

## Analyses and tests of interlamination short-circuits

**Abstract.** Since the interlamination short-circuits in stator cores can cause major damage to electrical machine a great emphasis is placed to detect such faults. ELCID (Electromagnetic Core Imperfection Detector) test is nowadays often used for testing of interlamination insulation in stator cores of large electrical machines. To investigate this relatively young method a laboratory model of stator core was built, which enables measurements and analyses of intentional short-circuits in the core. Interlamination faults were also simulated and analysed using FEM.

**Streszczenie.** Ponieważ zwarcia międzywarstwowe w rdzeniach stojanów mogą spowodować istotne awarie maszyn elektrycznych jest sprawą wielkiej wagi detekcja takich zwarć. Test detektorem uszkodzeń rdzeni magnetycznych jest współcześnie często używany dla testowania izolacji międzywarstwowej w rdzeniach stojana dużych maszyn elektrycznych. Do zbadania tej relatywnie nowej metody zbudowany został laboratoryjny model rdzenia stojana, który umożliwi pomiary i analizę celowych zwarć w rdzeniu. Uszkodzenia międzywarstwowe były także symulowane i analizowane za pomocą MES. (Analizy i testy zwarć międzywarstwowych)

**Keywords:** ELCID, fault diagnostics, interlamination short-circuit, stator core.

**Słowa kluczowe:** detektor uszkodzeń rdzenia elektromagnetycznego, zwarcia międzywarstwowe, rdzeń stojana

### Introduction

A traditional method for detection of interlamination faults is the *High Flux Ring Test*, often referred to as a *Thermal Loop Test*. The rotor is removed from the machine and the stator core is magnetically excited by a high voltage high current temporary winding. Magnetic flux produced in stator yoke should be near to that normally applied in service. Hot spots are detected by a variety of means including thermal cameras. Because of the required dismantling of the machine, high voltage excitation winding, high power source, that method is not very convenient.

One of contemporary methods is ELCID test [1], which is nowadays often used for testing of interlamination insulation in stator cores of large electrical generators and motors. The main advantages of the ELCID method are that the core is excited with just 4% of the rated flux and detection of damaged areas is sometimes possible even when the rotor of the machine is not removed. Positions and strength of the faults are determined with a measurement of leakage fluxes produced by the fault currents.

Investigation of the test method on a real working machine is difficult or almost impossible to perform, moreover the faults cannot be generated on purpose. To investigate the influence of the fault position and strength on measurements we performed several simulations of interlamination faults using FEM and compare them with measurements on a laboratory test core which enables measurements and analyses of intentional short-circuits in the core.

### Laboratory test core

To verify the results obtained using FEM and to test different sensing coils we carry out measurements on a real model of stator core (Fig. 1 and 2). All measurements were performed without a rotor in a stator bore. Since the model consists of separated sheets which are not welded together or fasten with building bars, the interlamination faults can be simulated using short-circuit turns.

In Fig. 3 an electrical scheme of the laboratory model is shown. It is similar to short-circuit of a transformer but in this case only a part of the ferromagnetic core is short-circuited. Separated sheets and short-circuit turns enable also the investigation of the fluxes in the core, since every part of the core can be embraced with a test winding.

A length and position of the short-circuit turn can be arbitrary chosen, while the value of the fault current can be determined using an external resistor. Furthermore, the

fault current can be simply measured and used as a reference value for results of a testing device. Introducing of artificial shorts at different places on the test core has been already presented in [2] where the core was intentionally irreversibly damaged. In such case the fault current could not be directly measured or changed.



Fig. 1. Test core for investigation of interlamination short-circuits for different positions and strength.

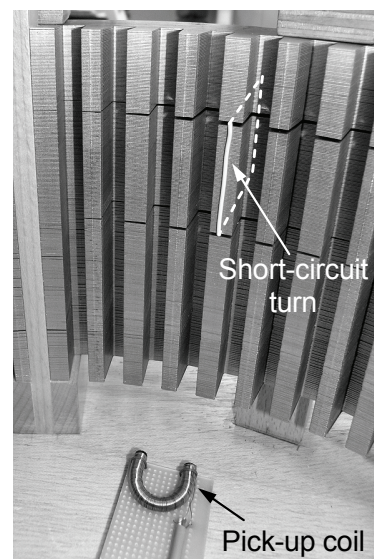


Fig. 2. Short-circuit turn at the top of the tooth and a pick-up coil.

