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Penetration of transverse magnetic field in a stack of laminations and induced voltages

***Abstract**. This paper aims at providing an accurate description and explanation of the behavior of the magnetic flux when it incomes in the transversal (unusual) direction to the magnetic sheets, as it appears in the front end zone of large turbogenerator cores. Several experiments on a basic apparatus have been carried out, monitoring fluxes in 2 directions, and induced voltages between sheets. In order to explain the flux distribution within the magnetic sheets stack, a simulation based on a simple reluctance network has been used.*

***Streszczenie.** Artykuł ma na celu otrzymanie dokładnego opisu I wyjaśnienia zachowania pola magnetycznego wnikającego w kierunku prostopadłym do blach magnetycznych na powierzchniach czołowych rdzenia dużego turbogeneratora. Kilka eksperymentów zostało przeprowadzonych na podstawowej aparaturze, w których monitorowano pole magnetyczne (dwa kierunki) oraz napięcie indukujące się między blachami. Dla wyjaśnienia rozkładu strumienia magnetycznego wewnątrz pakietu uwarstwionego przeprowadzone symulacją komputerową opartą na prostej sieci reluktancyjnej. (**Penetracja normalnego pola magnetycznego w uwarstwiony pakiet i indukowane napięcia**).*

Keywords: Transversal field, stack of laminations, induced voltages
Słowa kluczowe: pole poprzeczne, pakiet uwarstwiony, napięcia indukowane.

Introduction

In the end region of large turbo-generators, the magnetic field includes an axial component which comes from the air gap fringing across the core end, the stator and rotor end-winding currents and the differential saturation [5]. This axial flux, perpendicular to the plane of laminations, induces eddy currents, which generate additional losses and increased inter-lamination voltages. They depend on the grounding and the contact between core end packets and building bars [3]. Since these phenomena may severely damage the stator (hot points and/or insulator breakdown, such as mentioned in [8]), a better comprehension of the involved phenomena is required.

In this paper experimental results obtained on a basic apparatus are presented in order to evaluate the penetration of the transverse magnetic flux and inter-lamination voltage. A model based on a reluctance network explains some experimental observations. The rolling direction of the sheets is also taken into account.

Bibliographic review

The inter-lamination voltages and penetration of the magnetic field transversely to the sheets is only seldom the subject of publications. The experimental point of view have been dealt with in [6], where the authors have set up a full instrumentation on actual end regions of a 660 MW turbo-generator built in the laboratory for that purpose. It consists in around 1900 sensors (essentially search coils and voltage probes). However they provide only some scant selected results, but it appears nevertheless that the order of magnitude of the inter-lamination voltage is a few volts. In addition, currents flowing into the stator frame have been calculated and measured in [2] on a 500 MW turbo-generator, using search coils (for magnetic fields), Rogowski coils (for currents) and J-probes (for surface electric field).

Jackson [3] has studied the voltages in a 500 MW turbo-generator. His approach is mainly analytical: based on electrical equations (and experimental measures of magnetic flux), he estimates the values of inter-lamination voltages along the stator core. Depending on the grounding of the core, the voltages are maximal at the very end of the core (up to 0.8 V) but have a secondary maximum peak around 0.15 m from the end at a value 20% lower. However, the voltages are not higher than 0.1 V if the core is well grounded. Jackson notices that a voltage at least as high as 0.5 V is needed to damage the insulator.

In [7], the effect of operating conditions on axial flux (main cause of heating and inter-lamination voltage) is considered. A linear model, covering transient conditions, and linking axial magnetic flux with system parameters is developed. This model proves that the value of the magnetic field rises by a factor 10 when a pole slipping occurs. In order to measure the transverse flux, search coils have been printed on the sheets using a thick-film technique, keeping the thickness of the inter-laminar air-gap under 40 µm. Fujita et al. [1] confirm through a simple phasor diagram, linked with a FEM simulation, that the leading power factor operations induces much higher transverse fields than the lagging ones.

Penetration of magnetic field

An experimental apparatus, described in the figure 1, has been set up. It is aimed at investigating the penetration and direction change of a magnetic field incoming perpendicularly to the magnetic sheets and closing lengthwise. This simple apparatus allow to separate the magnetic phenomena from each other: in a real turbo-generator at operating conditions, the main flux (in terms of amplitude) would be indeed fully lengthwise and therefore impact the behavior of the transverse flux.

