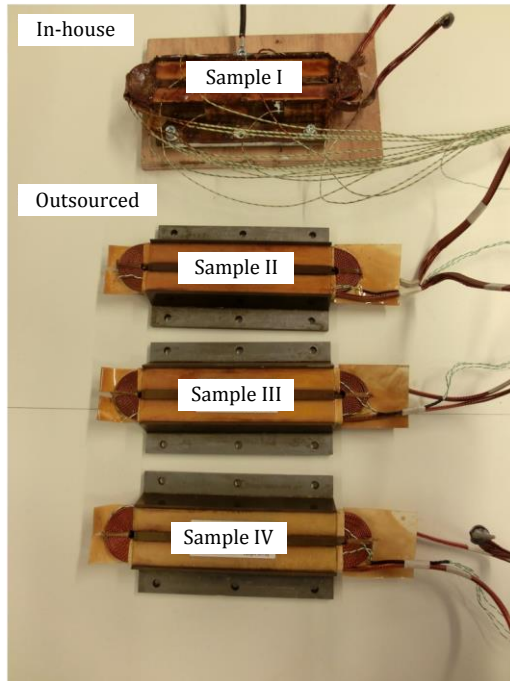


Fig. 4. Batch of motorettes with SLM1 insulation and VM1 impregnation

A hardware exemplar sample is mounted on the cold-plate and placed in the chamber prior to tests. The cold plate temperature is fixed at 15°C during the tests. Such a set-up allows for controlled and repeatable testing conditions with the main heat path being the winding body to the heatsinked stator core. The thermally insulated chamber assures adiabatic-like conditions for the sample surfaces, which are not in contact with the cold-plate. Consequently, the thermal conduction is the dominant heat transfer mechanism in the experiment. Here, the other heat transfer effects, i.e. convection and radiation have negligible impact on the overall heat transfer. The coil winding is energised from a dc power supply for a set of current levels. When the motorette sample reaches thermal equilibrium at a given excitation, the current is increased and thermal test is repeated until the thermal limit of the insulation system is reached. The power loss and temperatures within the hardware sample and cold plate are monitored and logged during the tests. To reduce temperature measurement uncertainty, a multiple type-K thermocouple arrangement has been used and the measured data for a given motorette region has been averaged. It is worth mentioning that the overall temperature measurement uncertainty is set by the accuracy of the type K-thermocouples used and is equal to $\pm 1.5^\circ\text{C}$ over the operating temperature range ($- 50^\circ\text{C}$ to $+ 260^\circ\text{C}$).

The testing procedure has also been used to evaluate repeatability of the manufacture and assembly process. Fig. 4 presents an initial batch of motoretts used in the analysis.

IV. THERMAL ANALYSIS

A. Thermal Model Definition

To provide a more detailed insight into the conduction heat transfer from the winding body to the stator core pack, a number of thermal analyses have been performed. A two-dimensional (2D) thermal finite element analysis (FEA) has been used here, with the solution region reduced to a half of the motorette's cross-section, Fig. 5. The end-winding region, which is frequently associated with location of the winding hot-spot [11]-[18], is not accounted for in the theoretical investigation.

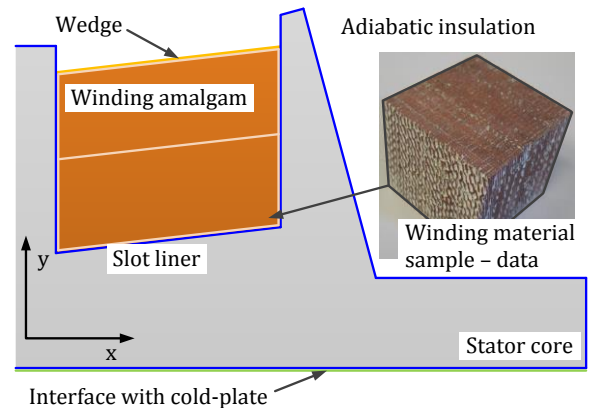


Fig. 5. Thermal model representation of a half of the motorette assembly cross-section

TABLE III. MEASURED THERMAL CONDUCTIVITY DATA USED IN THE FEA

Model sub-region	k_x [W/m·K]	k_y [W/m·K]
Winding amalgam	1.4	1.7
Stator core	22.0	22.0
Wedge	0.3	0.3

