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FEM modeling of inter-turn short-circuits in excitation winding of turbogenerator

***Abstract**. The paper presents an approach to modeling of shorted turns in rotor excitation winding of synchronous generator using FEM. It enables detailed analysis of magnetic field at several operating conditions under healthy and faulty states which are difficult to carry out by available measurement methods in industrial environment. Modeling of excitation winding faults is performed for a 156 MVA turbo generator operating in thermal power plant. Since the level of diagnostic signal is considerably influenced by combination of many machine and operating parameters, an extensive analyses are needed to assure accurate healthy/faulty state predictions.*

***Streszczenie.** Artykuł prezentuje podejście do modelowania zwartych zwojów w uzwojeniu wzbudzającym wirnika generator synchronicznego przy użycie MES. Umożliwia to dokładną analizę pola magnetycznego w kilkunastu reżimach pracy z uwzględnieniem stanów awaryjnych i bezawaryjnych, która jest trudna do przeprowadzenia dostępnymi w przemyśle metodami pomiarowymi. Modelowanie uzwojenia wzbudzenia zostało wykonane dla turbogeneratora 156 MVA pracującego w elektrociepłowni. Ponieważ poziom sygnału diagnostycznego w sposób istotny poddany wpływowi kombinacji wielu maszynowych i operacyjnych parametrów, ekstensywne analizy są niezbędne aby zapewnić dokładne predykcje stanu awaryjnego. (**Modelowanie za pomocą FEM międzyzwojowych zwarć w uzwojeniu wzbudzenia turbogeneratora**)*

Keywords: Failure analysis, fault detection, finite element method, synchronous generator.
Słowa kluczowe: analiza awarii, detekcja uszkodzeń, metoda elementów skończonych, generator synchroniczny.

Introduction

Supervision of electrical machines using non-invasive condition monitoring and diagnostic techniques has become a state-of-the-art tool for improving the reliability of machines operation in many branches of the industry in a last decade [1, 2], although the need for such topics existed already far in the past [3, 4].

The main advantage of diagnostic systems is that they can predict the possible breakdowns by on-line analysis of various machine parameters. Among several possible defects of synchronous generators, faults in rotor excitation windings are rather frequent and tricky to detect [4]. Rotor insulation of large synchronous generators must withstand severe electrical, mechanical, and environmental stresses. Excitation winding shorted turns can occur from many factors like: breakage and migration due to centrifugal forces and thermally induced expansion/contraction cycles, mechanical wear, overheating due to overloading, over-voltages induced from system events, contamination from ventilation or cooper dusting, etc. [5]. Shorted turns can have significant effects on a generator and its performance. If a percentage of total turns shorted out is small and does not propagate, the generator may be able to run at rated load for years without any problems. However, larger shorted turn percentages can cause degradation in operational characteristics. If the problems due to the fault propagation become severe, sudden forced outages may occur. Therefore, timely detection of such faults at an early stage of propagation, when they do not exhibit any obvious problems during operation, are vital for efficient and reliable condition monitoring and supervision of synchronous generators [6].

One possibility to detect shorted turns in rotor excitation windings is to monitor the symmetry of magnetic field using a flux probe [4, 6]. The advantage of this method is an exact and basic relationship between the cause and effects, while the main drawback is the requirement to install the flux probe in the stator near the air-gap.

Short-circuits in excitation winding of synchronous generator

The use of air-gap magnetic flux probes has proven effectiveness in the detection of excitation winding's shorted turns and ensures satisfying quality of predictive maintenance decisions. Analysis of air-gap flux probe data can in some cases even identify the number and location (pole and coil) of shorted turns without having to take the generator off-line.

