Experimental Study on Inter-Laminar Short Circuit Faults at Random Positions in Laminated Magnetic Cores

Hamed Hamzehbahmani[1*], Philip Anderson[1], Keith Jenkins[2] and Magnus Lindenmo[3]

[1]Wolfson Centre for Magnetics, Cardiff University, Cardiff CF24 3AA, UK
[2]Cogent Power Ltd., Newport NP19 0RB, UK
[3]Cogent Power Ltd., Surahammar, PO Box 201, 735 23 Surahammar, Sweden
* Corresponding author: HamzehbahmaniH@Cardiff.ac.uk

Abstract— **Inter-laminar short circuit faults between the laminations of electrical machines, and other magnetic devices, have been one of the major challenges for the suppliers and customers of electrical steels. Extra power losses caused by inter-laminar faults depend on many factors including the location of the fault points. In this work fundamental definitions and concepts of inter-laminar short circuit faults, effect of inter-laminar faults on configuration of the magnetic cores and FEM verification are presented. Experimental works were performed to study the effect of inter-laminar faults with different configurations on the total power loss to distinguish and locate the critical and destructive faults. In the relevant studies, artificial short circuits of different configurations were applied between laminations of packs of four Epstein size laminations of 3 % grain oriented silicon steel. Extra power losses caused by the inter-laminar faults were measured and the results were analysed.**

Index Terms- Inter-laminar fault, edge burr, FEM modeling, laminated core, core loss.

1. Introduction

MAGNETIC cores of commercial electrical machines, and other magnetic devices, are constructed from stacks of electrical steel laminations, typically 0.23 to 0.50 mm thick. Laminations are coated with insulating layers to prevent electrical contact between them [1]. This limits the circulation of eddy currents to the thickness of single lamination, rather than the whole core, and hence reducing the eddy current power loss and overall heating effect in the cores [2]. Electric paths for the induced eddy currents in magnetic cores with solid and laminated structures under time-varying magnetic field are shown in Figs 1-a and 1-b, respectively. In a perfectly assembled core, when the laminations are well insulated from each other, the eddy current loops are restricted to the individual laminations, as shown in Fig 1-b.

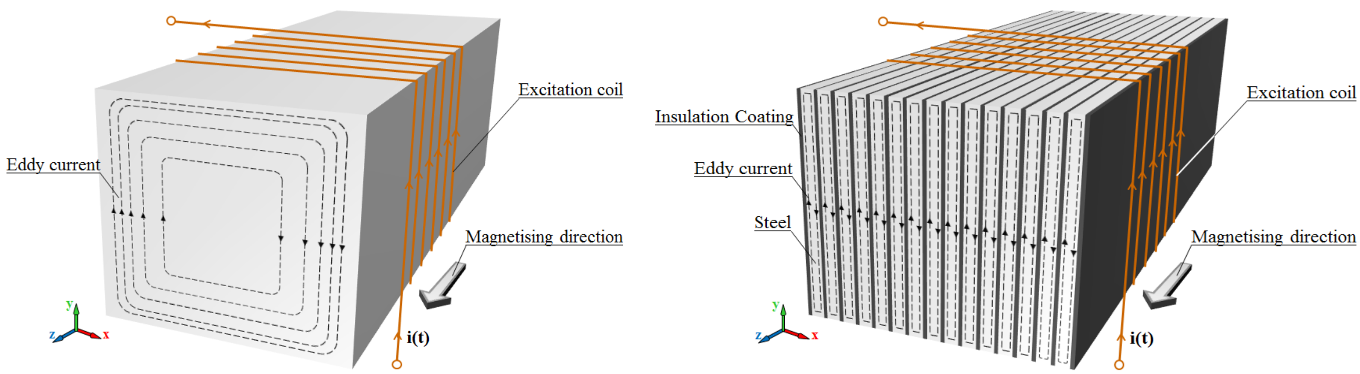


Fig 1 Eddy current in (a) solid core and (b) laminated magnetic core

The design and operation of electrical machines, requires accurate quantification of core losses over a wide range of frequency and flux density. However, in practical cores, the manufacturing processes introduce additional undesirable characteristics which will influence the machines performance. Key amongst these are inter-laminar faults between the laminations and their impact on the power loss and other magnetic properties [3-9]. Analytical and experimental studies have been done to detect inter-laminar faults and investigate their effect on the magnetic properties of the laminated cores [5-13]. In most of these investigations, however, it was assumed that inter-laminar faults occurred between the adjacent laminations of the core at set points which result in a short circuit volume with well-known locations and physical dimensions; while in practice they appear at random positions which create different patterns of inter-laminar short circuits. From this point of view, inter-laminar faults can be categorised based on the number of shorted laminations, location of the fault, distance and angle between the fault points of each particular fault current loop. Accurate experimental work, even on a small scale, can help to categories inter-laminar faults and distinguish critical faults.

The main emphasis of this work is to model inter-laminar insulation faults of different configuration and position, and investigate their influence on the magnetic properties of the laminated cores. In order to show the effect of inter-laminar faults on the configuration of the cores, 2-D FEM simulations were carried out using COMSOL Multiphysics. Experimental studies have been performed to survey the effect of inter-laminar short circuit faults. The studies were carried out on stacks of four Epstein size (305 mm × 30 mm) Conventional Grain Oriented (CGO) laminations. In order to model inter-laminar faults which would occur in a practical situation, different configurations of the inter-laminar fault were applied on the specimens.

2. Causes of inter-laminar core faults

Insulating materials used for the inter-laminar insulation are susceptible to decline and damage, therefore short circuits between the laminations, due to electrical failure, could happen due to a number of reasons [6-9]. Inter-laminar short circuit faults lead to circulating eddy currents between the laminations, which is larger than in normal operation [5-6]. This current is the *inter-laminar fault current* and the created current loop is the *fault current loop* [3]. Typically fault current loops are formed between the shorted laminations and fault points which are perpendicular to the direction of the magnetic flux density in the core.

2.1. Concept of edge burr as the main reason of inter-laminar faults

During manufacturing of magnetic cores, punching and cutting of the electrical steels to the required dimensions might cause microscopic burrs which are one of the most serious concerns of the manufacturers and customers of the electrical steels [5-9]. Burrs are most commonly formed in machining processes as a result of plastic deformation during mechanical process and have been defined as “undesirable projections of material beyond the edge of a workpiece” [14].

In order to show concept of the edge burr physically, magnetic laminations of 0.3 mm thick CGO *Fe* 3 % *Si* were cut by one sharp and one blunt guillotine. Stacks of four laminations were then made with clean cut samples and the laminations with edge burr. Side view of the samples and each stack was imaged using an ERCOLUX standard optical microscope with a resolution of 1 µm; the results are shown in Figs 2-a to 2-d, respectively. Fig 2-c shows an ideal configuration of a magnetic core in which the laminations are properly insulated from each other; however Fig 2-d shows the inter-laminar short circuit caused by the edge burr.

