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PHYSICAL PHENOMENA EXISTING IN THE TURBOGENERATOR DURING FAULTY SYNCHRONIZATION WITH INVERSE PHASE SEQUENCE*

ADAM GOZDOWIAK, PIOTR KISIELEWSKI, LUDWIK ANTAL

Wrocław University of Science and Technology, Department of Electrical Machines, Drives and Measurements, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland,
e-mail: adam.gozdowiak@pwr.edu.pl, piotr.kisielewski@pwr.edu.pl, ludwik.antal@pwr.edu.pl

Abstract: The present paper shows the simulation results of turbogenerator faulty synchronization with inverse phase sequence. Great emphasis is placed on the physical phenomena existing in the rotor because the measurement of rotor damper bar currents is difficult in practice. There are presented the comparisons of maximum magnitudes of stator current and electromagnetic torque determined during faulty synchronization with maximum magnitudes designated during sudden short circuit after both no-load and rated operation condition. In addition, the effect of synchronizing limits on faulty synchronization is presented.

Keywords: *turbogenerator, faulty synchronization, inverse phase sequence, finite element method*

1. INTRODUCTION

An occurrence of faulty turbogenerator synchronization is probable [1], [2]. The most dangerous case is faulty synchronization with inverse phase sequence. This incident can occur when one phase is connected correctly and is used only in synchronization device whereas the rest of two phases are inversely connected on account of a change in installation. Another reason is whether the cords coming to synchronization device are connected to incorrect terminals. This accident could happen after some modifications inside the installation without performing inspection.

Synchronization of turbogenerator to the grid must be performed carefully. The rotor speed and terminal voltages of isolated turbogenerator must be closely matched. Whereas stator voltage phase angle must be close to the instantaneous grid voltage phase angle prior to closing the breaker to connect the isolated turbogenerator to the grid.

Poor synchronizing can cause the following dangerous incidents:

– damage to the turbogenerator and step-up transformer windings caused by high currents which are significantly above the acceptable limits,

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– damage to both the turbogenerator rotor and the turbine because of high mechanical stresses caused by rapid acceleration or deceleration,
– huge power oscillation and voltage deviations from nominal level,
– tripping the turbogenerator from the power system resulting from the protection activation because power protection devices can interpret the accidents that occurred as abnormal operation states.

The instantaneous currents associated with a severely faulty synchronization can exceed three-phase short circuit fault. Large electromagnetic forces occurring in the turbogenerator and step-up transformer windings can lead to damage of windings as well as lead to catastrophic failure and consequently to reduce turbogenerator life time.

The goal of the research performed is to show the phenomena existing in the rotor damping bar during faulty synchronization and determine an impact of faulty synchronizing on the power system.

Previous analyses of faulty synchronization were based on a circuit model which allowed the maximum values of electromagnetic torque and armature current to be determined. This method could not reflect the saturation effect in rotor and stator cores nor the phenomena occurring inside the conductive parts of turbogenerator rotor [3]–[5]. The finite element method utilized in this paper allows us to reflect all of the phenomena mentioned above during the computation process.

In the paper, great emphasis is placed on computations of electromagnetic torque, stator current amplitudes, negative sequence of stator current and current flowing inside the rotor wedges which constitute the rotor cage. Additionally, different synchronizing limits such as voltage variation and frequency differences are taken into account during the computations. Those limits are defined in a rule [6]. The results obtained are compared with the results coming from sudden short circuit during no-load as well as rated operation condition.

2. ASSUMPTIONS TAKEN INTO ACCOUNT DURING SIMULATIONS

For the purpose of the analysis, a field-circuit model of the turbogenerator was utilized. The model was checked and its electromagnetic parameters were compared with the data obtained from the running test. These comparisons are published in articles [6]–[8]. The two-dimensional model possesses both the field and circuit part. A cross-section of the field part is shown in Fig. 1. In this model, a real distribution of stator and rotor windings as well as the damper windings were reflected. Besides the non-linearity of magnetizing curves for stator and rotor cores were implemented. In addition, the model contains the feature of the displacements of current in the rotor wedges and in the solid rotor as well. More information about field-circuit modelling of the turbogenerator can be found in [7]. The field model is coupled with a circuit model in which the resistances and the inductances representing the end-windings of stator and rotor are included.