The flux probe permanently installed on the stator is sensitive to the change of the radial magnetic flux in the air-gap. During generator operation, the magnetic flux from each passing slot will induce a voltage in the flux probe. As each rotor slot passes the flux probe, a difference in induced voltage waveform in a search coil caused by magnetic poles can be detected. The flux probe waveform displays a peak for each rotor slot. The magnitude of the particular peak is related to the ampere-turns in the slot. Since ampere-turns are directly related to the number of active turns in the slot, a coil with shorted turns will display a smaller peak than a coil without shorted turns. By comparing slot peak magnitudes between magnetic poles, the number of shorted turns can be estimated for each coil in the rotor.

Fig. 1 shows a typical voltage waveform from a flux probe. Each peak corresponds to an appurtenant coil of the excitation winding. An inter-turn short in a coil reduces the peaks associated with the two opposite slots containing the faulted coil, thus the presence of shorted turn could be detected. As differences in flux probe signal are rarely obviously noticeable, a precise detection algorithm have to be developed. For example, if 5 % of turns in a coil are shorted out, the pole's coil peak would be expected to decrease by approx. 5 %. This is true only when the so called FDZC (flux density curve zero-crossing) point is aligned with the affected coil's slot peak. Because of the interference of the main magnetic flux with the rotor slot's leakage flux, it is required to adjust the rotor load angle to the point of minimal interference. As seen in Fig. 2, in this point the flux goes from positive to negative and vice versa. The position of the FDZC is a function of the instantaneous real and reactive load of the machine [6]. At zero real power, the FDZC is positioned at the quadrature axis. As real power increases towards full load, the position of the FDZC significantly changes. To supervise the health state of the entire excitation winding with the best possible sensitivity, a series of load points is needed whose FDZC align with each of the coil slot peaks in the flux probe waveform, otherwise it is possible to miss the shorted turn indication if only one load point is used for entire analysis.

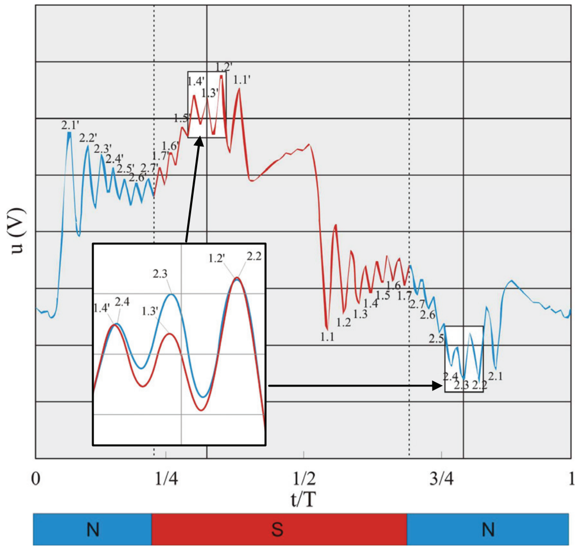

Fig. 1. Example of a voltage signal waveform from an air-gap flux probe.

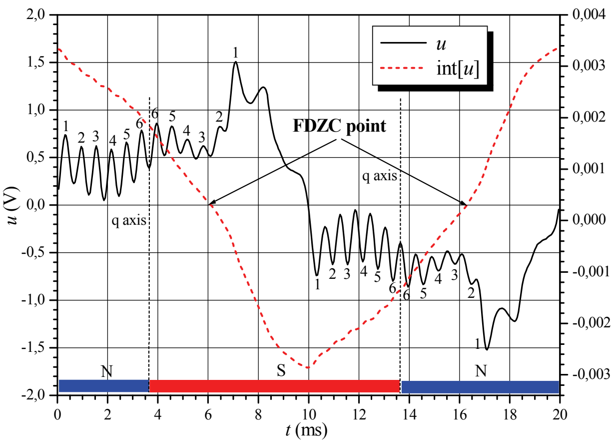

Fig. 2. Position of the FDZC point at the chosen load defining the highest fault detection sensitivity for slots 2 and 3.