Refer to Table I for the manufacturer provided thermal conductivity data for the analysed slot liner materials

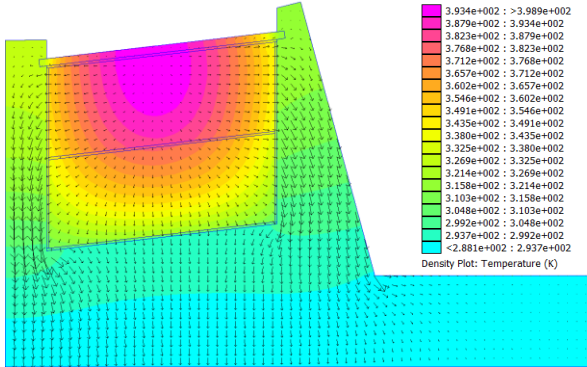


Fig. 6. An example of temperature distribution and heat flux paths within the motorette assembly from FEA

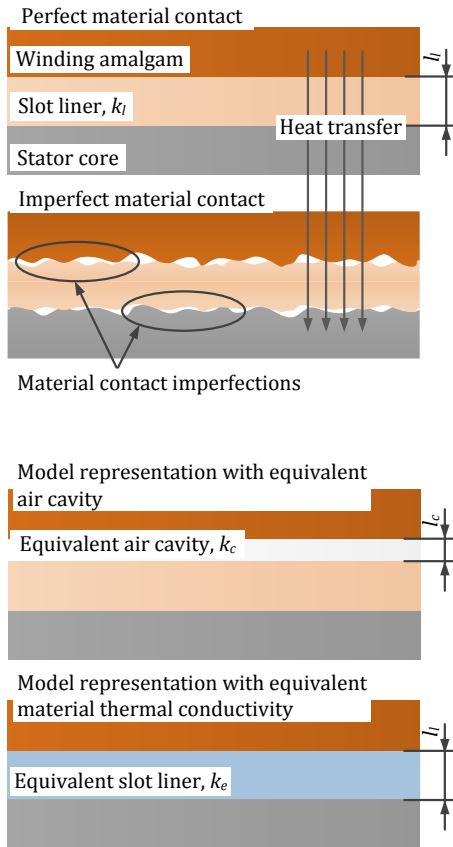


Fig. 7. Schematic explanation of material perfect and imperfect contact together with equivalent model representation

The experimental results have shown negligible temperature difference between the active and end winding regions,

consequently the 2D modelling approach has been found sufficient for the analysis. Such model definition has been assumed based on symmetries in flow paths for the heat flux and thermal tests on a number of exemplar assemblies.

The motorette's winding is represented in the model as a homogenous region with the composite material thermal properties derived from tests on representative material samples, Fig. 5. A complete set of measured thermal conductivities used in the analysis is listed in Table III. It is important to note that as the temperature distribution at thermal equilibrium is of interest in this investigation, the required material thermal data is limited to thermal conductivity only. The construction of material samples and testing procedure used to derive composite material properties is analogous to that presented in [10]. The interfacing surface of the motorette assembly model is set with a fixed temperature boundary condition, 15°C , whereas the remaining model surfaces are adiabatically insulated emulating the experimental setup. The model definition assumes that the main heat extraction is provided by conduction from the heat source (winding) to the heat sink (cold-plate).

B. Winding-to-Slot Contact Thermal Resistance

Fig. 6 shows an example output from thermal FEA illustrating the modelled temperature distribution and heat flux paths within the motorette assembly. When comparing the top and bottom layers of the winding body it is evident that low thermal resistance, 'good' heat transfer path from the winding assembly to the stator core, is essential in assuring the required dissipative power loss capability. The top layer of the winding is at higher temperature than the bottom one due to a poorer heat transfer path (higher equivalent thermal resistance). In this case, it is caused by less equivalent contact surface area between the winding and stator core for the top winding layer. It is important to note that the equivalent contact surface area depends on the geometrical contact surface area as well as quality of the contact, which is affected by various manufacture and assembly factors.