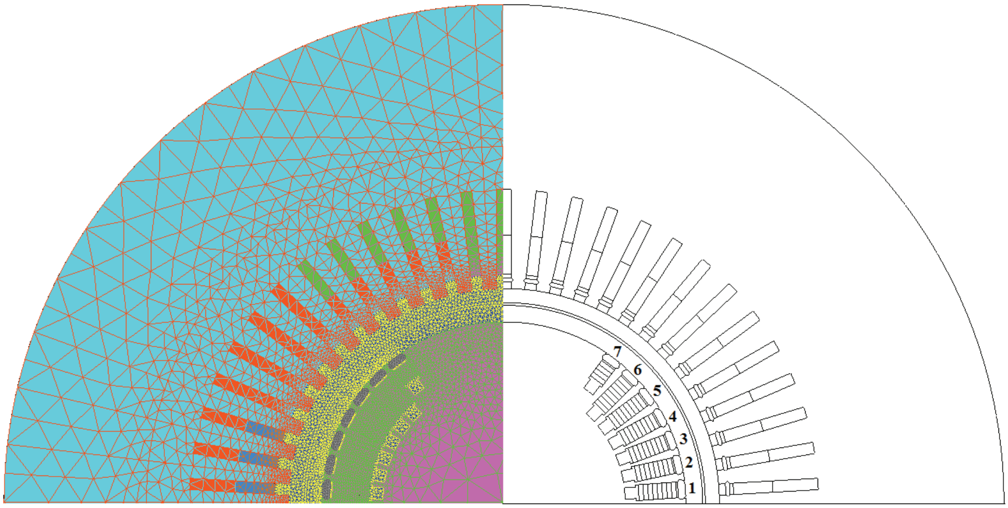

Fig. 1. Field part of turbogenerator model

The turbogenerator investigated possesses 2 poles and 2 parallel circuits in the armature winding. The technical data are gathered in Table 1.

Table 1. Main technical data of investigated turbogenerator

Name of turbogenerator technical data	Value	Unit
Rated apparent power	500	MVA
Rated terminal voltage	21	kV
Rated armature current	13.75	kA
Rated power factor	0.80	–
Rated field current	4.5	kA
Number of poles	2	–
Rated torque	1.273	MNm

The circuit model was expanded by the step-up transformer and the grid impedances computed for the strong power system (S_{kQ} = 15000 MVA) in order to reflect the inductances effect for the power and voltage oscillations and turbogenerator stability.

3. COMPUTATION RESULTS

3.1. FAULTY SYNCHRONIZATION WITH INVERSE PHASE SEQUENCE

The inverse phase sequence is simulated as a change of two phases during synchronization. The calculation results of faulty synchronization are presented in Figs. 2–11. In this investigation, before the synchronization process, the RMS value of terminal voltage is the same as voltage in the grid, whereas the rotor slip equals zero. The time step of computations is 0.2 ms.

On account of inverse two phases, huge stator current appears and therefore a huge amount of electromagnetic torque exists. This results from fact that two phases are shifted by 120 degrees. Maximum instantaneous amounts of waveforms determined are presented in Table 2.

