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Detection of inter-coil short circuits in coils of salient pole synchronous generator field winding on the basis of analysis of magnetic field in the machine

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Abstract. This paper deals with detection of inter-coil short circuits in coils of the salient pole synchronous generator field winding, on the basis of the analysis of the magnetic field in the machine. Applying FEM to the generator model, magnetic field wave forms in the machine were calculated, on the points of interests, under both, faultless and faulty conditions. When results were compared, changes in wave forms caused by the analyzed fault were identified. Using the model, flux density and magnetic flux were calculated on the points accessible for measuring with Hall's sensors and measuring coils in the actual machine. The aim of this paper is a contribution in the field of faults and failures identification in rotating machines, that is, improvement of monitoring systems aimed for rotating machine condition monitoring.

Key words FEM, synchronous generator, flux density, Hall's sensor, generator diagnostics.

1. Introduction

The area of fault and failure detection in various machines has a significant importance in nowadays industry. Analyzing the topic, it can be seen that there are a lot of various ideas and techniques used for detection of failures and faults, and that the scope of activities in that area is very intensive. Numerous ideas and technical solutions used in detection of failures and faults have been implemented into monitoring systems increasing the value of such systems themselves. Each monitoring system collects and processes data received from sensors and probes incorporated into the machine. The level of development, quantity of know-how integrated into it, and the applied methods determine the capacity of each monitoring system. Methods of failures and faults detection can be divided into two groups: those using mathematical models of the system they monitor and those not using mathematical models. This paper reports on detection of failures and faults based on comparisons of mathematical models, or in other words based on FEM analyses, and records of the monitored machine conditions.

2. Results of failure and faults analyses obtained by application of FEM

Analyses of inter-coil short circuits of field winding coils have been performed on the model of a four salient pole synchronous generator. The easiest way to analyze inter-coil short circuits is to monitor generator magnetomotive force (MMF) in the air gap, as shown for the analyzed machine with the concentrated field winding in Figure 2.1. The inter-coil short circuit of ΔN field winding coil turns is considered as an additional field coil having ΔN turns around the pole number 4. That coil is opposed to the action of the main field coil. The MMF of the additional coil $\Theta_{a1} is$ shown in Figure 2.1 and marked with red color.

The MMF of the additional coil is allocated over whole peripheral of the air gap and the following expressions are valid for it:

$$\Theta_{a1} \cdot \tau_p = \Theta_{a2} \cdot 3 \cdot \tau_p \tag{2.1}$$

$$\Theta_{a1} = 3 \cdot \Theta_{a2} \tag{2.2}$$

$$\Theta_{a1} + \Theta_{a2} = \Theta \cdot \Delta N \tag{2.3}$$

The total MMF in the air gap of the machine at no load with one pole decreased turn number results from the sum of the main excitation and the additional MMF. Figure 2.1 shows the total MMF. It can be seen that the reduction of the number of turns on one pole influences the MMF of all the poles in the following way: the MMF of the pole number 1 and the pole number 3, i.e. Θ_{t1} and Θ_{t3}, is decreased by the amount of Θ_{a2}; the MMF of the pole number 2, i.e. Θ_{t2}, is increased by the amount of Θ_{a2}; while the MMF of the pole number 4, i.e. Θ_{t4} is decreased by the amount of Θ_{a1}. From expressions (2.1), (2.2) and (2.3) the amounts of MMF Θ_{a1}, i.e. Θ_{a2} are derived:

$$\Theta_{a1} = \frac{3}{4}\ (\Theta \cdot \Delta N) \tag{2.4}$$

$$\Theta_{a2} = \frac{1}{4}\ (\Theta \cdot \Delta N) \tag{2.5}$$

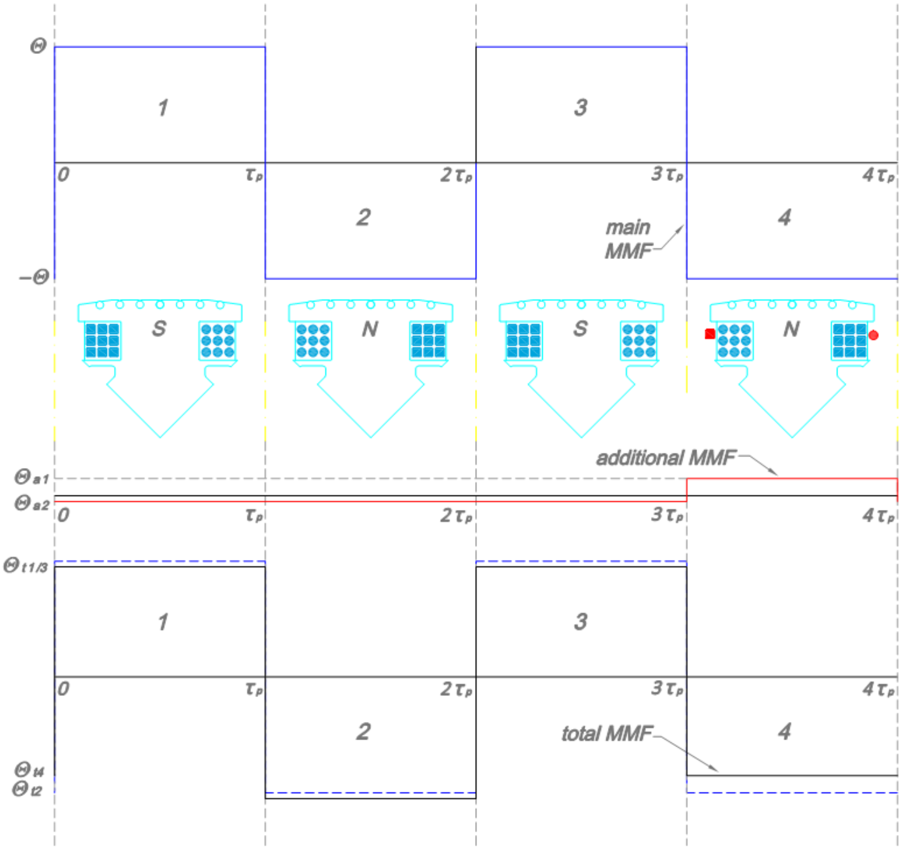

Figure 2.1. MMF in the air gap of the machine at no load with a decreased number of turns in the field coil: Curve 1 – basic MMF; curve 2 – additional MMF; Curve 3 – total MMF.

Expressions (2.4) and (2.5) define that reduction in the number of turns on one pole by 10 %, and in this particular case that is the pole number 4, the MMF of the pole number 1 and the pole number 3 will be reduced by 2.5 %, the MMF of the pole number 2 will increase by 2.5 %, while the MMF of the pole number 4 will be reduced by 7.5 %. In order to verify above statements, the wave form of the flux density in the air gap was calculated under all the poles, with a decreased number of turns. Flux density calculation results of each pole were interdependently compared, and a comparison was also made with flux density calculation data without any decrease of the number of pole winding turns. Results of the stated comparisons are presented in the continuation of this chapter.

Figure 2.2 shows distribution of flux density in the pole pitch for each of the poles at no load operation and decreased value of the field current. The shown distribution of flux density is monitored from a stator core tooth, and calculated for a decreased number of turns in one of the field winding coils by the amount of 10 %.

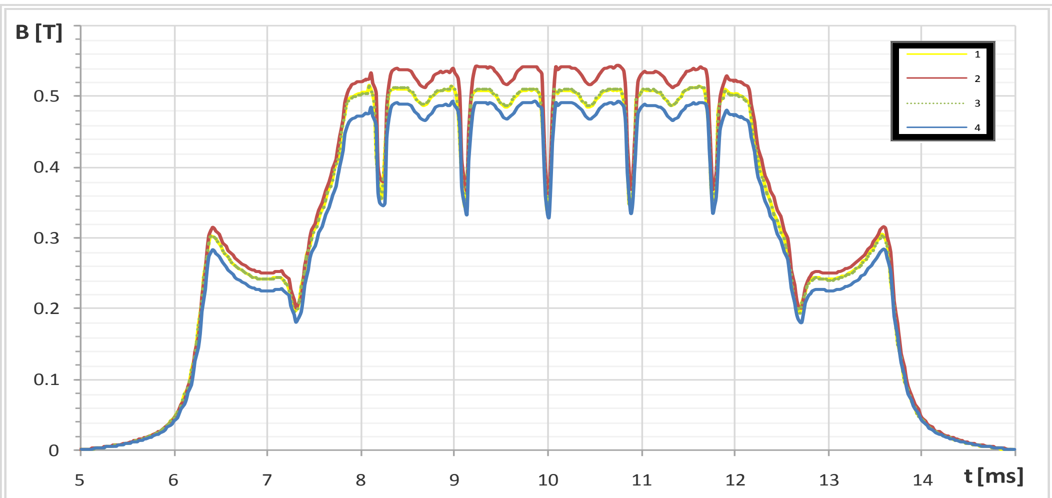

Figure 2.2. Distribution of flux density over a pole pitch monitored from a stator core tooth at no load and reduced excitation current: Curve 1 – for the pole number 1, Curve 2 – for the pole number 2, Curve 3 – for the pole number 3, Curve 4 – for the pole number 4.

