# Mechanical and Thermal Properties of Compressed Stator Windings

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## Abstract

This paper discusses coil pressing through which stator windings are compressed at high pressures to enhance the slot fill factor of electrical machines. Deterioration of insulation in compressed windings is investigated by performing quasi-static explicit dynamics finite element simulations. The results obtained from the proposed method are further investigated experimentally to validate the durability of the compressed coils. It is shown that stator windings can be compressed to a certain degree without observing material failure. In order to demonstrate the thermal advantages of densely packed stator windings, both steady state thermal finite element analysis (FEA) simulations and semi-analytical methods have also been studied. A good agreement between analytical and FEA simulations is obtained. It is noted that steady state thermal finite element modeling could be used to predict effective thermal conductivity of stator windings for different slot fill factors.

## 1 Introduction

Energy losses play an important role in obtaining high efficiency electrical machines. All conducted design and analysis methods aim at lowest machine losses including windage-friction losses, core losses and copper losses. However, there are some physical restrictions which restrain further reduction of overall machine losses, the most significant of which is copper loss.

Copper losses can be reduced by reducing the coil resistance, by minimising the coil length and improving the fill factor ($Total\ \ conductor\ \ area/Slot\ \ area$) [1]. Winding configuration, which affects both length and fill factor, is an important parameter regarding machine performance.

Fractional slot concentrated winding (FSCW) PM machines with segmented stator structures can improve the machine power density by reducing copper losses significantly, because non-overlapping concentrated windings help reduce overall coil length and enhance the slot fill factor [2]. Various methods have been investigated to obtain higher slot fill factors. In [2], "plug-in tooth" technique has been discussed to obtain very high fill factors. In [3], Akita *et al* reported a 75% slot fill factor using a method known as "joint-lapped core". All these developed methods are based on stator segmentation as this makes machine winding easier at the expense of less stator back iron rigidity. According to Jack *et al* [4], segmented soft magnetic core (SMC) stator structures could be coupled with pre-pressed windings in order to achieve significantly high fill factors. In addition, compaction of winding by pre-pressing is found to eliminate air between the turns which in turn provides more efficient heat transfer for stator windings. However, applying very high pressures ranging between 200 MPa to 800 MPa will lead to deformation on polymeric wire insulation of magnet wires which might lead to insulation failure.

This paper considers the mechanical process of coil pressing and its effect on conductor insulation, deformation and thermal conduction. Modern magnet wires use one to four layers of thermosetting polymer film insulations to withstand applied voltage and generated heat in current carrying conductors. Film insulation thickness usually varies from 0.05 to about 0.1 mm [5]. Magnet wires are usually classified by diameter, insulation class (grades) and temperature class. However, mechanical properties of magnet wires such as ultimate tensile strength, elongation and fracture strength are not considered as important as electrical and thermal properties as it is not crucial for a range of industrial applications. Nevertheless, mechanical properties are very important if coils are being pressed at high pressures to enhance the slot fill factor.

Although pressing coils at high pressures is known to increase slot fill factor dramatically, the conductor wire deformation process is still not clear. In this paper, the deterioration of the wire enamel in pressed coils has been investigated by conducting quasi-static, nonlinear explicit dynamics simulations. Moreover, thermal improvement due to high fill factor windings has been demonstrated by performing steady state thermal FEA simulations and semi-analytical Fourier law of heat calculations.

## 2 Non-Linear Explicit Dynamics Simulations

### 2.1 Explicit Dynamics Simulations

Transient dynamic simulations usually require extremely small time steps to converge an accurate solution. There are two types of time integration methods: implicit and explicit methods. Since explicit methods are very efficient for each time step, it allows calculation of a very large number of time steps within the duration of the simulation time. If the dynamic response of a system takes a few seconds rather than a few milliseconds, then many millions of time steps will be required to observe the complete dynamic behaviour of the system. This type of FEA analysis is required for certain physical problems such as metal deforming.

In order to solve highly non-linear coil pressing problem, Explicit Dynamics analysis of Ansys® computer aided engineering (CAE) package has been utilised.