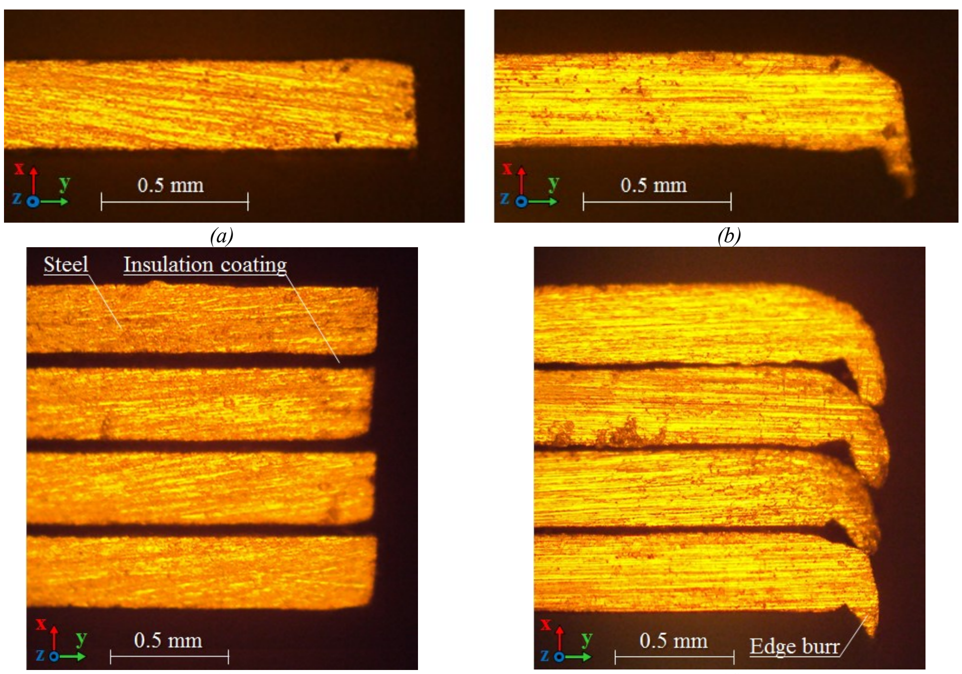


Fig 2 Side view of a single lamination cut by a (a) sharp (b) blunt guillotine; stack of laminations with (c) properly cut samples (d) samples with edge burr

Burr height or size of the edge burr is typically 2~10 % of the sheet thickness; however, it depends on many factors, e.g. sharpness of the tools, clearance between the cutting edges of the tool, thickness of the material, the shearing process and properties of the material. In accurate manufacturing processes, burrs should be removed after the sheet is machined by a proper deburring process. For certain critical applications e.g. large rotating machines, a deburring operation after stamping or cutting is followed by applying a second coating layer on the laminations. However, deburring processes are usually not very accurate and may decrease accuracy of the machined parts, damage edges or the surface of the sheet, and apply extra stresses on the lamination. Furthermore, deburring process requires an extra machining stage and extra manufacturing time which lead to extra cost [14].

3. 2-D FEM modelling of inter-laminar fault

A quantitative verification was performed by the authors [3] using COMSOL Multiphysics to survey the effect of inter-laminar short circuit caused by edge burrs on the configuration of the magnetic cores. The simulation model was then extended by considering the inter-laminar faults around the bolt holes. In this study a stack of four laminations exposed to a time-varying outward magnetic field with a frequency of 50 Hz was considered. Laminations were modelled by 3 % GO silicon steel. Partial blocks, of the same material as the lamination, were implanted to model inter-laminar fault caused by the edge burrs. Considering the theoretical base of flux density penetration into the magnetic laminations [15], each stack of laminations was magnetised at a typical peak surface flux density of B_{pk}=1.5 T. The model requires an extra fine mesh and hence a long calculating time, approximately 30 min for each model. Eddy current distribution in the stack with inter-laminar fault on one side only, on either sides, between the bolt hole and one side and a combination of the last two cases are shown in Figs 3-a to 3-d, respectively.

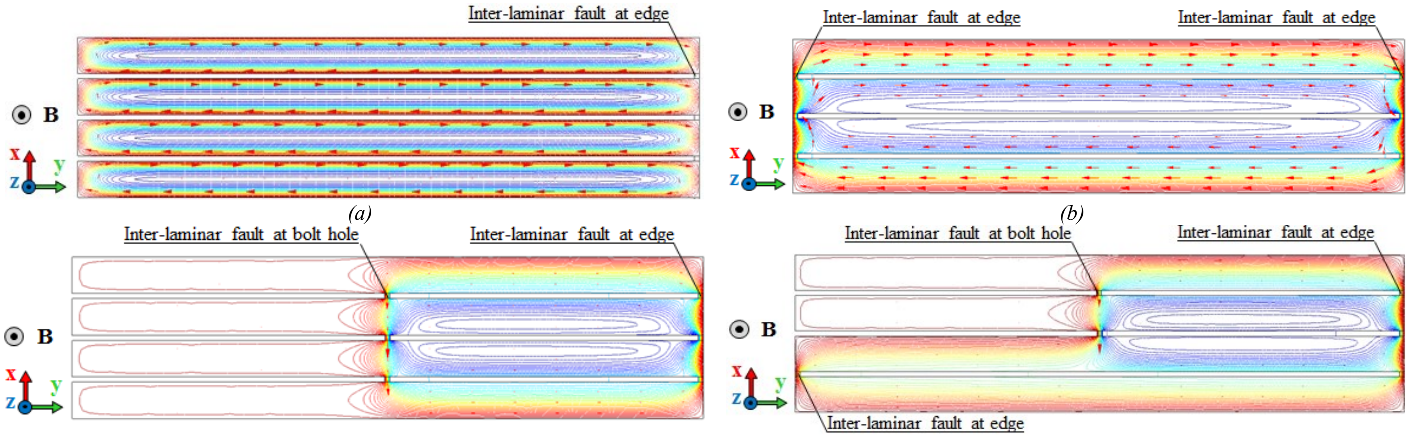


Fig 3 Eddy current distribution in the stack (a) with fault on one side only (b) with fault on either sides (c) with fault on bolt hole and one edge (d) combination of faults "b" and "c"

Four important points could be concluded from the FEM results of Fig 3:

1. Inter-laminar fault on one side of the magnetic cores, does not create fault current loop and hence does not affect the normal distribution of eddy current in the individual laminations and eddy current power loss.
2. The fault current loops change the configuration of the magnetic cores to be similar to a solid core which leads to inter-laminar fault currents and larger eddy current loops in the shorted laminations.
3. Inter-laminar faults between the bolt holes and one side of the stack create a smaller fault current loop, Fig 3-c. In this case, fault currents flow between the fault points and those parts of the steels which are shorted by the fault points. Eddy currents in the other parts of the steels are almost zero; because inter-laminar faults around the bolt hole make a short path with lower resistance to flow the inter-laminar fault current.
4. Eddy current density at the shorted points is much higher than the laminations placed between them which result in high local power loss and high local heat. This is the main reason for damaging of the magnetic cores affected by inter-laminar faults.