Table 2.1 shows mean values of flux density displayed by Figure 2.2, in the part of the pole shoe with a constant air gap. Relative values are also shown in relation to the flux density value under the pole number 4.

Table 2.1. Flux density mean values in the area of the pole shoe with a constant air gap, and a reduced value of turns of the pole number 4 by 10 %.

Pole	B_{SR} [T]	B_{SR}/ B_{SR2}	ΔB_{SR} [%]
1	0,508	0,950	- 2,5
2	0,535	1,000	+ 2,5
3	0,508	0,950	- 2,5
4	0,482	0,900	- 7,5

In addition to the 10 % reduction, flux density distribution was calculated with 5 % and 2,5 % decreased number of turns on one pole, at full and decreased no load excitation current. Based on the calculation results, it can be concluded that the ratio of the change of number of turns and the change in the value of the flux density under the pole depends on the field current. Namely, dependency between them is determined by the slope of the open-circuit characteristic for the monitored state. The above mentioned dependency will be in accordance with expressions (2.4) and (2.5), as long as the magnetic circuit of the machine is not saturated. As magnetic circuit of the machine becomes saturated, the change of value in flux density (caused by the change of the field winding turns) becomes less expressed. Therefore, it follows that for any analyzed machine with $2p$ salient poles, the change of flux density under a pole, caused by the change of the number of turns ΔN of the n-th pole, amounts to:

$$\Delta B_{MEANn} = -\frac{2p-1}{2p} \cdot \Delta N \cdot k_{nl} \tag{6.6}$$

$$\Delta B_{MEAN(n\pm i)} = -\frac{1}{2p} \cdot \Delta N \cdot k_{nl} \tag{6.7}$$

$$\Delta B_{MEAN(n\pm j)} = +\frac{1}{2p} \cdot \Delta N \cdot k_{nl} \tag{6.8}$$

where: $i = 1, 3, 5 \ldots p$, $j = 2, 4 \ldots p-1$, and k_{nl} represents the factor that is determined by the slope of the open-circuit characteristic for the monitored state of flux density. For the unsaturated magnetic circle of the machine $k_{nl} = 1$. As magnetic circuit becomes saturated, the factor k_{nl} takes values lower then 1. It therefore follows that the influence of the reduction in the number of turns on one pole, to the flux density of the other machine poles, is as much lower, as the machine has larger number of poles. It means that any magnetic field disturbance in the machine caused by the reduction of the pole winding turns will be more expressed in comparison to the rest of poles, as number of the machine poles gets higher. Influence of the decrease in pole winding to the flux density basic harmonic of the rest of poles is shown on figure 2.3 (4 pole machine) and figure 2.4 (18 pole machine).

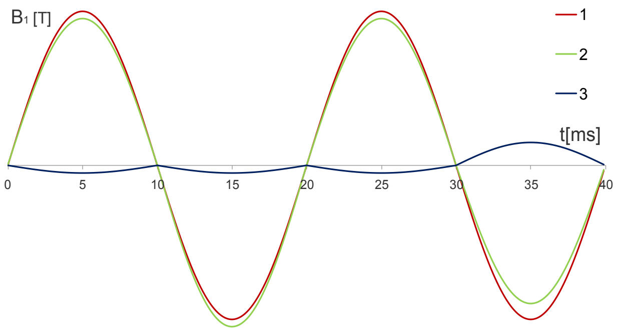

Figure 2.3. Influence of the decrease in the number of pole winding turns to the flux density basic harmonic of the rest of poles in 4 pole machines: Curve 1- without decrease of pole winding turns, Curve 2- with 10% decrease in pole winding turns, Curve 3 – flux density basic harmonic change.

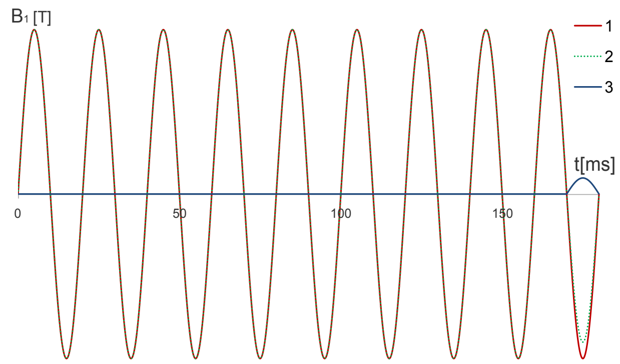

Figure 2.4. Influence of the decrease in the number of pole winding turns to the flux density basic harmonic of the rest of poles in 18 pole machines: Curve 1- without decrease of field winding turns, Curve 2- with 10% decrease of pole winding turns, Curve 3 – flux density basic harmonic change.