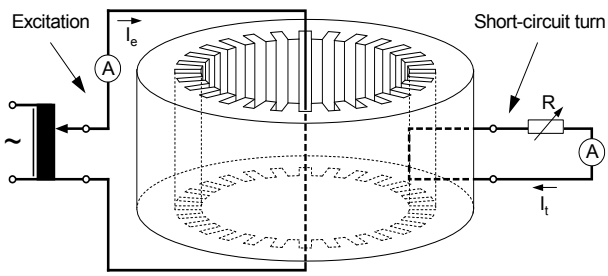


Fig. 3. Electrical scheme of the laboratory model.

Using a pick-up coil the induced voltage is measured. The positioning of the pick-up coil on stator teeth is shown in Fig. 4. If the short-circuit turn exists, the measured voltage should be proportional to the fault current in the turn [4].

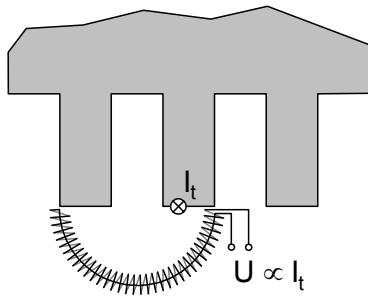


Fig. 4. Position of pick-up coil on stator teeth.

### FEM model

Since the interlamination fault is a genuine 3D problem, a 3D FEM model would be adequate for simulation. In spite of that the investigation of ELCID core testing was performed using a 2D FEM model. The geometry of the model was simpler and the calculation of parametric analyses was not time consuming. Before the FEM model is introduced let us get familiar with the problem definition. Figure 5 shows the structure, which has to be calculated using FEM (figure does not include the excitation). Short-circuit turn does not embrace the whole cross-section of the core. Length of the core is  $l_c$ , while  $l_t$  is length of the short-circuit turn. The total magnetic flux in the core  $\Phi$  can be written as the sum of a turn flux  $\Phi_t$  and remaining core flux  $\Phi_c$ . Since the excitation is sinusoidal, all mentioned magnetic quantities are complex.

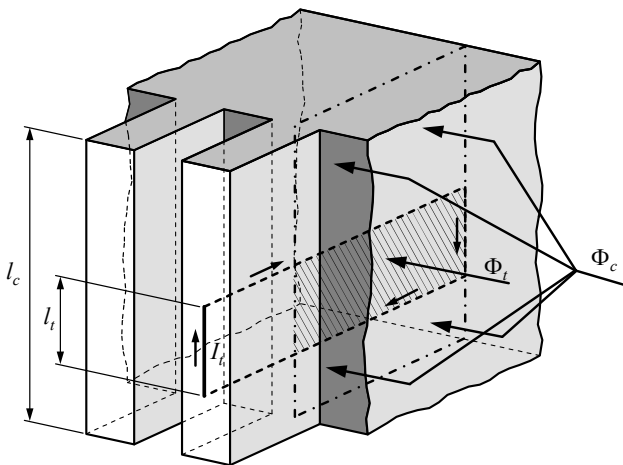


Fig. 5. Problem definition of interlamination short-circuit for FEM simulation.

Considering some negligible simplifications, a magnetic circuit of such magnetic structure is shown in Fig. 6, where can be noticed a flux source  $\Phi_f$  in a branch  $\Phi_t$ , which represent a flux produced by a short-circuit current  $I_t$ .

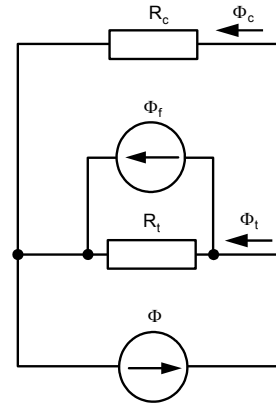


Fig. 6. Magnetic circuit of core model with interlamination short-circuit turn.

Having the magnetic circuit in mind a FEM model can be introduced. Figure 7 shows the geometry, material properties and boundary conditions of the model.

The material properties were linear and eddy-current (AC) solver was used. Instead of the whole iron core only slots around the fault were included in the model. Since the fault (short-circuit turn) can have a variable but specific length, two parallel ferromagnetic branches were introduced also in the model geometry. The first branch (lower core) represents the core embraced with the short-circuit turn, while the second (upper core) represent a remaining stator core.

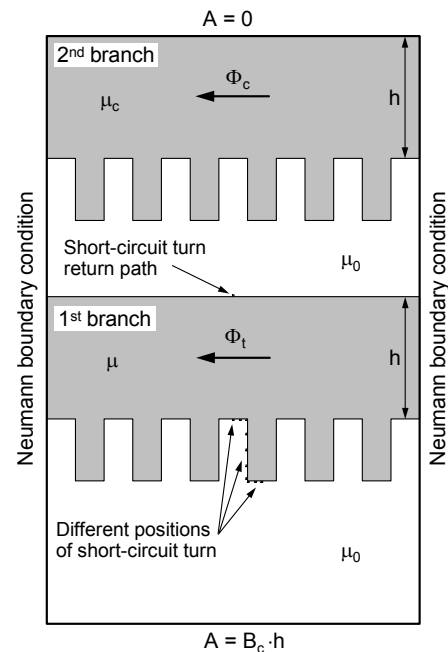


Fig. 7. FEM model with boundary conditions and material properties.