In the FEA models, the representation of the stator/winding assembly assumes perfect contact between model sub-regions, i.e. no contact thermal resistance stator-to-slot is present. The temperature predictions from such models are likely to be underestimated compared with experimental data from tests on equivalent hardware exemplars. The discrepancy is likely to be a result of imperfect contact between various assembly sub-regions, which introduces an additional thermal resistance in the heat transfer path. Fig. 7 present a schematic illustration of the material contact issue, indicating irregular cavities between various stator-winding sub-regions. The interface between winding, slot liner and stator core pack has been shown to have a significant impact on the heat transfer from the winding body and consequently a machine's power output capability [15], [16], [19], [26]-[29]. A good understanding of the interface thermal resistance between various sub-regions is therefore necessary for accurate thermal design and machine performance predictions. Here, an approach based on experimental calibration of the mathematical models has been adopted. Fig. 7 shows

correspondent model definitions accounting for the contact imperfections including the equivalent air cavity region and equivalent slot linear region. In this analysis the latter approach has been adopted with model calibration performed by adjusting thermal conductivity for the equivalent slot liner region to account for the manufacture and assembly imperfections, i.e. the equivalent thermal conductivity is altered to match the FE temperature predictions with measured data from tests on the motorette hardware. The resultant thermal resistance across the slot liner is a sum of two components:

$$R_l = \frac{l_l}{k_l A} + \frac{l_c}{k_c A} = \frac{l_l}{k_e A}, \quad (1)$$

where l and A refer to thickness and surface area respectively, across which the heat is transferred and k is the thermal conductivity, see Fig. 7.

The first term in (1) represents the liner sub-region, whereas the second term denotes an equivalent sub-region representing manufacture and assembly imperfections. The resultant thermal resistance is given by the last term in (1). It is important to note that all contact imperfections between the stator/winding sub-regions are accounted for by k_e . Such an approach allows for the model geometry to remain unchanged and only material properties, k_e , for the linear sub-region are adjusted. Also, the slot liner sub-region has been subdivided into a section associated with the vertical and horizontal heat transfer, e.g. heat flow from the winding body to the stator back iron or stator teeth. It has been shown in the literature that due to different conductor lay in the vertical and horizontal paths, separately adjusted k_e for both heat transfer planes is frequently required [19].

V. RESULTS

A. Impregnation ‘Goodness’

To compare dissipative heat transfer capability for various hardware samples considered in this analysis, the hot-spot winding temperature rise above the back iron (ΔT) versus winding dc power loss (P) plots have been used. This approach allows for the maximum power loss handling capability for the stator-winding assembly to be estimated. Fig. 8 presents measured results for the in-house hardware exemplar (Sample I) built with SLM1 insulation and VM1 impregnation at various impregnation stages: stator-winding prior to impregnation (Unimpregnated), after first impregnation (Impregnated $\times 1$) and after second impregnation (Impregnated $\times 2$). It is important to note that for in volume manufacture, a single impregnation with appropriate material is usually employed to reduce the overall machine fabrication time and cost. Here, the example of multiple impregnation is presented to illustrate the concept of impregnation ‘goodness’. The impregnation ‘goodness’ is frequently referred to in the literature, when describing stator-winding thermal properties for a given insulation system [27]-[29]. The measured results shown in Fig. 8 represent different levels of impregnation ‘goodness’ from relatively ‘poor’ to ‘moderate’ for the unimpregnated and impregnated exemplars respectively.

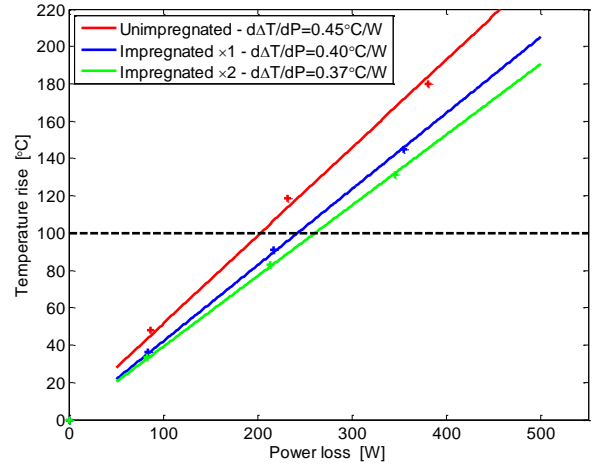


Fig. 8. Winding temperature rise above back iron vs. winding dc power loss for SLM1 insulation and VM1 impregnation where appropriate