As a result, investigation of the inter-laminar faults on the performance of electrical machines is an essential requirement at the design and manufacturing stages. Reliable and accurate methods are also required to distinguish the destructive faults and investigate their impact on performance of the magnetic cores of the electrical machines and other magnetic devices.

4. Distinguishing faults in magnetic cores

Partial inter-laminar fault in the stator cores of the rotating machines could be more destructive than transformer cores, because laminations of stator cores are welded or held together through either key-bars or the housing at the base of stator yoke [5-6], [13]. The key-bars can be, but are not always, insulated from the laminations or the frame of the stator to prevent the flow of current between cores and frame; but if not, it makes a permanent short circuit at the outer side of the core. Therefore if the stator laminations are shorted together, even on one side only, inter-laminar fault currents could be induced in the fault current loop that consists of the fault point, the shorted laminations and the key-bars, welds or housing. In order to distinguish destructive faults, a perspective view of a transformer limb with three possible inter-laminar faults and a stator-rotor core with four possible inter-laminar faults are shown in Figs 4-a and 4-b, respectively. 2-D FEM modelling was performed to visualise the distribution of the magnetic flux in both transformer and stator-rotor cores and distinguish the fault current loops; the results are shown in Figs 4-c and 4-d, respectively.

In Fig 4-a, short circuit I is formed between the bolt hole and one side of the core step and short circuit II is formed between two sides of the core step. Both of these defects are perpendicular to the direction of the magnetic flux in the core and therefore create fault current loops. Short circuit III, on the other hand, does not meet the definition of fault current loop, because it does not make a closed loop perpendicular to direction of the magnetic flux in the core. Considering the flux density distribution in the stator core, neither short circuits I nor II of Fig 4-d cut the magnetic flux lines and hence do not meet the definition of the fault current loops. On the other hand, short circuits III and IV make closed current loops perpendicular to the direction of the magnetic flux in the yoke and tooth respectively and therefore create fault current loops in the core. However if the outer side of the stator core is shorted by the key-bar or stator frame, short circuits I and II create fault current loops in the core.

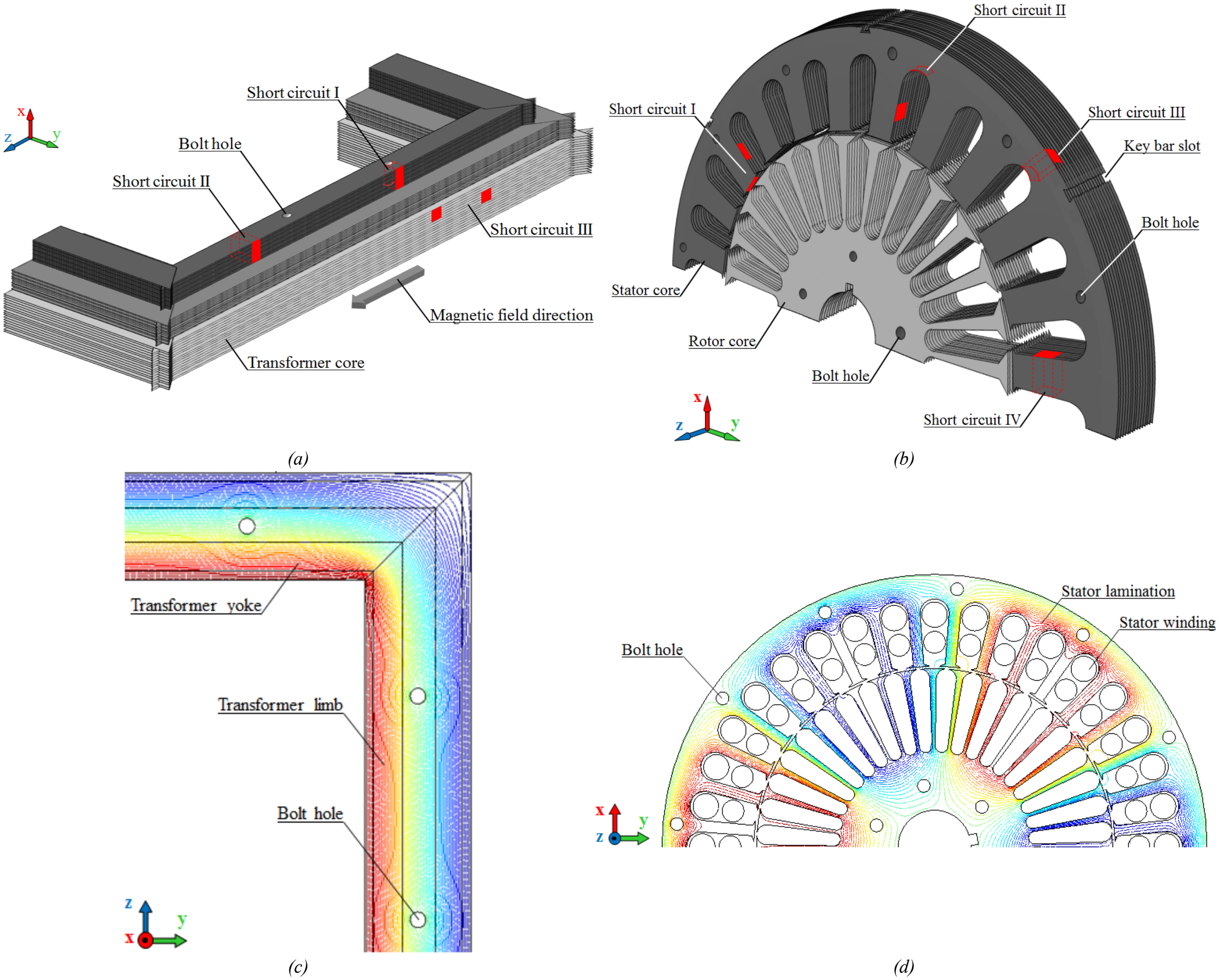


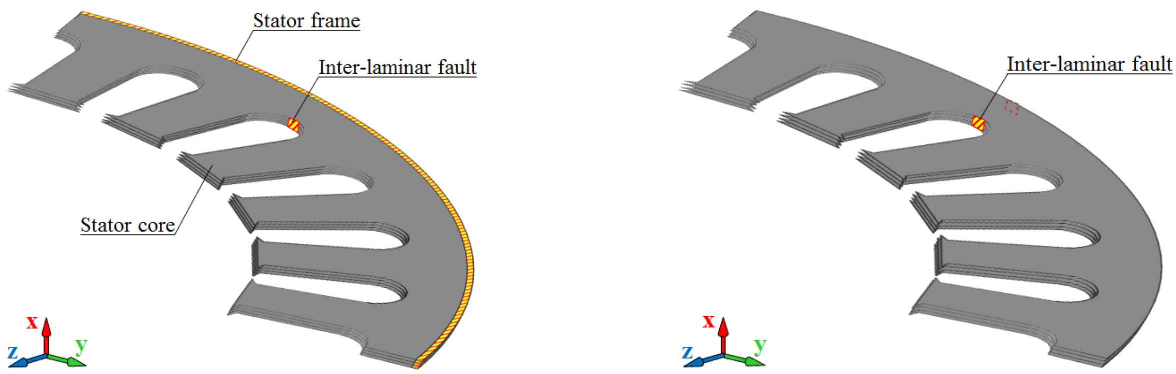
Fig 4 Perspective view of (a) a transformer limb with inter-laminar short at three possible positions and (b) a stator-rotor core with inter-laminar short at four possible positions; magnetic flux path in (c) transformer core (d) three phase 6 poles stator-rotor core