**2.2 Quasi-Static Problems**

Explicit methods are usually suitable for high speed collision tests and blast problems due to very small time durations. A typical time integration time step is about 1 nanosecond to 1 microsecond for explicit dynamics simulations [6]. Although coil pressing phenomena is not a short duration problem, explicit methods will result in better accuracy in terms of nodal stress-strain calculations.

Quasi static simulations, which are considered to be a part of low speed explicit dynamics simulations, are usually suitable for metal forming applications such as drawing, strain hardening, rolling etc. Therefore, explicit solvers are more efficient for this class of problems. Coil pressing could be considered in this class of problems due to complex body-contact conditions, large deformations and material non-linearity.

There is an important factor that should be considered when low speed problems are analysed using explicit solvers:

*Since natural time period of a quasi-static problem is relatively long compared to high speed impact problems, quasi-static problems with long time duration are usually impractical to model as millions of time increments would be required.*

In order to solve this problem, there are some methods which might be applied during the solution setup of quasi-static explicit dynamics solvers. These are summarised as given below:

*1)* Artificially increasing the speed of the process

*2)* Artificially reducing the time scale of the process by increasing loading rate – although this will cause higher strain rates during the calculation of nodal stress and strain.

*3)* Artificially increasing the material density by a factor of $f^2$, increases the stable time increment by a factor of $f$. This allows us to reduce CPU execution time of an explicit simulation.

**2.3 Loading Rates**

Fundamental period or first mode of vibration is important in order to choose reasonable loading rate for the analysis of a quasi-static coil pressing simulation.

As the natural frequency of a first mode vibration is required to choose a loading rate, corresponding time period for first natural frequency should be estimated. Angular natural frequency, $\omega$ of a degree of freedom (DOF) model can be written

$$\omega = \sqrt{\frac{k}{m}} \tag{1}$$

In (1), the natural frequency of a structure is proportional to the square root of the stiffness of the structure and inversely proportional to the square root of the total mass ($m$) of the body. First natural frequency of the model can be estimated using modal vibration analysis FEA software tools for complex mechanical structures. From the point of view of coil pressing simulations, obtaining a natural frequency for a piece of stator winding would be very difficult to estimate due to physical complexity of a bobbin.

The principal aim to calculate impact velocity here is to limit the impact velocity to 1% of the wave speed of the material. Typically, wave speed in metals is 5000 m/ sec [7]. Since the wave speed for an electrical bobbin is not known, a method has been suggested in [7]. This was given in the following order:

*1)* A series of simulations can be run in the order from fastest load rate to the slowest. As load rate decreases, analysis time will be greater. This in turn increases the solution accuracy.

*2)* After conducting a series of simulations, results such as deformed shapes, stress, and strain values are examined to have an understanding for the effects of varying loading rates.

*3)* Excessive speeds will result in unrealistic mesh deformation with localised stress and strain rates. In quasi static simulations, if excessive loading is used, a steep initial slope in the load versus displacement curve might occur. This means that response of a simulation during the solution process should be examined.

**2.4 Mass Scaling**

Importance of material strain rate is dependent on the application. If the material is strain rate insensitive, this is irrelevant. However, if material strain rate is an important parameter to observe deformation, material strain rate should be considered for failure criteria of the material.

For FEA of coil pressing, material strain rate is an important parameter. If the simulation is not analysed in its natural time period, which is usually longer time durations for quasi-static experiments, material strain rate will be calculated incorrectly. In order to be able to increase time duration which is very costly computationally, mass scaling can be adapted to the system by increasing material density 10 times artificially to obtain more accurate results with longer time period simulations.