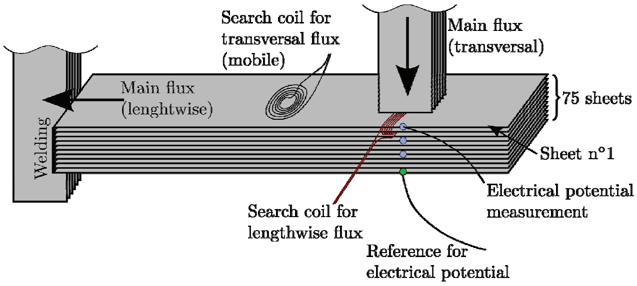

Fig. 1: Scale model used to investigate the behavior of magnetic field incoming transversely to the plane of laminations and the induced inter-lamination voltages. The exciting circuit is not shown in this figure.

With the same purpose of separating the phenomena, all short-circuits between laminations have been wiped out by the use of an adhesive thin insulator on the upper face of every sheet (which however increases the inter-laminar air-gap). All laminations are welded together (see figure 1), like the building bars connect laminations in a turbo-generator, with a single welding line on an edge to prevent any unexpected current loop. Since the oxidation of the magnetic steel is fast, and because of the insulator, a welding point has been made on each sheet in order to measure the inter-lamination voltage distribution. All welding points have been checked with an precision mill-ohmmeter; and the voltages measurements have been made using a scope voltage probe (coaxial cable) between the lowest sheet (which is grounded) and the different laminations.

The magnetic sheets (140x30 mm) are HGO quality, and have a thickness of 0.35 mm. The direction of lamination of the steel and the lengthwise direction form an angle of 60° (all sheets share the same orientation). Actually, in a turbo-generator stator core, the magnetic flux is indeed not collinear with the lamination direction (esp. in the teeth).

Magnetic transverse flux has also been recorded using a thin flat search coil made of 0.14-mm-diameter wire of 20 turns; and 10-turn coils have been wound around the sheets by pack of 2 under the exciter. The value of flux density is calculated from the voltage across the coils (assuming the relation in steady state, which is not exact for non-sinusoidal waveforms).

The main flux in the exciting circuit is provided by a 400-turn coil fed by an auto-transformer. A secondary coil has been set up in order to check the flux density level in the circuit (whatever the saturation) and check the incoming waveform.

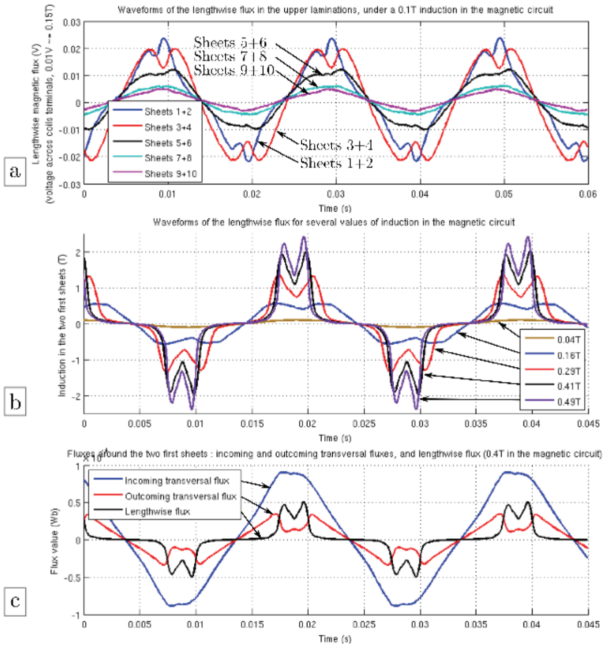

Fig. 2: Comparison between flux's waveforms. a) Waveforms of the lengthwise fluxes in the 10 upper laminations with and flux density of 0.1 T in the magnetic exciter. b) Waveforms of the lengthwise flux in the first pack of sheets (sheets 1+2) for several values (RMS) of flux density. c) Waveforms of the incoming transverse flux (above the first pack of sheets), the out-coming transverse flux (under the first pack of sheets) and the lengthwise flux in the first pack of sheets with a flux density of 0.4 T RMS in the magnetic circuit.