5. Experimental set-up

Experimental studies were performed on stacks of four Epstein size laminations of CGO *(3 % silicon iron),* 0.3 mm thick, with a grade designation of M105-30P. Similar to the previous work [4], lead-free solder was used to simulate inter-laminar faults between the laminations. A single strip tester (SST), with reduced number of turns N_1=108 and N_2=82, for measurement of power loss over a wide range of frequencies and flux densities was developed to magnetise each stack. Hardware, software and flowchart of the system was designed and set to meet the requirements and criteria in [16]. More detail of the experimental setup are available in [15], [17]. Each pack of laminations was magnetised separately using the SST at peak flux densities of 1.1 T, 1.3 T, 1.5 T and 1.7 T and magnetising frequencies from 50 Hz up to 1000 Hz. Total power loss of each stack was measured three times at each flux density and frequency in all experiments with repeatability of better than 0.3 %. Experimental results presented in this paper are the average of three measurements. Nominal power loss and power loss of a stack with a 10 mm wide inter-laminar fault applied at set-points were considered as two reference values to compare the results of each test.

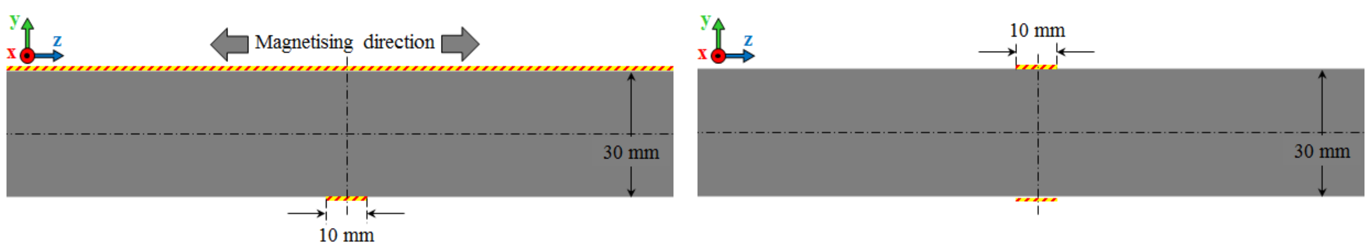
6. Modelling of inter-laminar fault caused by key-bar of stator cores

Two types of short circuit on a part of stator core are shown schematically in Figs 5-a and 5-b. In Fig 5-a the outer side of the core is shorted totally and a partial fault is applied between the lamination of one of the slots; while in Fig 5-b two partial faults are applied on opposite sides of the slot at set points. As the first part of the experimental study, these types of faults were modelled separately on stacks of four laminations. A top view of the stacks showing the location of the applied short circuits are shown schematically in Figs 6-a and 6-b, respectively. The measured power losses of each stack together with the nominal loss of the material versus peak flux density at different frequencies are shown in Fig 6-c.

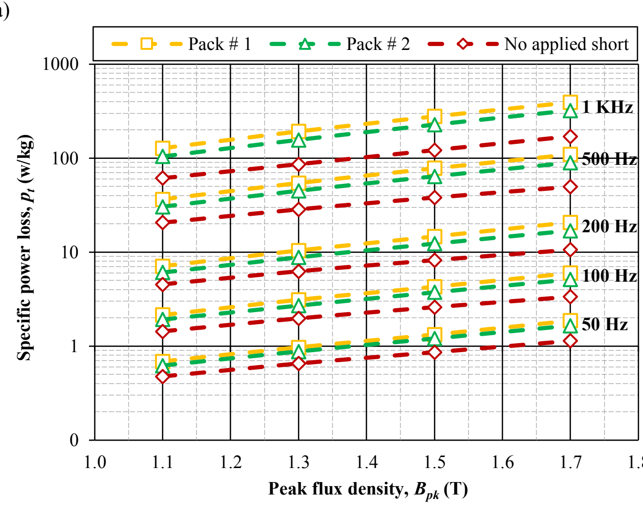


(a) *(b)*

Fig 5 Perspective view of a stack of stator laminations (a) with permanent short in the outer frame and inter-laminar fault in core slot (b) with inter-laminar fault between the outer frame and core slot



(a) (b)



(c)

Fig 6 Top view of a stack of laminations with inter-laminar short circuit to model the inter-laminar faults of Fig 5-a (pack # 1) and 5-b (pack # 2) Comparison of total loss of the packs #1 and #2 with the normal loss of the material vs. peak flux density at different frequencies

Fig 6-c shows extra power loss in the shorted stacks compared to the normal power loss which is caused by the fault current loops created in the stacks. However, the power loss of pack 1 is higher than that of pack 2 at all flux densities and frequencies with the maximum difference of about 18 %. Although the bottom sides of both packs are shorted with artificial shorts of the same width, the higher power loss of pack 1 indicates a bigger fault current loop than pack 2, which is caused by the applied short circuit alongside on pack 1. As a result, permanent short circuits caused by the key-bar or welded frame should be considered in the study of inter-laminar short-circuit faults on the stator cores. Furthermore in order to reduce the risk of creation of fault current loops, the laminations preferably should be isolated from the key-bar of the stator frame.

7. Modelling of inter-laminar fault in a stack of laminations at set positions

In the next part of the experiments, effect of inter-laminar short circuits at set positions on total power loss was studied. Specific power loss of the stack without inter-laminar faults was initially measured. Artificial shorts, 10 mm wide, were applied at three positions and the total power loss of the stack was measured in each stage. A schematic side view of the stack with one, two and three shorts are shown in Figs 7-a to 7-c, respectively and a top view of the stack with three shorts is shown in Fig 7-d. In order to obtain the extra power loss caused by the applied short circuits, the power loss in normal operation was subtracted from the total power loss of each stage. The extra losses versus number of the applied short circuits at magnetising frequencies of 50 Hz, 500 Hz and 1000 Hz are shown in Fig 8-a to 8-c, respectively.