## 3 Modelling Coil Pressing

The process of coil pressing is investigated using a coil consisting of nine turns of copper magnet wire. Polyimide based enamel has been considered for modelling because polyimides are mechanically and chemically more stable and operate at temperatures in excess to 240°C [8]. The low turn number is for simulation simplicity, each turn has an overall diameter of 1.9 mm and Grade 2 polyimide coating. Mechanical limits of high quality modern copper magnet wires with polyimide coating are tabulated in Table 1.

| | | |
|---|---|---|
| Density | $1.3 \times 10^3 - 1.8 \times 10^3$ | $kg/m^3$ |
| Young's Modulus | $2.44 - 4$ | $GPa$ |
| Compressive Modulus | $2.82 - 2.97$ | $GPa$ |
| Shear Modulus | 0.91 – 0.955 | $GPa$ |
| Yield Strength | 72 – 158 | $MPa$ |
| Compressive Strength | 133 – 227 | $MPa$ |
| Fracture Strength | 345 | $MPa$ |
| Elongation | 2 – 3 | $mm/mm$ |

Table 1 Material properties of polyimide

Young's modulus of polyimide is very low compared to high conductivity metals such as copper, aluminium or silver etc. Most of the deformation will therefore occur in the magnet wire enamel. This implies that the mechanical weak point of copper magnet wires is actually the coating. Yield Strength of polyimide is 158 MPa after which plastic deformation occurs. Below this stress value, only elastic deformation will occur. Elongation which is described as strain rate during the material failure will be included for FEA modelling to investigate whether material fracture occurs after certain stress value.

In reality, coils are pressed with pressing tools that apply high pressure. Although pressure load is applicable to coil pressing simulations, this was not preferred, because a 'pressure' boundary condition cannot control the amount of displacement with respect to time. This is very important for quasi-static analysis methods which must provide low speed collision for the model by considering natural time duration of the event.

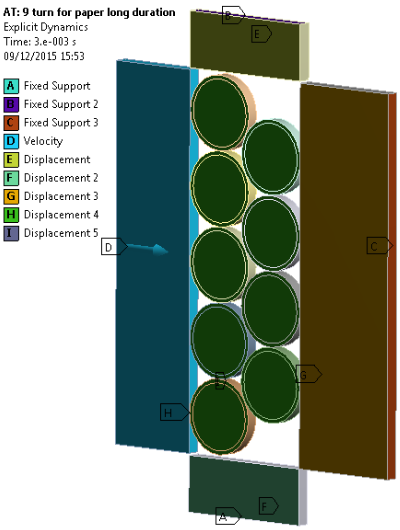


Fig. 1 FEA boundary conditions

Compression of the coil is achieved by applying velocity load onto the punch, made of Steel 4340 as shown in Fig. 1. The applied velocity load will control the total displacement of the punch while pressing the coil. Time integration of the velocity profile gives the total displacement of the punch, 0.875 mm. Maximum speed of the punch is 350 mm/s, corresponding to 35 cm displacement of the punch in one second at constant speed. This shows that the simulation is artificially accelerated to press the coil over a very short period of time, due to computational cost of the quasi- static simulations.

The distance between the layers is set to 0.015 mm, which is very small and could not be achieved in reality. However, this will help reduce the effect of high speed collision between the layers during the simulation. Initial fill factor for this case is calculated to be 0.59 higher than conventional fill factors. As explicit methods are used to model dynamic behaviour of the coil pressing with very small refined mesh size, the simulation has taken about 70 hours to solve with 24 GB memory, 4-core PC.

## 4 Results

In this section, simulated results from Section 3 are compared to experimental results obtained in the laboratory. As the most important factor is to verify if the coil is damaged, stress and strain results should be examined at the same time. Before presenting simulation results, accuracy of solution should be checked via investigation of the conservation of energy during the simulation.

### 4.1 Conservation of Energy for pressing simulations

If the velocity load is increased to simulate the model over a shorter time, strain rate will be increased artificially at the same rate. If the velocity is decreased to simulate the model over a longer time period, this implies that the solution will be more static as the speed of the punch is lowered. There is no direct way to understand if the compression of the coil is static rather than dynamic. However, kinetic energy produced during the compression of the coil could be examined. It is expected that kinetic energy of the compression should be sufficiently low compared to the internal energy of the system.