Several experiments have been carried out. First, in the figure 2a, the waveforms of the magnetic lengthwise fluxes through the upper sheets are presented. The position of search coils is shown in the figure 1, and are wound around 2 sheets each, so their section can be valued at two times the sheets section (since the metal's permeability is much greater than the air's), *i.e.* $2.1\cdot10^{-5}m^2$.

As expected, the flux density level is high (compared to the values in the circuit) in the first sheets: the peak value of the signals is around 0.3 T. The waveforms have a non-negligible third harmonic (17% of fundamental) even if the incoming flux density level remains low.

When the incident flux grows, the saturation becomes obvious, as presented in the figure 2b. It is very noticeable that a distortion begins to appear even at a low flux density, were the behavior of the sheets should still be linear (and the flux density in the exciting circuit remains sinusoidal). This is mainly due to the direction of lamination [4]. Under higher flux densities, the waveform is very typical of the saturation phenomenon.

Finally, three fluxes around the first pack of sheets (1+2) are presented in the figure 2c. They are estimated (extrapolation) assuming the field is homogeneous in the considered areas (which is not exact, but it allows the comparison between fluxes). As expected, the measured waveforms are complementary (the out-coming and lengthwise fluxes are roughly equal to the incoming flux due to the flux conservation).

The voltages between the lowest sheet and the upper one have been measured for different values of flux density in the exciting circuit (figure 3). It has been found that the voltage between two adjacent laminations is of an order of magnitude lower than 1 mV. The maximum of voltage is reached inside the sheet stack, and its position is function of the flux density: the higher the excitation level is, the deeper is the maximum position.

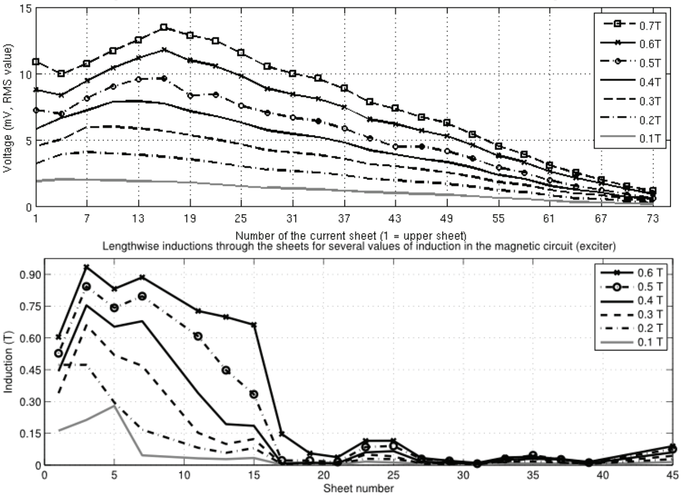

Fig. 3: Comparison between the voltages across laminations (upper graph) and the lengthwise flux (lower graph) for several values of flux density in the magnetic circuit. Higher curves correspond to higher excitation in magnetic circuit.

This position of the maximum voltage seems correlated with the saturation, matching with the last highly saturated lamination, as seen in the figure 3. For example, if the 0.5 T-curve is considered, the flux density level drops greatly (50% of its maximum) around the sheet 14, while the maximum of voltage is reached also around this same sheet (for the 0.3 T-curve, it would be sheet 10).

Reluctance network considering saturation and rolling direction

A simulation of the experimental apparatus of the figure 1 based on a reluctance network has been carried out. It relies on the classic analogy between electricity and magnetism (summed up in the table 1 as a reminder), and is a convenient tool for the study of magnetic circuits. In this study, all the laminations are represented and divided into small elements, instead of considering the system globally.

Since reliable tools for the simulation of complex electronic networks do already exist, with a high robustness, the implementation of a large network of saturable resistances (*i.e.* reluctances) has been carried out through Matlab simulink.

Table 1. Analogy between electricity and magnetism.