FEM modeling of short-circuits in excitation winding

For simulation and analysis of short-circuits in excitation winding a 2D finite element analysis was used [9, 10, 11]. In presented case the rotor of turbo SG is a non-salient type and has two poles. Due to the symmetry, only half of the turbo generator cross-section could be modeled, but in almost all cases the faults in rotor windings forms magnetic asymmetry and consequently the FEM model has to include the whole cross-section of the machine (Fig. 3a).

A time domain transient solver was used to simulate a rotation of the rotor, while its mechanical speed had rated value and it was constant. From a modeled flux probe, mounted on the top of a stator tooth (Fig. 3b), magnetic flux and induced voltage were obtained. Simulated operating conditions (load current and power factor $\cos\varphi$) of the machine, shown in Fig. 4, were achieved using an external circuit, connected to stator windings, which represents the electric load. For each load, the corresponding excitation current was determined. The analysis of the rotor faults was limited to shorted turns at various chosen positions (slots) in the excitation winding, which are defined in Fig. 3a. Analyses were performed for different number of shorted turns of the same slot. Since the inter-turn short-circuit eliminates a damaged turn, the excitation in that rotor slot was proportionally decreased.

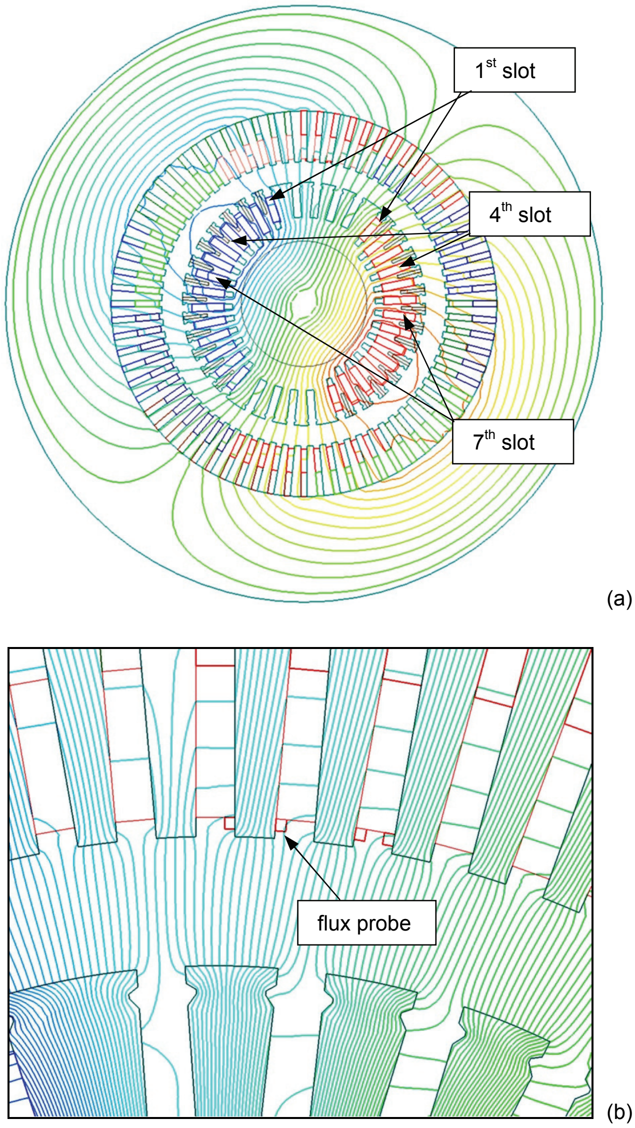

Fig. 3. Magnetic field distribution in the cross-section of a synchronous generator and marked slots with inter-turn faults (a); position of the search coil near the air-gap (b).