Determination of reduced number of turns (inter-turn short circuits) of the pole can be based on analysis of induction wave form amplitude change in time domain. But for this method to be reliable enough, and for making of any appropriate conclusions, frequency composition of the wave form should be analyzed as well, or in other words, a continuous frequency analysis is to be performed. On the basis of changes in the harmonic composition of the analyzed flux density wave form, it can be unambiguously determined whether the number of turns in any of field winding coils is reduced, or, in other words, whether inter-turn short circuits are present in any of them. Figure 2.5 shows a frequency analysis of flux density in the pole pitch of the pole number 4 and the pole number 2, that are shown in Figure 2.2.

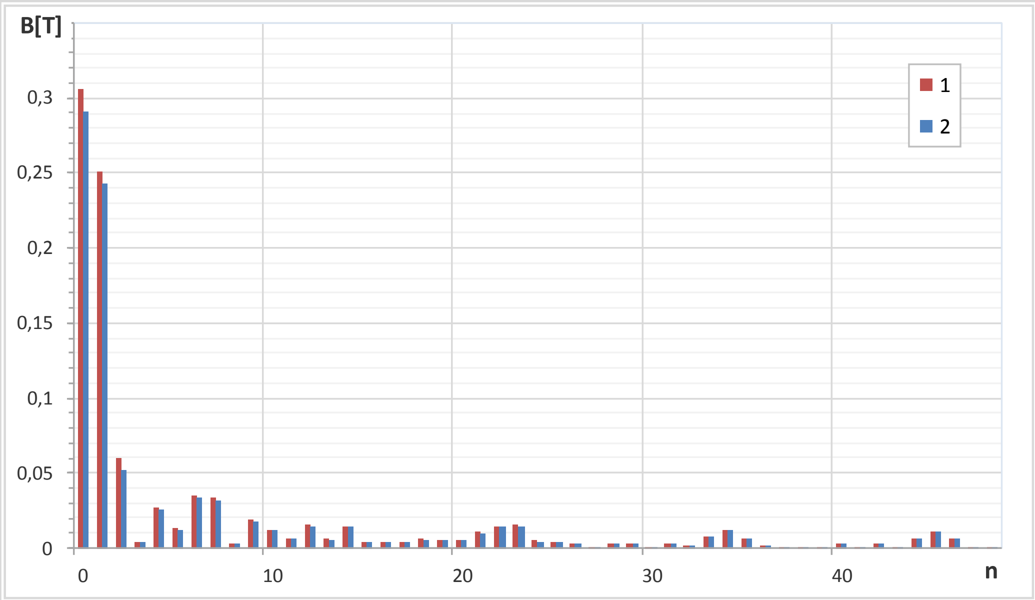

Figure 2.5. Frequency analysis of flux density in the pole pitch: 1- for the pole number 2; 2 – for the pole number 4.

From the data shown in Figure 2.5 it can be seen that the change of the pole winding turns number does not influence all the expressed harmonic terms in the same way. Based on the calculation results, it is determined that at different values of the field current, and at different percentage of the pole winding number decrease, the change of amplitudes of individual expressed harmonic terms is not harmonized with the given expressions, i.e. it is not foreseeable. Therefore the presence of the pole winding number decrease shall be indicated only by those harmonic terms for which the amplitude change, is in accordance with conclusions and expressions made earlier in the text. For the analyzed generator, the zero, the first and the second harmonic term, as well as harmonic terms caused by the damping winding and its higher harmonics, were selected as regarding indicators of field winding number change of the pole. The amplitude change of selected harmonic terms, caused by a reduction of the field winding turns of the pole is shown in table 2.2.

Table 2.2. Amplitude changes of selected harmonic terms caused by the reduction of the amount of field winding turns of the pole by 10 %.

Harmonic number	Change in amplitude Δ A[%]
0	-10,3
1	-9,9
2	-11,1
6	-10,1

Harmonic number	Change in amplitude Δ A[%]
7	-11,3
12	-10,1
14	-11,9

Results of the frequency analysis of the flux density wave form shown in Figure 2.5 and in Table 2.2 are obtained for the time period corresponding to the pole pitch τ_p. Figure 2.1 on the other hand shows that if there is a field winding number reduction of one of the poles, the first and the third harmonic term will be significantly changed when the frequency analysis is performed on the time period, i.e. if it is performed for the whole revolution of the generator rotor. Results of the change of the first and the third harmonic term are shown in Table 2.3.