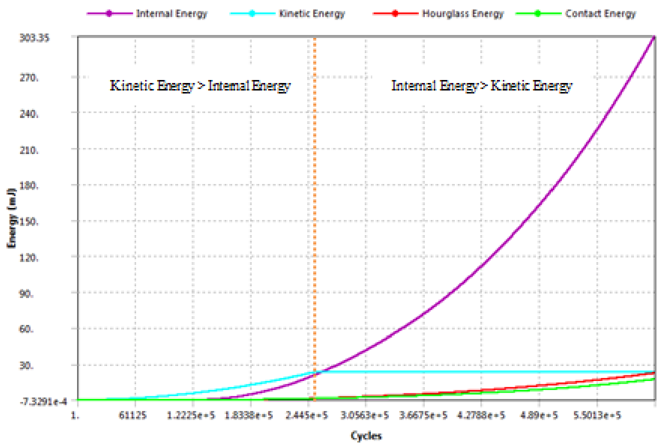


Fig. 2 Energy summary of the coil pressing model

In Fig. 2, solution cycles versus energy content of the simulation are plotted. In the beginning of the simulation, kinetic energy increases and internal energy is lower. This will create artificially higher strain rate results in the simulated model. Nonetheless, total amount of kinetic energy throughout the simulation is sufficiently small (less than 10%) compared to internal energy consumed by the magnet wires.