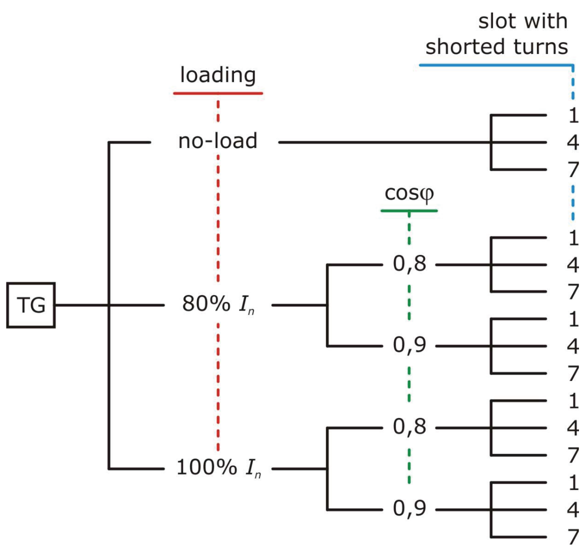

Fig. 4. Simulated load conditions of the turbo generator and slot numbers with modeled shorted turns.

Simulation results

Results of FEM calculations for several locations of modeled short-circuits in rotor excitation winding for various load conditions (load current and cosφ) defined in Fig. 4 are presented in Figs. 5-8. The induced voltage in the modeled flux probe is obtained and then compared to values which belong to a healthy machine. Fig. 5 shows the shape of the flux probe signal for a healthy machine, which changes from symmetrical at no-load to shifted with regard to the quadrature axis at usual load conditions due to armature reaction. As expected, when a fault of a few shorted turns in excitation winding occurs, no particular changes are observed in the signal waveform (Fig. 6), which makes fault detection rather difficult and potentially untrustworthy.

Differences in the diagnostic signal (induced voltage u) at low levels of excitation current asymmetry are normally very small (Fig. 6), therefore it is more convenient to observe the relative deviations Δu in comparison to the healthy or initial state. Fig. 7 shows the case of simulated two shorted turns at several positions (in slots no. 1/4/7) and gradually increased load current at rated power factor, while Fig. 8 presents similar case of varying power factor at the rated load current. Notice that the same fault is more pronounced when placed in slot 7 than in others two, which is due to the mutual positions of the rotor and total magnetic flux axis. Furthermore, there is also a difference between the peaks caused by leading (right) and lagging (left) slots of the same faulty coil.

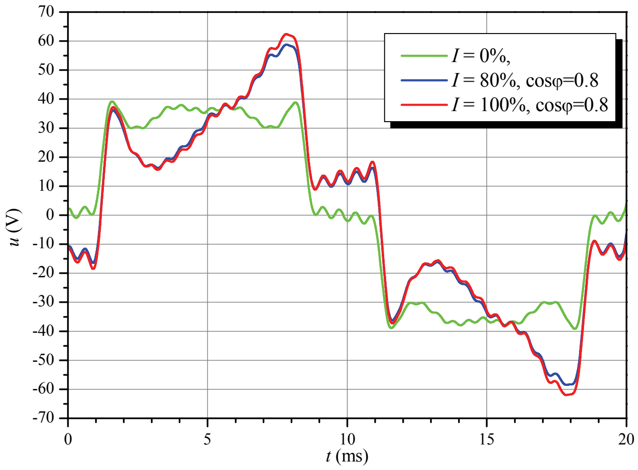

Fig. 5. Signal of the flux probe in the air-gap: healthy excitation winding; increasing load from no-load to rated load operating condition.