As can be seen the geometries of both branches are equal. Furthermore, the model does not change if the length of the short-circuit turn changes. Different cross-sections of both magnetic branches are considered with applying appropriate permeability for the second branch. Permeability  $\mu$  that defines the magnetic property of the real ferromagnetic core is assigned for the first branch, for the

second branch a new fictitious permeability  $\mu_c$  has to be calculated:

$$(1) \quad \mu_c = \left( \frac{l_c}{l_t} - 1 \right) \cdot \mu$$

where  $l_c$  is the length of the whole core and  $l_t$  is the length of the short-circuit turn. In such a way only permeability  $\mu_c$  has to change when we analyse conditions at different fault lengths. Because the FEM model is two dimensional, different fault lengths can only be used to analyse the core fluxes and fault current values but not to find the influence of the length to induced voltage in the pick-up coil.

Excitation of the model was not a sinusoidal current source but a prescribed sinusoidal magnetic vector potential  $A$  at the lower boundary of the model (see Fig. 7). Considering relation  $B = \text{curl } A$ , the magnetic vector potential  $A$  for a specified magnetic flux density  $B_c$  is:

$$(2) \quad A = B_c \cdot h$$

where  $h$  is the height of the stator core (see Fig. 7). Using such boundary condition it was assured that the flux through the core is constant what is also the case in a real core.

Interlamination short-circuits were modelled as short-circuit turns at different positions and with different material properties. The FEM model consists of 10 conductors at different positions and one outer conductor as return path outside the core. If we would like to simulate a real interlamination fault the position of the short-circuit turn should be at the edge but in the ferromagnetic core. Since an insulated wire was used to make a short-circuit turn in the laboratory model, same position and properties were used also in FEM model.

Only one pair of conductors was included in every calculation. The pair consists of one conductor at specific position (1 to 10) and the outer conductor. Figure 8 shows the positions and numbers of conductors and the defined lines (1-2, 2-3, 3-4) along which the integrals  $\int Hdl$  were calculated. Positions and labels of the defined lines were used also for positions of pick-up coil during the measurements on a test core.

### Fault position

A fault position can be recognized by analysing the voltage induced in the pick-up coil, considering also results from the neighbouring teeth. Since the pick-up coil is actually a Rogowski coil [4] the measured voltage is proportional to derivative of the fault current. In conditions where the current is sinusoidal or almost sinusoidal and the frequency is constant we can simplify that and just say that the voltage is proportional to the current. Therefore, the results obtained from measurements on the laboratory model are simply presented as voltages, while the results obtained using FEM are presented as integrals  $\int Hdl$  along the defined lines between the stator teeth (Fig. 9, 10). We just compared the models therefore the absolute values were not so important.

In both measurements and calculations the induced voltage due to excitation flux was deducted from the obtained signal so we could analyse only a "clear" signal caused by the fault current. The influence of the fault length was not included in the investigation since the FEM model was only a 2D model, while the faults on the laboratory model were 40 mm long and much longer than the pick-up coil dimensions. Therefore, the end effect was neglected.

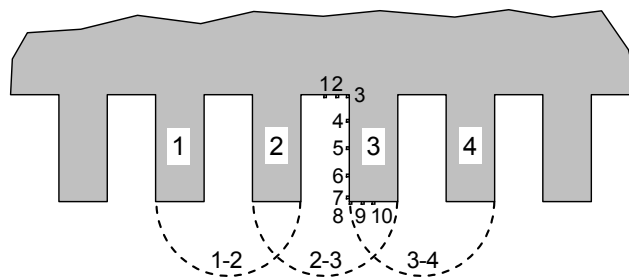


Fig. 8. Positions of the faults and defined lines between teeth.

Figure 9 shows that we can only determine whether the fault is at the top of the tooth (positions 8-10) or in the slot (positions 1-7), while the exact position can not be specified. Authors [1], [3] describe that also the fault at the vertical edge of the slot can be determined (position 6 or 7 in the model, see Fig. 8), but results of our calculations and measurements do not show that. On the laboratory model only three fault positions were examined (1, 5 and 10) and comparison of the measured results with the calculated values shows good agreement (Fig. 10).