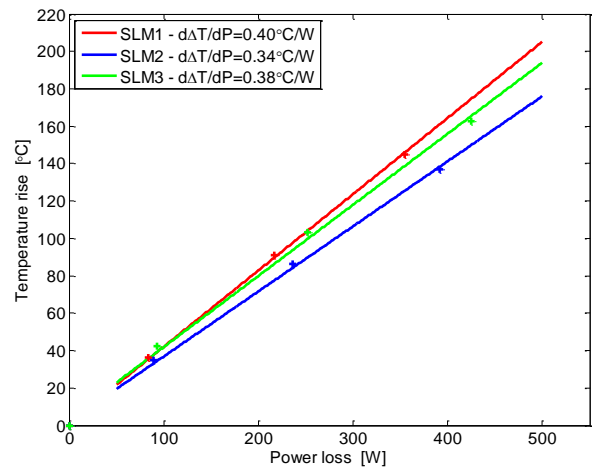


Fig. 9. Winding temperature rise above back iron vs. winding dc power loss for alternative slot liner materials and a single VM1 impregnation

The results confirm considerable improvement in heat transfer for the doubly impregnated sample, approximately 20% improvement post-second impregnation as compared with unimpregnated sample. This is caused by better fill of air cavities within the stator-winding assembly for the multiple varnish impregnation resulting in overall improvement of the stator-winding impregnation ‘goodness’. In general, the solvent based impregnation enables a moderate impregnation ‘goodness’ due to the material chemistry, i.e. when solvent evaporates during the impregnation curing process, the air pockets are still present within the stator-winding assembly. The use of impregnation materials with different physical properties, e.g. epoxy resins allows for better impregnation ‘goodness’ and improved winding thermal conductivity [11], [26]. The rate of improvement is given here as $d\Delta T/dP$, which is an equivalent thermal resistance between the stator back iron and winding body. In the context of the analysed machine and its target power output, the unimpregnated winding provides

3% margin, whereas double impregnated 20% margin to accommodate an increase in overall power loss generated within the machine stator assembly at ac operation assuming allowable 100°C winding temperature rise above the back iron. For example, assuming that the ac loss is negligible as compared with the dc winding loss contribution, the improved $d\Delta T/dP$ corresponds here, with 1% and 10% per unit output power increase respectively.

B. Slot Liner Comparison

Fig. 9 compares measured data from tests on motorette assemblies with alternative slot liner materials considered in the analysis. It is important to note that a single varnish impregnation has been used for the set of hardware exemplars tested in this investigation. The results suggests that the motorette with SLM2 provides the lowest thermal resistance from the winding body across into the stator core pack, whereas the exemplar with SLM1 provides the highest stator-winding thermal resistance among the analysed hardware samples. The rate of improvement of $d\Delta T/dP$ for the extremities is equal to 17%. It is interesting to note that the overall thermal behaviour of the analysed motorette assemblies follow a trend set by the material thermal conductivity data listed in Table I. The SLM2 slot liner has the highest thermal conductivity and consequently provides the lowest thermal resistance across the stator-winding interface with SLM3 next and SLM1 the last. An insight into microscopic structure of the analysed slot liner materials has been provided in [24]. When comparing the analysed slot liner materials, it is evident that SLM3 has the most porous construction as compared with SLM1 and SLM2. The individual elements of the SLM3 material composition are prominent and include fibres of glass, microfibres and fillers [20]. The material structure for SLM1 and SLM2 does not have visible cavities and consequently results in a more impermeable/less absorbent material structure.

Before the thermal tests, it was expected that the motorette assembly with SLM3 might assure the best thermal behaviour due to slot liner superior impregnation absorption. However, the experimental data suggests otherwise. This might be attributed to the impregnation material used, which in case of solvent-based varnish provides relatively low thermal conductivity as compared with alternative epoxy-resin impregnation solutions [11], [26], and consequently does not contribute to improvement of post-impregnation liner material properties. Also, the manufacture and assembly factors affecting the individual hardware samples in a different manner might have had an impact on the thermal behaviour and overall outcome of this comparison.