Electricity	Magnetism
I (A)	Φ (Wb)
U (V)	ε (ni)
R=ρl/S	R=l/μS
U=RI	ε=RΦ

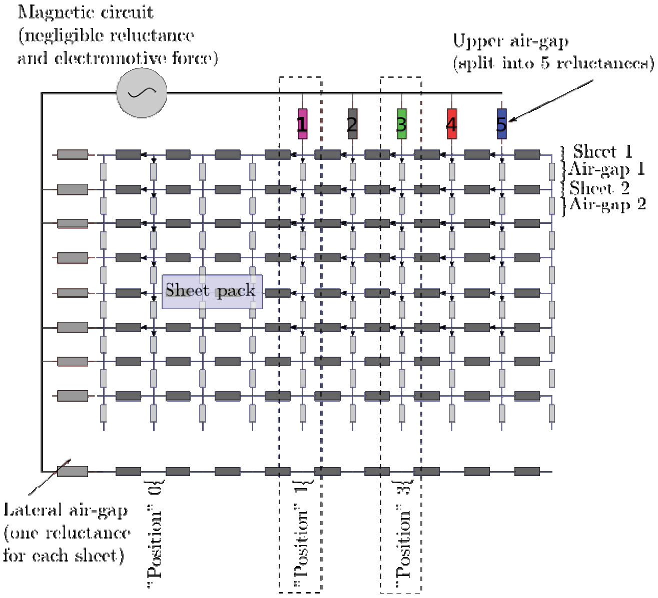

Fig. 4: Model use in the simulation. Each sheet is divided into reluctances (one horizontal line of dark resistances corresponds with one sheet), connected to the adjacent sheets trough the air gap reluctances (lighter ones). The eddy current magnetic reaction is neglected, and the hysteresis is not considered.

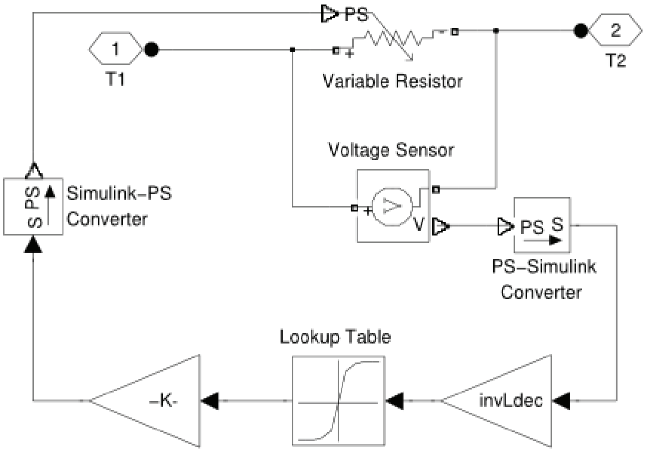

Fig. 5: Implementation of a resistance with saturation in Matlab simulink.

As presented in the figure 4, every sheet is divided into small elements (reluctances with saturation, presented in the figure 5). Each node between two elements of one sheet is connected through an air-gap reluctance (without saturation) with the corresponding node of the adjacent sheets. The model is *per se* 2D; the exciter magnetic circuit is not studied so does not appear in the model and the electromotive force is forced between the terminal air-gap elements. The characteristics B(H) were experimentally measured as a function of the lamination direction in [4]. Thanks to that work, the influence of the lamination direction can be studied through this simulation.

The simulations have been performed with two different waveforms of the main flux: slope and sinusoidal waveform. Thus allows determining the effect of saturation and plotting time variation of fluxes.

In the first results, the excitation is a slope, then the x-axis represents the level of flux density (proportional with time) in the magnetic circuit. In the figure 6, a predictable phenomenon might be observed: under the left side of the exciter (position 1), the most part of the flux is driven by the first sheet, until the saturation occurs. At this very moment (x=0.025 in the figure), in the second sheet, the slope of the flux density increases, until its saturation, and then the phenomena occurs successively in the following laminations.

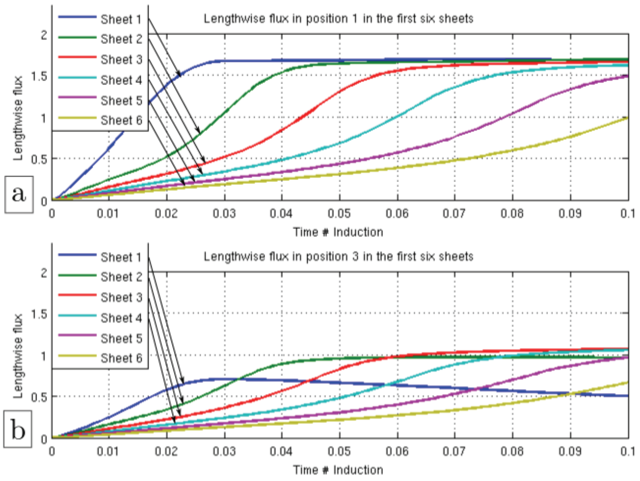

Fig. 6: Lengthwise flux under the exciter: a) on the left (position 1) b) centered (position 3) (*cf.* figure 1) for the 6 first sheets, the excitation growing linearly (slope) in the exciter.