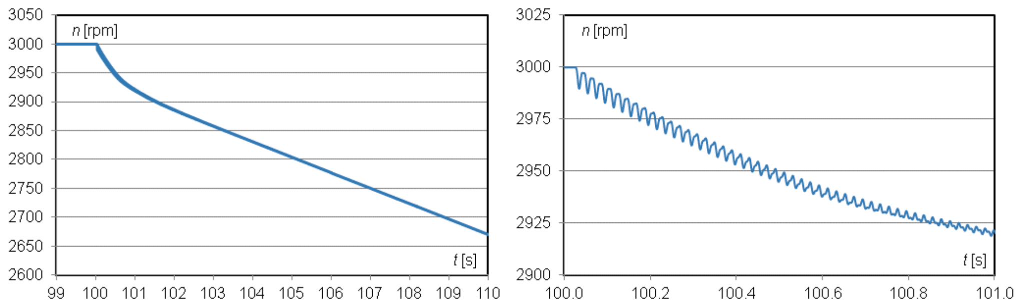

Fig. 2. Rotor velocity

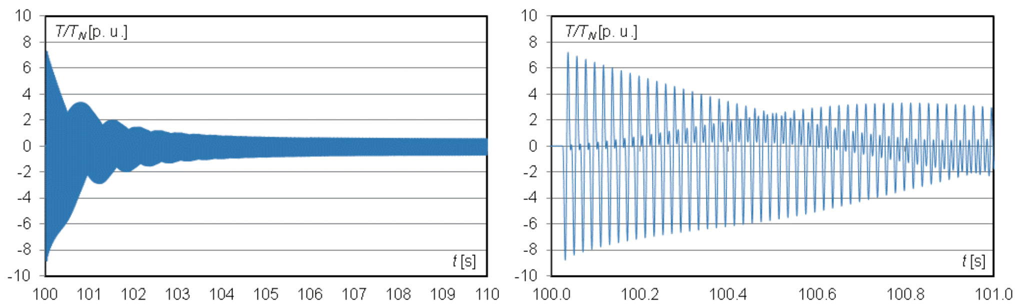

Fig. 3. Electromagnetic torque

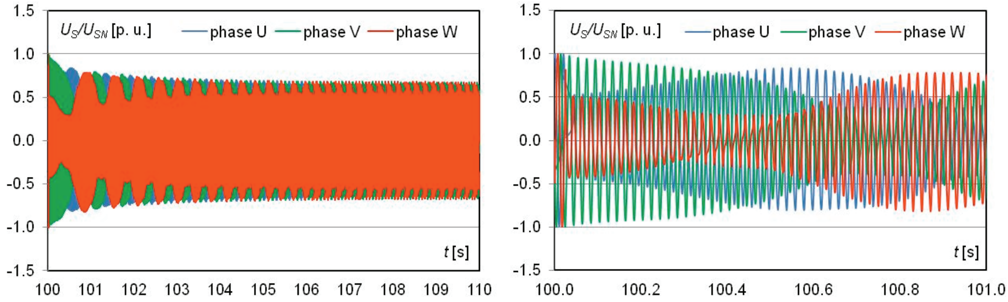

Fig. 4. Terminal voltage waveform in each phase

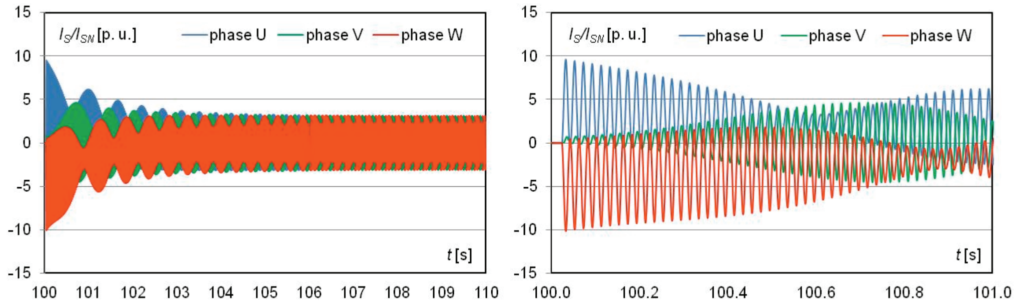

Fig. 5. Stator current waveform in each phase

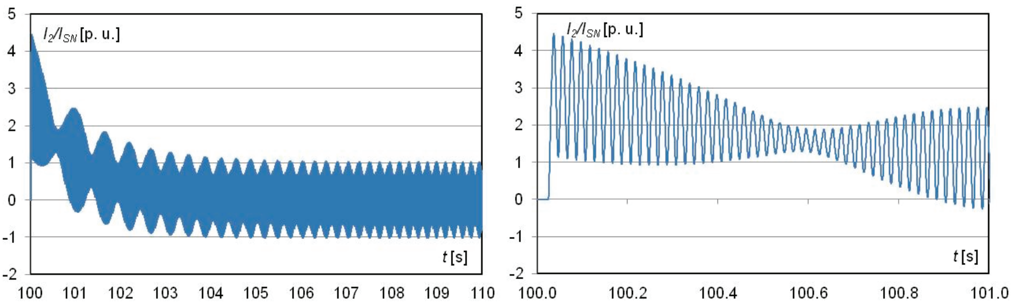

Fig. 6. Negative sequence of stator current

Huge amount of negative sequence of stator current causes that huge currents with double grid frequency, $2f_N$, are induced in the rotor wedges, solid rotor shaft and in field winding. The waveforms of these currents are shown in Figs. 7–9. The most vulnerable construction element is rotor wedge number 7 localized near to rotor big edge, see Fig. 1. Current flows in each of the rotor wedges investigated are presented in Fig. 9.