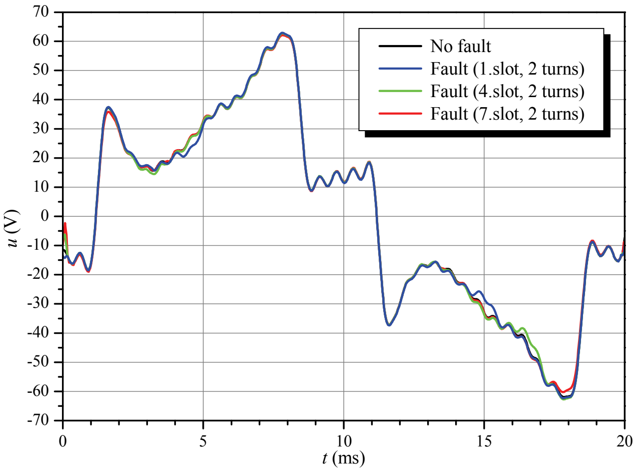

Fig. 6. Signal of the flux probe in the air-gap: different positions of inter-turn faults; 100% of rated load, power factor cosφ = 0,8.

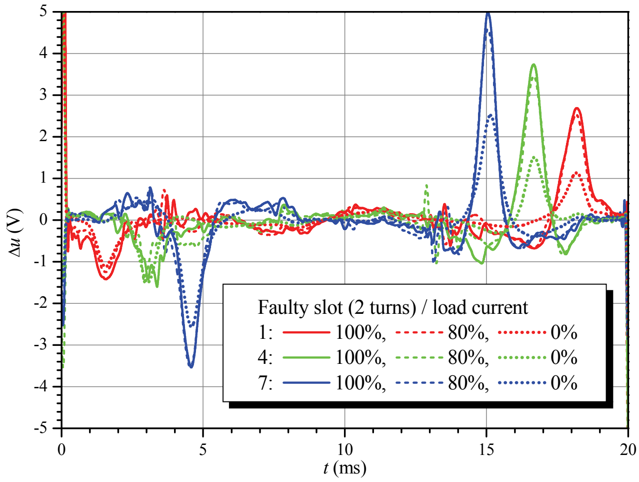

Fig. 7. Deviation of the flux probe signal for different fault locations (1/4/7 slot), load currents, and constant cosφ = 0,8 from the case of healthy rotor winding.

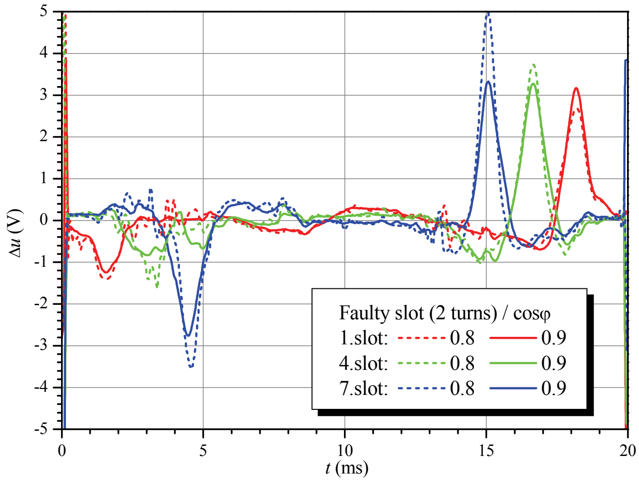

Fig. 8. Deviation of the flux probe signal for different fault locations (1/4/7 slot), increasing power factor cosφ, and rated load current from the case of healthy rotor winding.

Various values of load and power factor were achieved using an external circuit representing an electric load connected to stator three-phase windings. For each operating condition the corresponding values of serially connected resistance and inductance was calculated. That values define the chosen load and power factor, while the required excitation current was determined by a trial. Trial-and-error method for determination of excitation current was used since different estimation methods were not precise enough.

In Fig. 9 phasor diagrams of the analysed operating conditions of turbo generator are shown. Required excitation currents for the rated power and power factors 1.0, 0.9, 0.8, and 0.7 were 1200 A, 1520 A, 1570 A, and 1600 A, respectively.