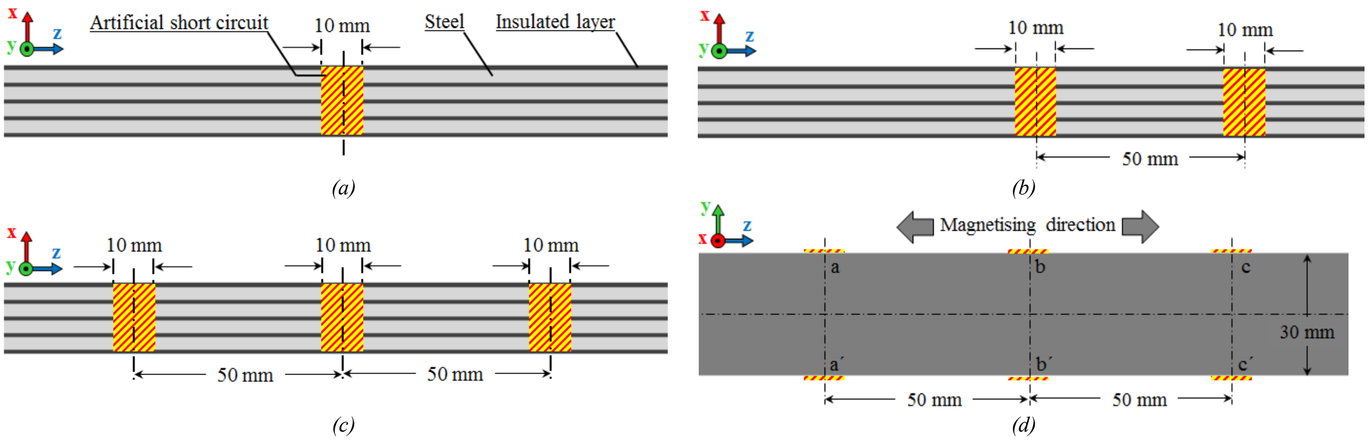


Fig 7 Side view of a stack of four laminations with inter-laminar short circuit applied at (a) one set point (b) two set points and (c) three set points (d) top view of the stack of laminations with inter-laminar short circuit applied at three set points

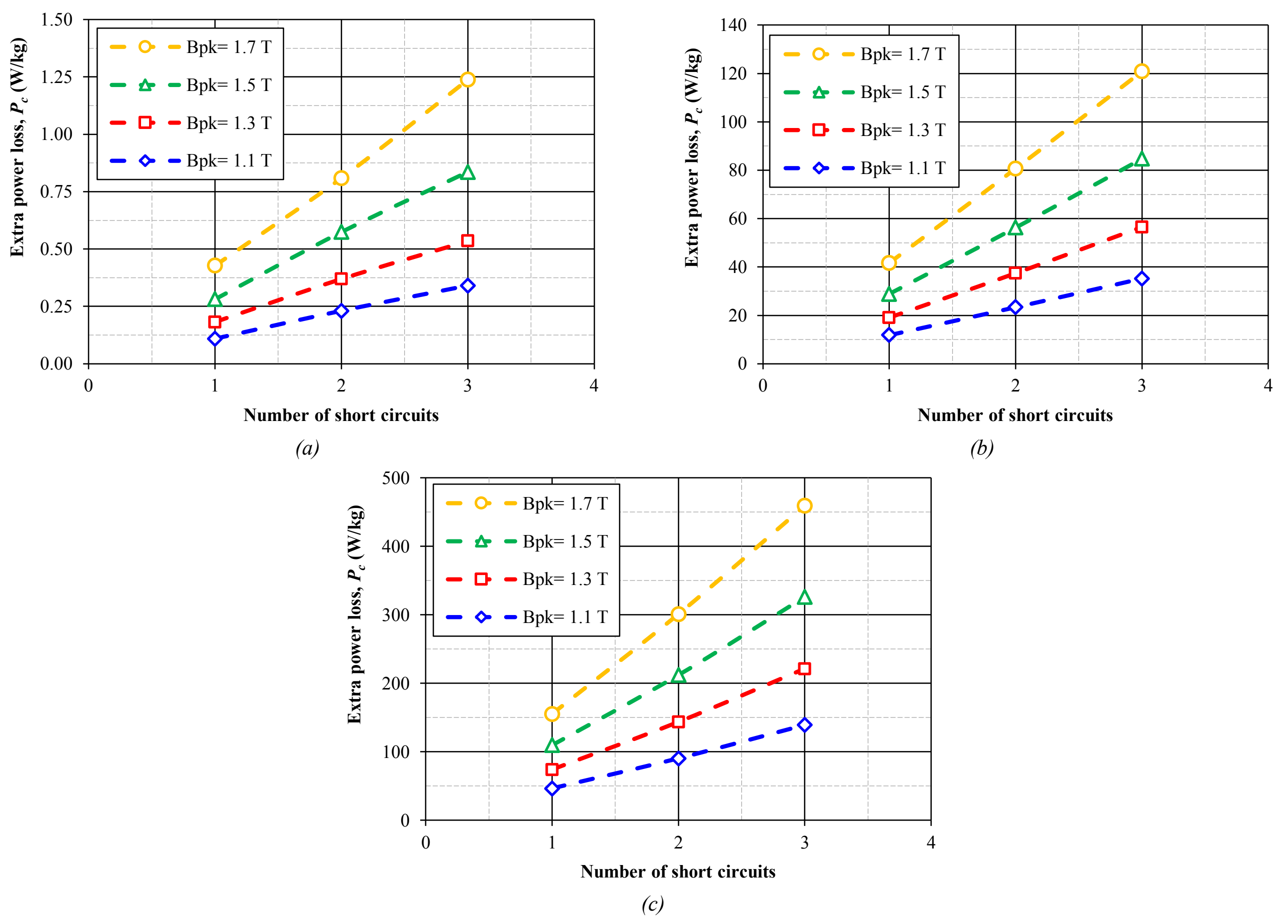


Fig 8 Extra power loss caused by the artificial faults of Fig 7 at frequency of (a) 50 Hz (b) (b) 500 Hz and (c) 1000 Hz

The experimental results of Fig 8 show a linear relation between the extra power loss caused by the applied short circuits and number of the shorts at all flux densities and frequencies. The reason is related to the tendency of the electric currents to flow through the path of least resistance, i.e. in Fig 7-d electric resistance between points *a-a´* is less than that of points *a-b´* or *a-c´*. Therefore in can be concluded that the artificial shorts applied to the stack create three independent fault current loops in the stack and hence there is no current flow between the shorted volumes.

8. Modelling of inter-laminar fault in a stack of laminations with step-like positions

As outlined in the introduction, in practice, inter-laminar faults occur at random positions. In order to model this kind of defect, a pack of four laminations were shorted in a step-like configuration with inter-laminar fault between two laminations in each step, Fig 9-a. To qualify the results, another stack of four laminations with a concentrated fault at the centre of the pack was prepared, Fig 9-b. The power loss accompanied by the nominal loss of the material versus peak flux density at different frequencies are shown in Fig 9-c.