C. Sensitivity Analysis

To provide an insight into the manufacture and assembly issue the experimental work has been supplemented with theoretical analysis. The motorette samples with alternative slot liners have been analysed using the approach described in the previous section. A number of FEA simulations for perfect and imperfect contact between stator-winding sub-regions have been performed. The FE models with imperfect thermal properties have been calibrated using the experimental data. Fig. 10 presents an example of a contour plot of $d\Delta T/dP$ versus

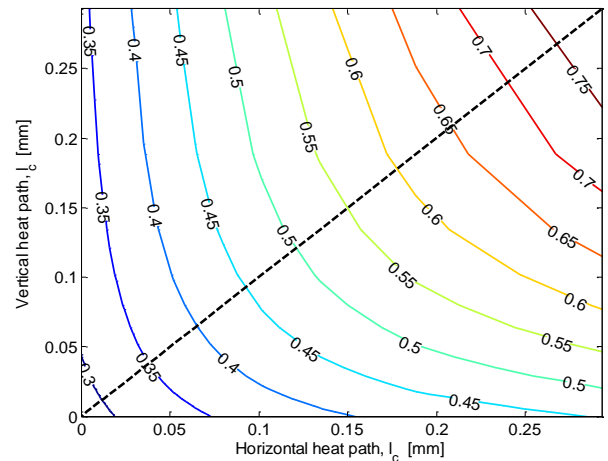


Fig. 10. Contour plot of $d\Delta T/dP$ vs. cavity thickness l_c for the vertical and horizontal heat paths – model representation of motorette assembly with SLM1 insulation and VM1 impregnation

equivalent cavity thickness, l_c , associated with heat transfer from the winding body into the stator core pack across the slot liner, see (1). It has been assumed here that thermal conductivity for the cavity region, k_c , is equal to that of air, 0.0181W/m·K, [27]-[29]. When inspecting the calculated results, it is evident that there are a number of alternative combinations of l_c in the horizontal and vertical heat paths assuring a match for the calculated and measured $d\Delta T/dP$. For example, in order to calibrate the model with SLM1 insulation and VM1 varnish impregnation ($d\Delta T/dP = 0.40^\circ\text{C/W}$) we could assume perfect contact for the vertical heat path and 0.16mm cavity for the horizontal path or 0.04mm cavity in the horizontal path and 0.31mm cavity in the vertical path for the extremities. This ambiguity is caused by the limited number of temperature measuring points used during tests on the motorette samples. A higher fidelity, resolution temperature measurements and/or supplementary tests would allow for a more definite calibration approach. Due to a limited number of temperature measuring points, it has been assumed in the analysis that the equivalent thermal conductivity, k_e , is identical for both the horizontal and vertical heat paths, as shown by the dashed line in Fig. 10.

D. Calibrated Results

TABLE IV. EQUIVALENT THERMAL CONDUCTIVITY AND CAVITY THICKNESS DATA; VM1 IMPREGNATION

Property	SLM1	SLM2	SLM3
Equivalent thermal conductivity k_e [W/m·K]	0.046	0.067	0.053
Air-gap cavity thickness l_c [mm]	0.06	0.05	0.06

Table IV includes the adjusted thermal conductivity, k_e , for the slot liner region and equivalent air-gap cavity thickness, l_c . The results suggest that the motorette assembly with SLM2 slot liner has a better build factor resulting in smaller winding-

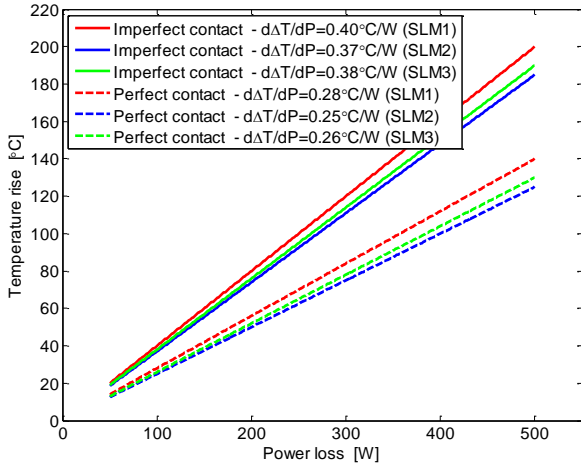


Fig. 11. Winding temperature rise vs. dc power loss for alternative slot liner materials – experimentally adjusted results to account for the same contact air-gap cavity (imperfect contact) and theoretical results (perfect contact); VM1 impregnation