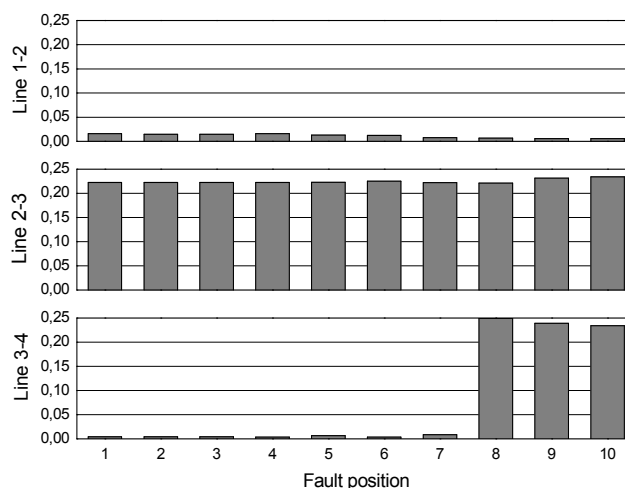


Fig. 9. Calculated  $\int Hdl$  along defined lines at different fault positions using FEM.

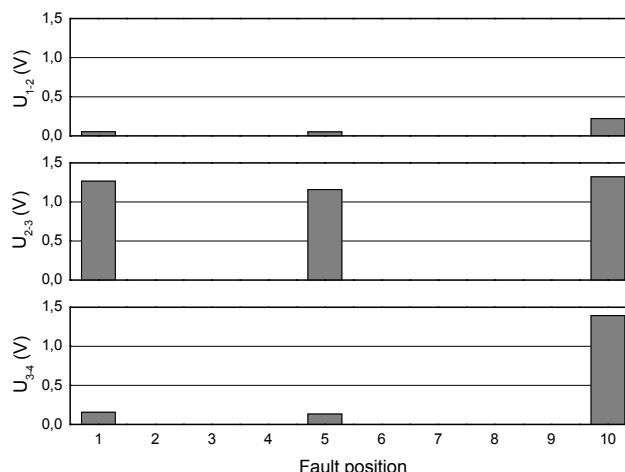


Fig. 10. Magnitudes of measured voltages using a pick-up coil at different fault positions.

### Fault strength

Using the FEM model the power losses of interlamination faults during the ELCID test can be simply calculated and investigated. The resistance of the short-

circuit turn in the model represents a contact resistance together with resistance of lamination in a real stator core. The obtained results for different conductance of short-circuit turn were used just to show that the fault current, which can be recognized and evaluated by the ELCID test, can not be a measure for the fault strength (Fig. 11).

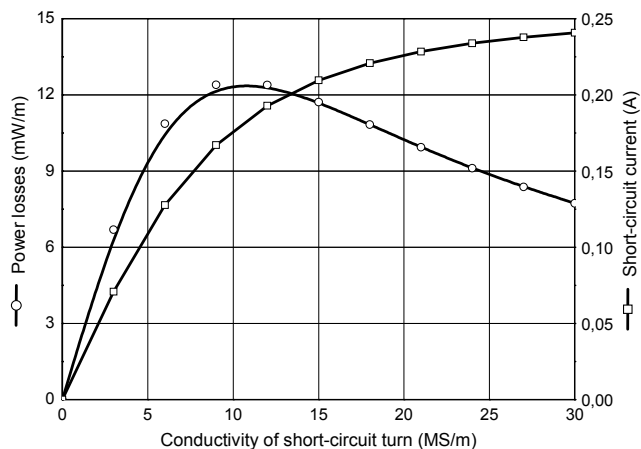


Fig. 11. Power losses in short-circuit turn for different conductance of the turn.

### Conclusion

Laboratory test core and FEM model offer a lot of possibilities for investigation, evaluation and research in the field of diagnostics of laminated stator cores. Tests and calculations showed that the interlamination faults can be recognized using ELCID testing, but the fault strength can not be easily determined. There are possibilities to combine ELCID with additional methods, such as described in [5], to

diminish the disadvantages of ELCID. Our goal is to develop a measuring device with the sensing coil which will automatically scan the whole circumference of the stator bore. The scan results would be used for generation of a "flux image" of the stator bore which could be a replacement for thermal image obtained from thermal camera at *Thermal Loop Test*.

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**Authors:** Danilo Makuc, E-mail: [danilo.makuc@fe.uni-lj.si](mailto:danilo.makuc@fe.uni-lj.si), Maks Berlec, E-mail: [maks.berlec@fe.uni-lj.si](mailto:maks.berlec@fe.uni-lj.si), Damijan Miljavec, E-mail: [damijan.miljavec@fe.uni-lj.si](mailto:damijan.miljavec@fe.uni-lj.si). All authors are with University of Ljubljana, Faculty of Electrical Engineering, Department of Mechatronics, Trzaska 25, 1000 Ljubljana, Slovenia.