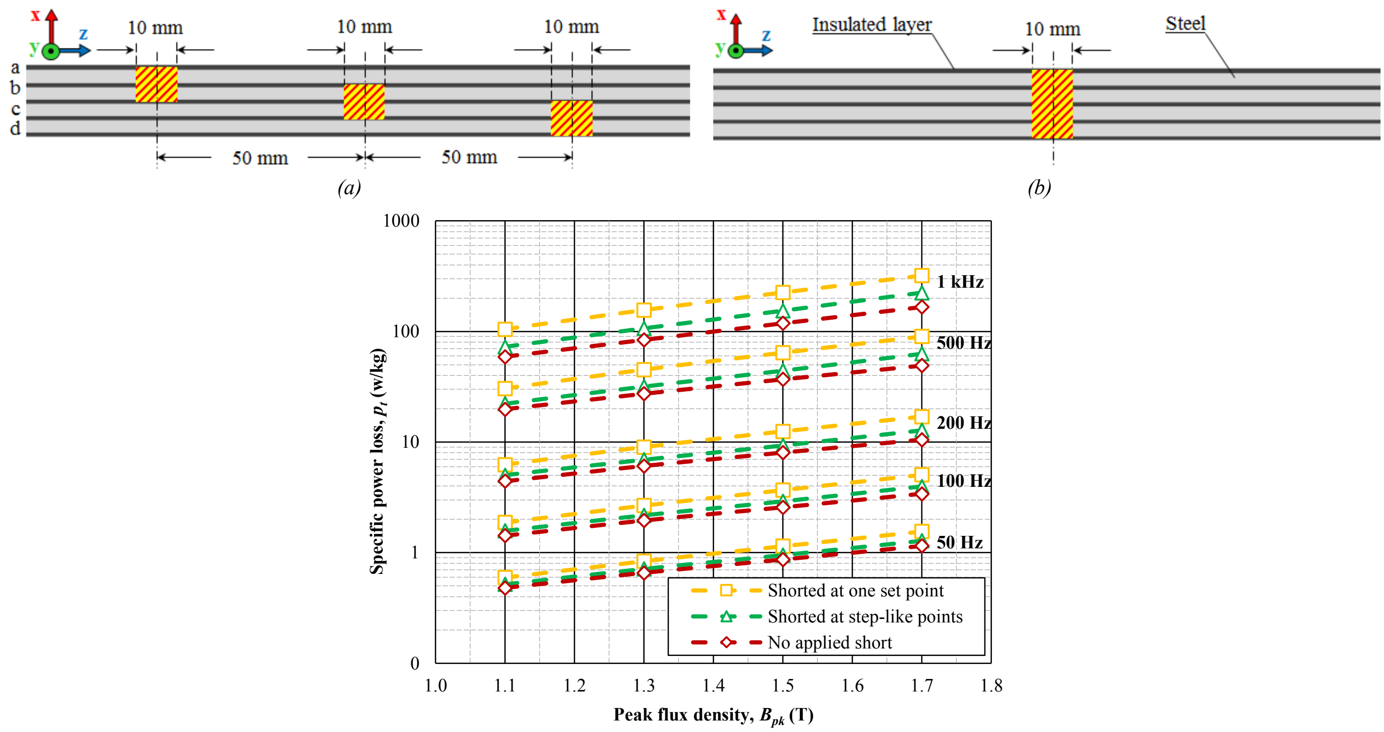


Fig 9 Side view of a stack of four laminations with inter-laminar short circuit at (a) three step-like points (b) one set point (c) total power loss caused by the artificial faults versus peak flux density at magnetising frequencies of 50 Hz to 1000 Hz

Although in both configurations of Figs 9-a and 9-b all of the laminations are shorted, total power loss of the stack with inter-laminar fault at three step-like positions, is less than that with inter-laminar fault at a concentrated point. The reason is related to the nature of the fault current loops created by the artificial shorts. In order to make this issue clear, 2-D FEM modelling was performed at frequencies of 50 Hz and 1000 Hz. The results are shown in Figs 10-a and 10-b, respectively.

An analytical model was already developed by the authors [3] to investigate the distribution of flux density along the thickness of single strip lamination. The model was then extended for packs of shorted laminations. Using the developed model it was proved that a pack of n shorted laminations can be modelled by a single strip with equivalent thickness of $2na$, which $2a$ is thickness of one lamination. It was also shown that an inter-laminar fault causes skin effect to become more significant, which affects the distribution of inter-laminar fault current and hence extra power loss caused by the fault, even at low frequencies. Based on the developed model, distribution of normalised magnetic flux density along the thickness of the shorted packs of Figs 9-a and 9-b at magnetising frequencies of 50 Hz and 1000 Hz and a typical flux density of 1.3 T were calculated; the results are shown in Figs 10-c and 10-d, respectively.

Fig 10 shows that distribution of the inter-laminar fault current and flux density in the shorted stack strongly depend on size of the fault current loop; which in turn depends on the number of the shorted laminations. In Fig 9-a, although there are three fault current loops, the total power loss is less than that of Fig 9-b with only one fault current loop. The reason is related to the size of the fault current loop which is larger in Fig 9-b.