Similar to Fig. 8, Fig. 10 clearly presents the influence of fault position and load condition to the sensitivity of the fault detection. Shorted turns in slot no. 7 are better detectable at lower cosφ values than in slot no. 1, whereas at cosφ ≈ 1 the situation is just the opposite. Since mutual combination of many parameters considerably influence on the level of diagnostic signals, an on-line diagnostic system has to be connected to the synchronous generator to achieve the desired information on the healthy state of the excitation winding.

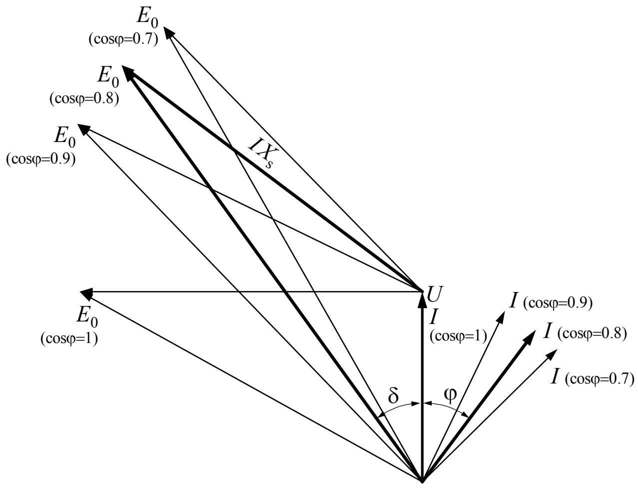

Fig. 9. Phasor diagrams of analysed turbo generator's operation conditions.

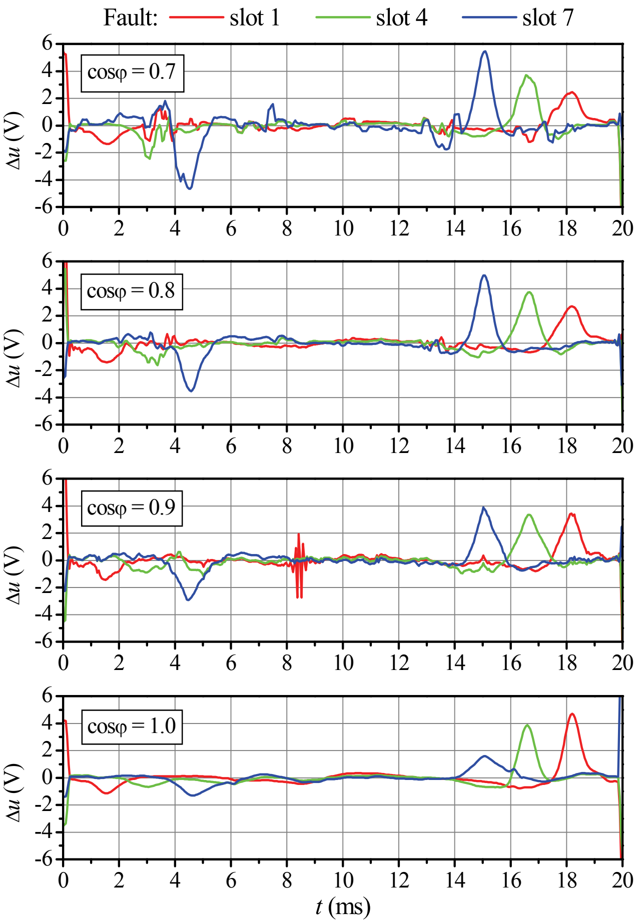

Fig. 10. Two shorted turns at different position (slots), varying cosφ at rated load.

Conclusions

As it is almost impossible to perform testing of large electrical machines under faulty states in industrial environment, computer simulations were used to study the influence of shorted turns in excitation winding on the operational performance of synchronous generator. In this way necessary information are obtained in the development phase of diagnostic system hardware set-up and software procedures. Level of the diagnostic signal is considerably influenced by mutual combination of many parameters like number and position of shorted turn(s) in excitation winding, load current and power factor, thus an extensive analyses should be performed to assure accurate diagnostic predictions.

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