However, this saturation has consequences on the lengthwise flux centered under the exciter (position 3 in the figure 4). When the flux density remains low, the evolution is the same as previously, but when the excitation increases, the flux in the second sheet becomes higher than the first sheet's one. It is simply due to the saturation and to the lowest reluctance path, but it explains why the maximum of flux in the figure depends on the flux density and does not occur on the top first lamination. So the saturation in an area of the sheet has a major impact on the flux through *other* areas in terms of value and distribution; this can be observed experimentally on the waveform of the figure 2 (with a high distortion in non saturated areas).

Results shown in the figure 7 are very close to the experimental observations of the figure 3. The maximum of the repartition of the lengthwise flux is not in the upper sheet, and depends on the flux density level. The sheets numbers does not match because of the rough estimation of simulation parameters (3D effects...).

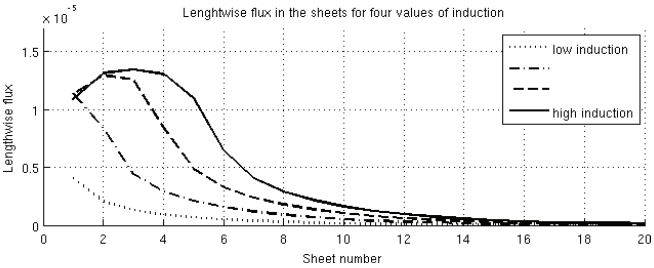

Fig. 7: Lengthwise flux in the sheets for several values of induction in the exciter circuit. The observed area is centered just under the exciter (position 3 in the figure 4).

With a sine excitation, it is hard to reproduce the waveforms observed previously. However, the simulations in the sheets with an angle of 60° between the lengthwise direction and the lamination direction have a similar behavior near the intersections of the waveform with the x-axis, as shown on the figure 8. With an angle of 0°, the shapes remain sinusoidal.

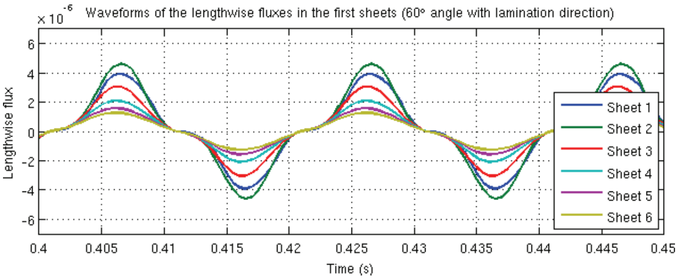

Fig. 8: Waveforms of the lengthwise flux in the first sheets with a high value of induction. The shapes are flat when they cross the x-axis due to their characteristic, and the flux in the second sheet is higher than the flux in the first one. However, the characteristic shape of saturation does not appear.

Conclusion

Experimental results were presented aiming at accurately understanding the behavior of the magnetic field incoming transversely to a stack of magnetic sheets. A simple simulation based on a network of reluctances (much faster than a FEM simulation, and without the convergence problems linked with the packs of thin large sheets meshes) has been carried out, and explains qualitatively the shape of the repartition of the lengthwise flux under the exciter. Because of the simplifications within the model, it is difficult to adjust the parameters in order to verify quantitatively the experimental results.

These results may be consequential for further experiments on actual turbo-generators: the importance of the position of the sensor has been exposed. In an actual turbo-generator, the influence of lamination direction also appears to be significant and complex (since it varies along the flux path).

Finally, the voltages between laminations have been measured. It has been shown that inter-lamination voltages depend on the flux density level of transverse flux, flux pattern through the steel sheets and saturation curve of magnetic steel. In stator end packets this voltage is induced by the transverse flux and the main flux (air-gap flux). Our work will be continued with measurements on a real scale stator of a large generator.

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