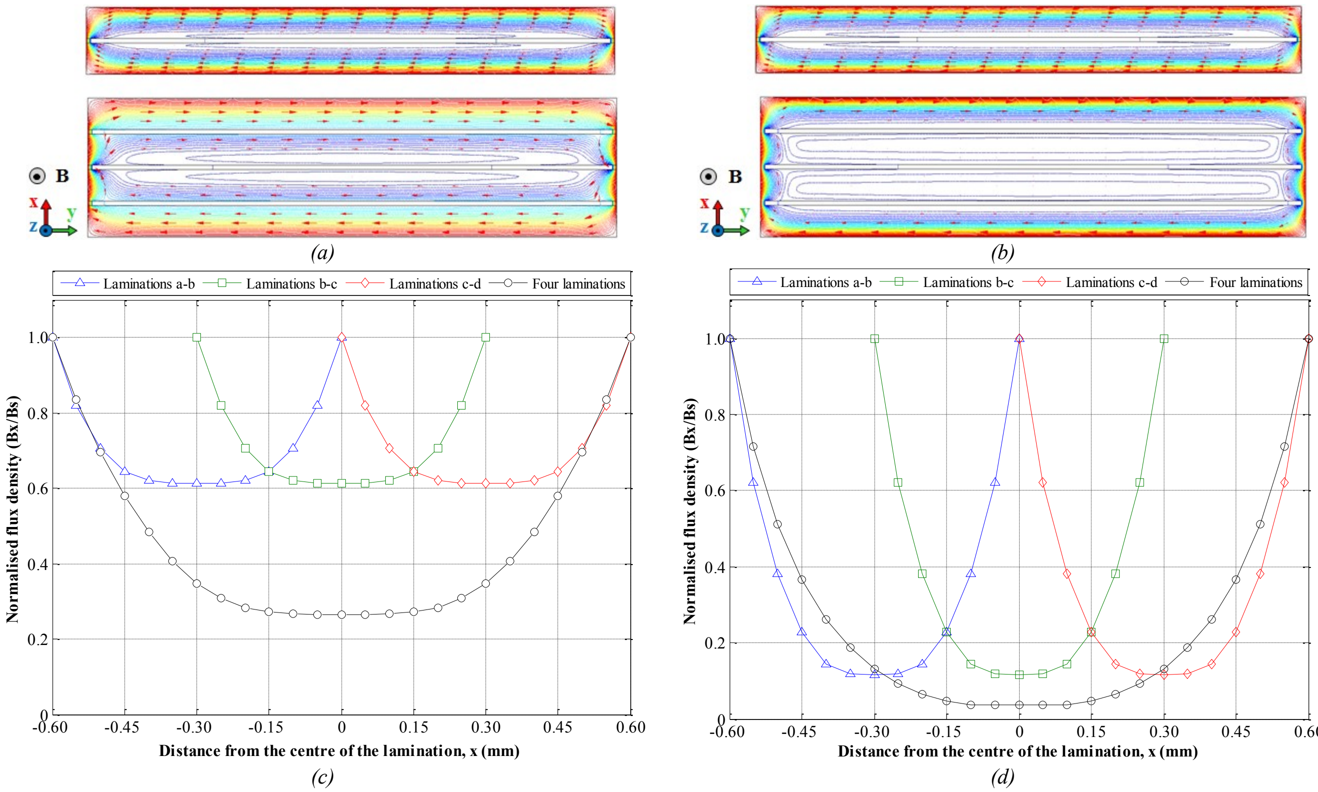


Fig 10 Distribution of inter-laminar fault current between two and four laminations at magnetising frequency of (a) 50 Hz and (b) 1000 Hz; normalized flux density penetration into the stacks of shorted laminations shown in Fig 9 at peak flux density of B_{pk}=1.3 T and frequencies (c) 50 Hz and (d) 1000 Hz

9. Modelling of inter-laminar fault in a stack of laminations at off-set positions

When laminations are shorted together at random points by burr at the cut edges, it is also highly likely that there will be a displacement or off-set between the axes of the shorted points of the fault current loops. An off-set between the shorted points in top view of a stack of four laminations is shown schematically in Figs 11-a. In order to simulate these kinds of defect, inter-laminar faults with axial off-sets from 10 mm up to 200 mm were applied separately on opposite sides of packs of four laminations, according to the schematic of Fig 11-a. Each pack was then magnetised and the total magnetic power loss of each stack was measured and recorded separately. The measured power loss versus axial off-set at different flux densities and magnetizing frequencies of 50 Hz, 500 Hz and 1000 Hz are shown in Figs 11-b to 11-d, respectively. Similar to previous sections, nominal power losses of the stacks, with no inter-laminar fault, were measured initially; the results are shown in Fig 11.

Four important notes could be concluded from the experimental results of Fig 11 at all flux densities and frequencies as follow:

1. When the fault points are applied at set points on the same axes, resistance of the fault current loop is at a minimum which leads to a maximum inter-laminar fault current, and hence maximum power loss in the stack.
2. By increasing the axial off-set between the fault points, resistance of the fault current loop is increased, which results in a reduction of the inter-laminar fault current and total power loss of the stack.
3. Significant reduction in power loss was observed up to about 70 mm off-set between the axes of the fault points.
4. Power loss is approaching to the nominal loss of the material when the off-set is above 100 mm. Therefore inter-laminar shorts with high off-set between the shorted points can, in many circumstances, be ignored.

10. Modelling of inter-laminar fault in a stack of laminations multiple off-set positions

In the last part of this study the effect of inter-laminar faults at multiple off-set points was investigated. In this work two packs of four laminations were stacked and each pack was shorted at four points with different displacements in the axial axes between the shorted points to make multi off-set faults. Top views of both packs are shown in Fig 12-a and 12-b, respectively. Similar to the other parts of the paper, total power loss of each pack was measured separately. The results obtained from both packs were very close to that of the pack with one short with 20 mm off-set between the shorted points. A comparison between the total power loss of each stack and power loss of the stack with 20 mm off-set and nominal loss of the material are shown in Figs 12-c and 12-d, respectively. Therefore it could be concluded that, the fault current loop in each pack is closed through short circuit points *a´* and *b*, and short circuit points *a* and *b´* do not make a significant impact on the formation of the fault current loop, inter-laminar fault current and hence extra power loss. The reason is related to the tendency of electric current to pass through low resistance path which, is created between the shorted points *a´* and *b*.