to-slot air-gap cavity as compared with other motorette exemplars. To make the comparison between the slot liner materials clearer, the results for SLM2 have been adjusted for the same 0.06 mm air-gap cavity using the FEA thermal model. Fig. 11 shows results for all the liner materials for perfect and imperfect contact between winding body and stator core assembly. It is worth recalling that the imperfect contact refers to the experimentally calibrated FE models adjusted for the same air-gap cavity. As expected, the adjusted results for SLM2 indicate lower rate of improvement as compared with experimental data, 0.37°C/W and 0.34°C/W respectively, Figs. 9 and 11. The general trend in terms of $d\Delta T/dP$ for the analysed linear materials remains unchanged.

E. Manufacture Repeatability

To provide an insight into the manufacture and assembly related issues and their impact on the motorette's thermal behaviour, an initial batch of supplementary motorette samples has been manufactured by an external electrical machine manufacturing company, Fig. 4. The materials, manufacture and assembly processes employed were identical to that used for the in-house built prototypes. The batch of motorettes considered here has been manufactured using SLM1 insulation and VM1 impregnation. Fig. 12 presents experimental data from tests on the set of motorettes (Sample II - IV) together with results for the in-house built exemplar (Sample I). The data indicates a degree of discrepancy between the samples with 8% to 25% $d\Delta T/dP$ variation when comparing the in-house manufactured and outsourced samples, and up to 15% for the outsourced samples only. It is evident that a non-negligible degree of discrepancy between alternative motorette samples exists, which in the context of complete machine assembly has important implications, i.e. undesirable non-uniform temperature/hot spots distribution around the winding circumference. As a number of analysed motorette samples is relatively small, it is difficult to draw any more comprehensive conclusions regarding repeatability of the manufacturing and

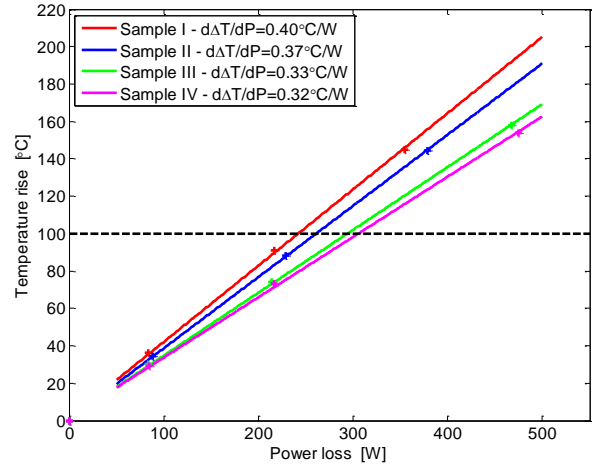


Fig. 12. Winding temperature rise vs. dc power loss for a batch of motorettes with SLM1 insulation and VM1 impregnation.

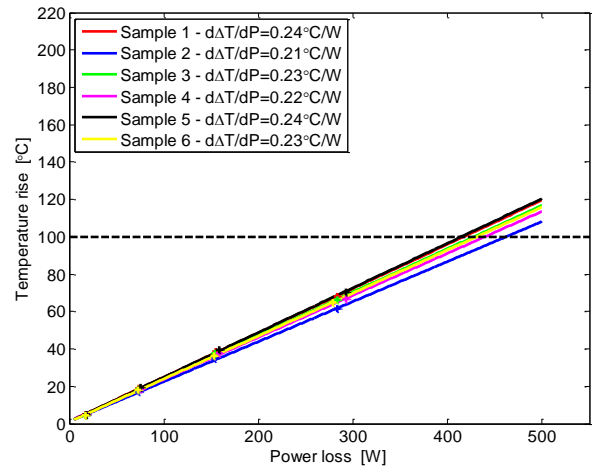


Fig. 13. Winding temperature rise vs. dc power loss for a batch of motorettes with SLM2 insulation and VM2 impregnation.

assembly processes used in construction of the motorettes with SLM1 insulation and VM1 impregnation. A statistics based approach making use of a larger batch of test samples would be more informative/appropriate here.