### 4.2 Quasi-Static FEA Results

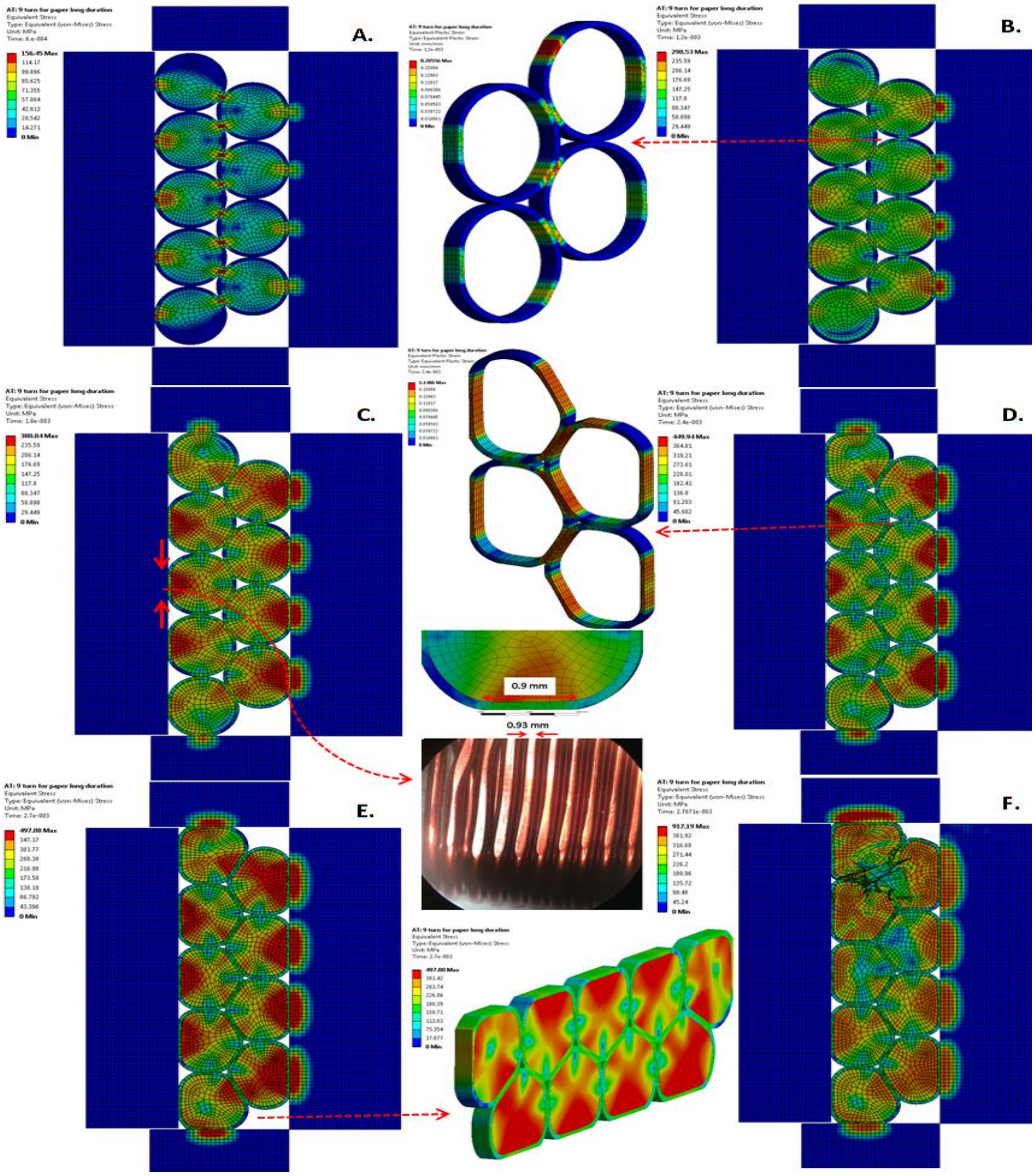

Fig. 3 Equivalent von-Mises stress and plastic strain results

As shown in Fig. 3, the 9-turn bobbin was pressed by applying horizontal load which leads to reduce total slot area by deforming the coil permanently. Equivalent plastic strain should be examined to inspect the magnet wire deformation. Applied velocity function will lead to artificially increased strain rates in the simulation results, because loading rates have been increased more than 100 times in comparison to experimental coil pressing tests. Therefore, strain rates obtained from the simulation results will be down-scaled to obtain original strain rates.

According to distortion energy theory, ductile failure occurs when maximum von Mises stress ${\sigma_e}^{max}$ exceeds the material yield strength $S_y$ [9]. As compression of coils cause significant plastic deformation in the magnet wires, fracture strength of polyimide will be considered to be failure.

In Fig. 3, highest strain rate of 1.6573 mm/mm occurs in the region between the steel punch and bobbin. This should be down-scaled to get original strain value in the deformed model. Therefore, plastic strain could be predicted to be around 0.016 mm/mm, under the elongation strain rate (0.03 mm/mm) of the polyimide material.

Maximum equivalent von-Mises stress on the wire enamel at time $2.7 \times 10^{-3} s$ as shown in Fig. 3E is 264.6 $MPa$ which is lower than fracture strength of polyimide. Fig. 3F shows material failure because equivalent plastic strain is higher than the maximum plastic strain occurring at material elongation. Moreover, equivalent von-Mises stress on the wire enamel reaches suddenly to 341 MPa which is almost material fracture strength in Fig. 3F. Therefore, it is convenient to state that the 9-turn bobbin can be safely pressed to a 0.74 slot fill factor.

### 4.3 On-tooth coil pressing

On-tooth coil pressing is where a modular stator tooth is pressed after it is wound with a required number of turns. Advantage of this method is that pressed bobbin will not be inserted into the stator tooth after pressing operation. If the bobbin is taken off a dummy tooth shape and inserted into the original stator tooth, this will increase the chance of insulation failure between the bobbin and ground wall. In order to prevent this, a bobbin could be compressed on the original stator lamination.

In order to validate the simulations, a 23 turn windings was wound directly onto the tooth as shown in Fig. 4. The dimensions are the same as the 9 turn simulations discussed above. The wound bobbin was placed into a die which has tapered sides to squeeze the coil from the surfaces. Applied pressure is used not to press the coil from the top face of it. Instead, it is squeezed from lateral faces when it moved into the die. This will reduce the voids between the layers and pack the magnet wires in a smaller volume. By doing this, slot fill factor of the bobbin has been improved. Slot fill factor was calculated to be approximately 0.69 after pressing. It was around 0.56 before pressing.