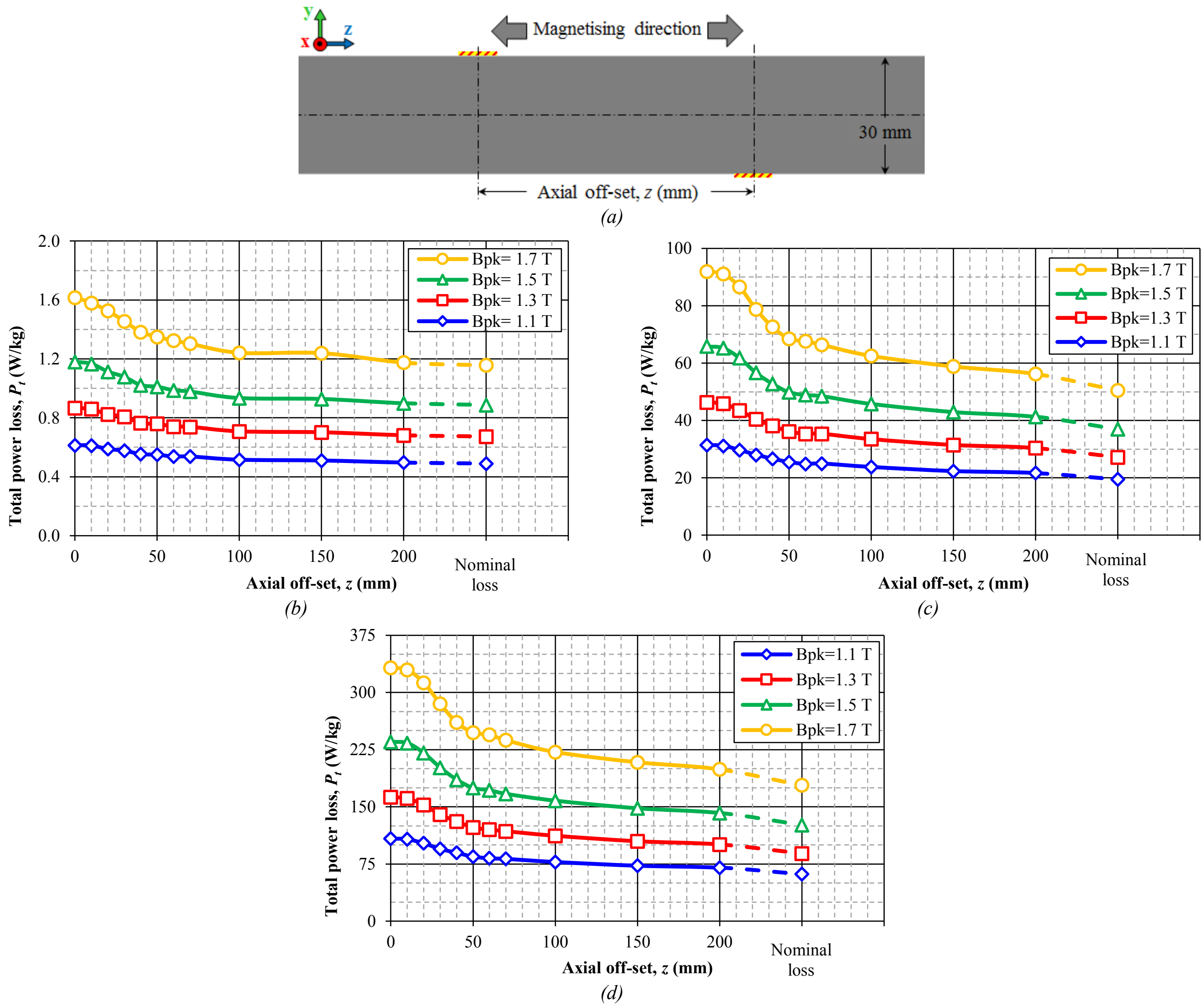


Fig 11 (a) Top view of a stack of four laminations with inter-laminar short circuit with axial off-set position; specific power loss of the stack at magnetising frequencies of (a) 50 Hz (b) 500 Hz and (c) 1000 Hz

11. Conclusion

In this paper fundamental concepts of inter-laminar short circuit faults and their consequences on the magnetic cores were presented. 2-D FEM modeling was performed to visualise fault current loops created by different types of inter-laminar fault and resulting inter-laminar fault current. Based on the FEM modeling, it was found that high values of inter-laminar fault currents occur in the shorted laminations as a result of increasing the effective thickness of the shorted volume of the laminations. Experimental studies have been done to investigate the effect of inter-laminar short circuit faults with different configurations on total power loss of the magnetic cores. The studies were performed on stacks of four Epstein size CGO laminations. Different configurations of inter-laminar short circuit faults, which could occur in real scale magnetic cores, were applied on each stack and total power loss was measured over a wide range of flux density and magnetising frequency.

Based on the experimental results, it was found that numbers of the inter-laminar shorts, position of the fault points, angular off-set between the fault current loop, magnetising direction and electrical resistance between the fault points are key-factors in the determination of the fault current loops and the extra loss caused by the inter-laminar fault. Although the situation of inter-laminar short circuit faults in real scale electrical machines is more complicated, the results presented in this paper could be extended to practical machines.

12. Acknowledgment

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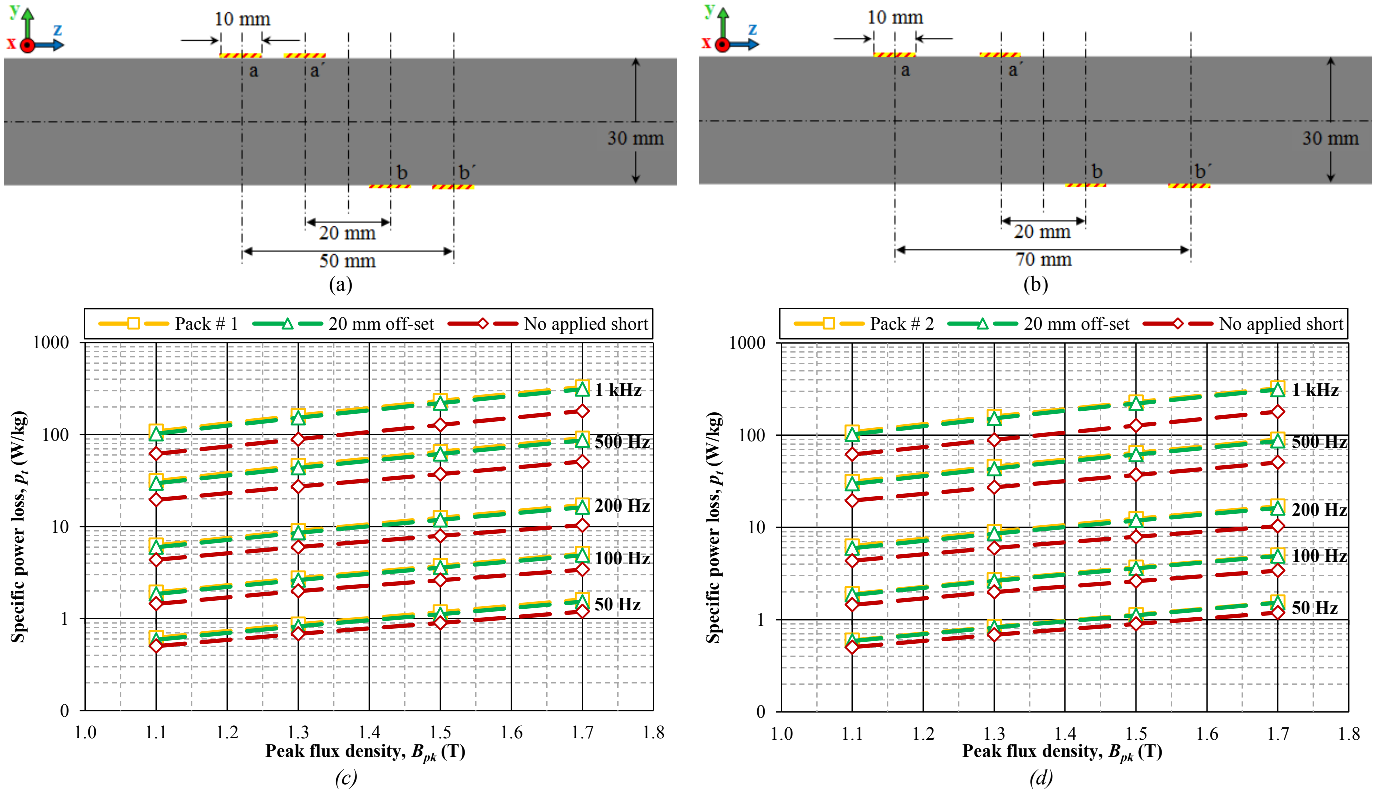

Fig 12 Top view of a stack of four laminations with inter-laminar short circuit at multi off-set positions (a) pack # 1 (b) pack # 2; comparison of total power loss of the packs # 1 and # 2 with the normal loss of the material vs. peak flux density at different frequencies

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