Based on the initial findings from tests on the motorette samples and trial manufacture techniques, a further set of motorettes has been manufactured and tested. Here however, SLM2 insulation together with VM2 impregnation has been used. This combination of materials has been selected as it has shown to be the most promising in terms of electrical and thermal behaviour, and ease of use for in volume manufacture. Some of the material features include 'good' impregnation fill resulting in improved impregnation and short curing time allowing to reduce the manufacture cost. Also, a more refined manufacture and assembly process has been implemented based on prototyping trials from the initial motorette batch. In particular, a more consistent coil preforming and insertion into the stator core pack has been implemented.

The number of motorettes has been increased to six to evaluate the manufacture repeatability issue in a more comprehensive manner. Fig. 13 presents measured results of the winding temperature rise versus winding power loss showing on average 28% improvement of $d\Delta T/dP$. This is a significant enhancement of the dissipative heat transfer from the winding body into the stator as compared with the initial motorette trials. Also, the experimental data suggests a more consistent and repeatable manufacture with up to 12% variation of $d\Delta T/dP$ for the individual motorette samples.

It is important to note that the winding-to-slot heat transfer is also affected by the ageing of the insulation system. The latest research in the field has shown that the insulation system ageing has a prominent impact on the overall heat transfer from the winding body into the machine periphery [25]. This is particularly important in the context of machine in service exploitation, which might lead to accelerated insulation degradation and consequently premature machine failure. This research theme however, is out of scope of the presented body work and will be investigated by the authors in the future.

VI. CONCLUSIONS

This paper has investigated the use of alternative insulation slot liner materials and impregnation varnishes commonly employed in construction of electrical machines. The research focus has been placed on a more systematic experimental characterisation of the ‘in situ’ materials thermal behaviour, where the interactions between various elements of the stator-winding assembly are accounted for. An approach making use of a representative hardware stator-winding segment has been adopted in the analysis, to derive heat transfer performance measure across the stator-winding assembly for the complete machine. A number of motorettes utilising combinations of various insulation and impregnation materials have been manufactured and tested. The proposed experimental approach allows for time and cost effective evaluation of alternative stator-winding builds prior to prototyping of the complete machine assembly.

The experimental results have shown that in the analysed case, with vacuum varnish impregnation, the slot liner with higher thermal conductivity assures improved heat transfer between the stator and winding subassemblies as compared with alternative materials exhibiting poorer thermal properties. Also, the use of slot liner materials with higher impregnation absorption has not shown improvement to the overall heat transfer from the winding body. Moreover, the application of varnish material enabling better impregnation ‘goodness’ resulted in improved heat transfer across the stator-winding assembly, e.g. 28% improvement in dissipative heat transfer for the stator-winding exemplar utilising SLM2 and VM2 as compared with the initial motorette builds (SLM1 and VM1). Furthermore, the results indicate significant impact of the winding-to-slot contact thermal resistance on the heat evacuation. These general trends observed from the hardware tests are largely in line with the initial expectations. However, as the build factors related with thermal design of electrical machine are notoriously difficult to predict theoretically, the measured data from the ‘in situ’ material characterisation provides a ‘good’ starting point for thermal design of electrical

machines utilising materials and fabrication techniques equivalent to these analysed in the paper.

The theoretical sensitivity analysis of the winding-to-slot thermal contact resistance has revealed a difference in build ‘quality’ between selected motorette samples. These are attributed with the manufacture and assembly factors affecting manufacture repeatability. The results from tests on the motorette batches built to the same specification have shown that the initial manufacturing inconsistencies can be significantly reduced by introduction a more controlled fabrication process, e.g. $d\Delta T/dP$ initial discrepancy of 25% has been reduced to 12%. Also, the theoretical investigation has shown a level of unambiguity of the thermal model calibration with a reduced number experimental data points. In order to provide a more informed calibration process accounting for localised heat transfer discrepancies, a higher fidelity/higher resolution experimental approach is required. This however, is usually limited to the prototype machine development or specific research project only, as a number of temperature sensors used for in volume machine manufacture is limited to the necessary minimum.

Further work is required to identify the manufacture and assembly deficiencies affecting the winding-to-slot heat transfer in a more detail. Experimental tests using a statistically relevant sample size of motorettes would provide more robust approach to account for natural variations in manufacture and assembly. Additional work could also evaluate different commercially available slot liner and varnish materials in other combinations to assess the compatibility of the materials.

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