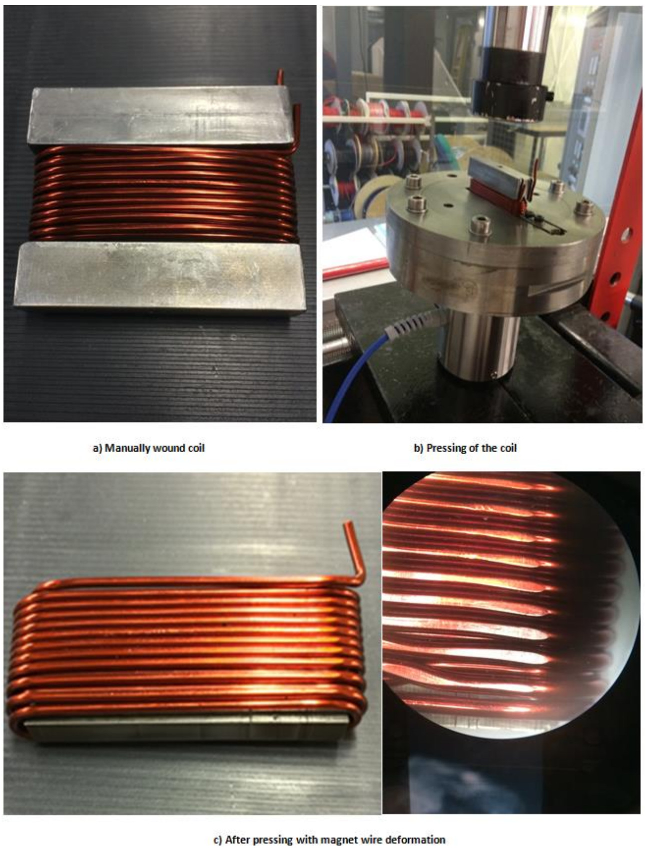


Fig. 4 On-tooth coil pressing

Less than 3 tonnes were required to press the bobbin. The obtained slot fill factor in the experiment shown in Fig. 4 matches to the Fig. 3C as the pressed model at time $1.8 \times 10^{-3} s$ has approximately 0.68 fill factor. Equivalent stress on the magnet wire enamel at this time instant is 190 MPa. For both simulation and experimental results indicate that magnet wire enamel experience flattened surface during the compression. The width of flattened wire surface is around 0.9 mm as demonstrated in Fig. 3. In terms of mechanical properties of the material, even though there is deformation in magnet wire insulations, material fracture was not observed after compression of the bobbin. The coils have also been tested electrically after pressing. Inter-turn and turn to ground wall insulation failures were not observed.

## 5 Thermal Properties of High Fill Factor Windings

Electrical machine designers usually do not model random wound mush winding, as it is very difficult to model the position of each conductor [10]. For this reason, they prefer to model solid copper bodies. However, this approach might cause inaccuracy due to neglecting of non-homogenous distribution of magnet wires inside the slot. Furthermore, machine designers sometimes use equivalent analytical lumped parameter model for thermal analysis of an electric machine. Since this method requires analytical calculation of thermal resistances between certain nodes, effective thermal conductivity of a stator winding will be crucial for higher precision. This demonstrates that it is useful to predict thermal conductivity of a stator winding by modelling individual turns so as to predict average thermal conductivity.

To calculate thermal conductivity, repeating part of a piece of winding with magnet wires of 1.9 mm overall diameter was taken into consideration. For boundary conditions, temperature on upper surface is selected to be 150°C and for the lower surface is 130° C. This gives ΔT = 20°C. Heat flux will flow from upper surface to lower surface by passing copper conductor, polyimide coating and air region. Table 2 shows the thermal conductivity of the materials at room temperature.

| Material | Thermal Conductivity | Unit |
|---|---|---|
| Air | 0.026 | $W\ m^{-1}\ °C^{-1}$ |
| Polyimide | 0.25 | $W\ m^{-1}\ °C^{-1}$ |
| Copper | 400 | $W\ m^{-1}\ °C^{-1}$ |

Table 2 Isotropic thermal conductivities of the materials

Steady state thermal FEA simulations have been carried out by conducting similar approach given in [11]. Thermal conductivity can be calculated using Fourier law of thermal heat conduction which is shown in (2).

$$Q = -k\frac{\partial T}{\partial X} = -k\left[\frac{T_{x=l} - T_{x=0}}{l}\right] => k = \frac{Q \times l}{\Delta T} \qquad (2)$$

where $\partial T / \partial x$ is temperature gradient and $k$ stands for thermal conductivity. $Q$ is heat flux density in the direction of heat flow. Heat flux density can be estimated by taking samples across the basic repeating unit of the winding segment which was shown in Fig. 5. 9-paths with equal intervals are used to obtain average heat flux density across temperature boundaries. At each certain path, magnitude of one dimensional heat flux is varying due anisotropic geometry.