Table 2.3. Presentation of changes of amplitudes of the first and the third harmonic terms caused by a decrease of the number of turns of the pole by 10 % obtained in a frequency analysis performed during a time period

Harmonic number	Amplitude B [T]	
	Without the reduction of turns of the pole	With reduction of turns of the pole by 10 %
1	0.000034	0.0142
3	0.00025	0.0094

A significant change of the first and the third harmonic term is caused by a shift of the flux density wave form, i.e. shift of the MMF shown in Figure 2.1. This causes the wave form having theoretical zero mean value for the time period, of the machine with ideal geometry, to become different from zero when a pole winding turns reduction is present. Due to imperfections of the real machine, the theoretical mean value is different from zero, but is still lower by at least one order of magnitude, compared to the mean value of the case when the number of turns is reduced. The change of the mean value, when the number of turns is reduced, is mostly expressed through the first and the third harmonic term for machine with 4 poles. Therefore this change in the value of the first and the third harmonic term, obtained by the FFT analysis, can be used for detection of the reduced number of field winding coils, in addition to other stated indicators. Figure 2.6 shows a frequency analysis of flux density, performed during a time period, with and without field winding turns decrease of the pole.

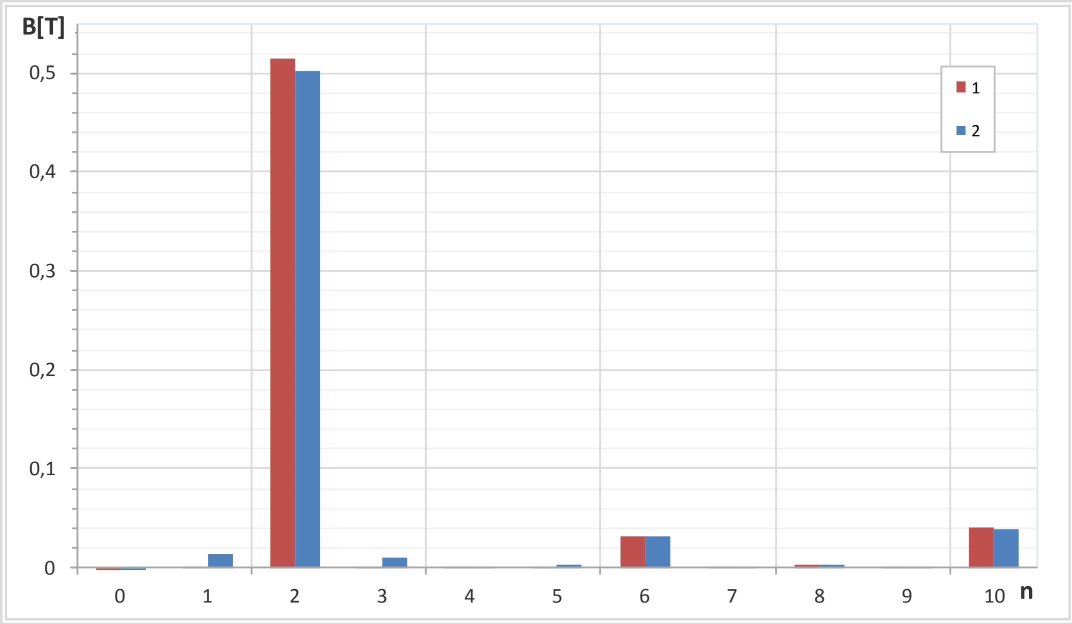

Figure 2.6. Frequency analysis of flux density performed during a time period; 1 – without decrease in the number of turns of the pole, with 10% decrease in the number of turns of the pole.

3. Conclusion

This paper describes a new method of detection of inter-turn short circuits of the field winding in a synchronous generator with the concentrated field winding coils. The method is based on results of FEM magnetic field analysis supported by MagNet Infolytica software, and can be applied to a wide range of synchronous generators and motors. Measurement of generator air gap flux density is required on a real machine in order to detect inter-turn short circuits of field winding coils. This can be performed by a Hall's sensor integrated on the dynamo lamination of the stator core tooth. Measured data should be collected by an appropriate monitoring system and processed in a corresponding way. Based on the conclusions of this paper, the monitoring system can detect inter-turn short circuits of excitation winding coils in the monitored machine.

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