Therefore, each path will have different effective thermal conductivity.

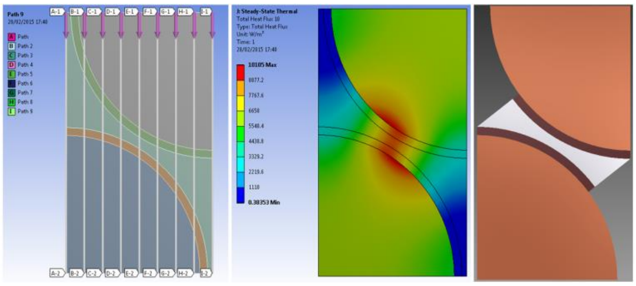

Fig. 5. Winding segment with sampled paths, heat flux density and approximated geometry (from left to right)

FEA steady state thermal simulation results are validated by conducting semi-analytical average thermal conductivity calculations. To do this, FEA heat flux density contour shown in Fig. 5 was utilised. Some air regions could be ignored due to very low heat flux density. If the magnitude of heat flux density is less than 10% of the maximum heat flux density in the model, corresponding parts between the conductors has been neglected as given in Fig. 5. Approximated winding segment is then considered to be a uniform slab with different material lengths. Thus, thermal conductivity is calculated by using well-known general thermal resistance equation.

### 5.1 Effective thermal conductivity results

Slot fill factor is varied by altering the distance between the magnet wires uniformly. Improvement of effective thermal conductivity has been studied in relation to variation of slot fill factor. Effect of thermal potting material of epoxy with a thermal conductivity of 1.26 $W/mK$ was also shown by considering vacuum potting of the stator winding. Relationship between fill factor and thermal conductivity, based on analytical and FEA methods is given in Fig. 6.

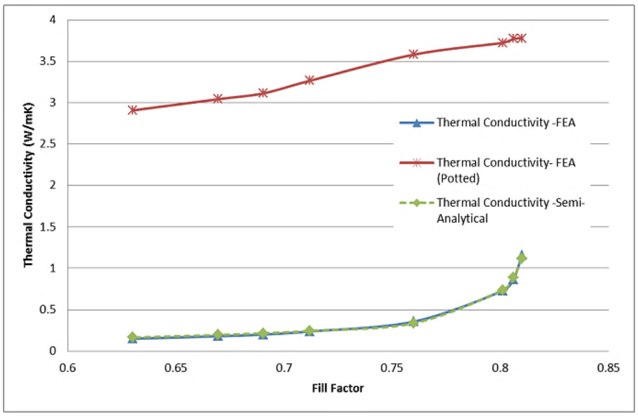


Fig. 6. Slot fill factor versus effective thermal conductivity

Results show that FEA approach and semi analytical thermal conductivity predictions are in the same fashion. Since fill factor for the compressed bobbin discussed in Section 4 is 0.69, thermal conductivity at this fill factor can be predicted to be 0.22 $W/mK$ as shown in Fig. 6. It can be noted that this prediction does not consider contact pressure between the conductors, which help increase the thermal conductivity.

## 6 Conclusion

In this paper, mechanical stress analysis of the compressed coils has been investigated by performing finite element simulations. A thorough description of quasi static modelling is introduced for complex geometries such as electric bobbins. According to simulation results, stator windings can be compressed to a 0.74 fill factor without observing magnet wire insulation failure.

Thermal modelling of electrical machine windings was also investigated by performing analytical calculations and finite element analysis to predict effective thermal conductivity of stator windings. A good agreement between analytical and FEA simulations is obtained. It was stated that compression of the coil to a 0.69 fill factor increased the thermal conductivity slightly. However, it was also demonstrated that effective thermal conductivity of a bobbin can be improved up to 0.33 $W/mK$ which is at 0.74 slot fill factor.

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