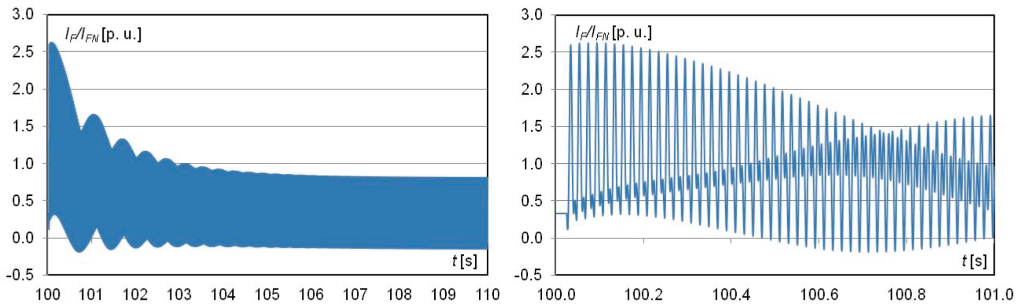

Fig. 7. Field current waveform

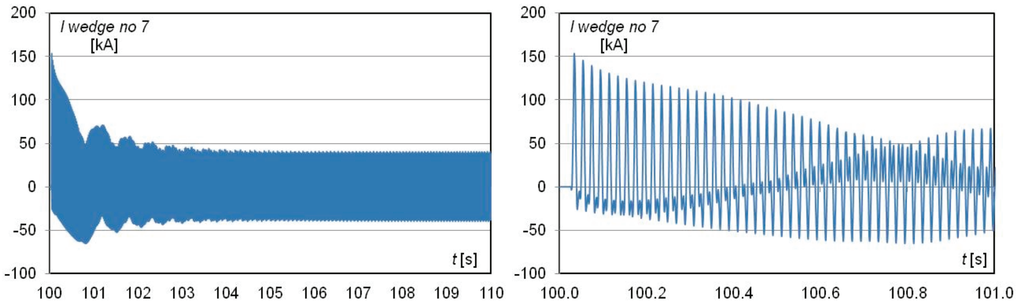

Fig. 8. Current waveform in the rotor wedge no. 7

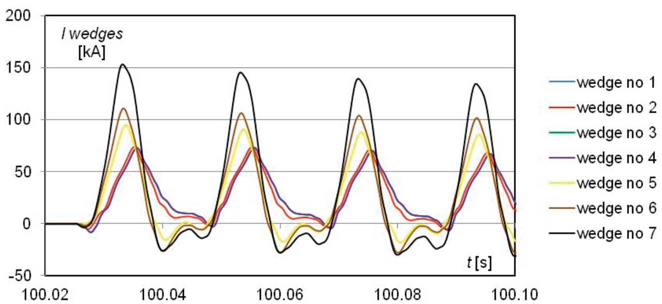

Fig. 9. Current waveforms in the rotor wedges

Additionally, the absorbed active power and reactive power from the power system are determined by using measurement algorithms, as shown in Figs. 10 and 11, respectively.

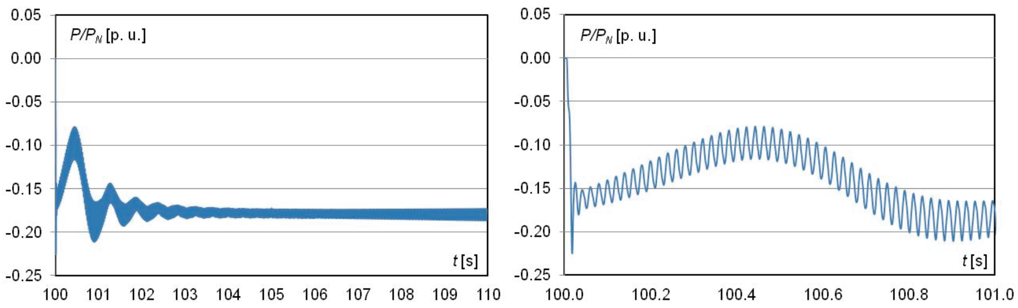

Fig. 10. Active power absorbed from the power system

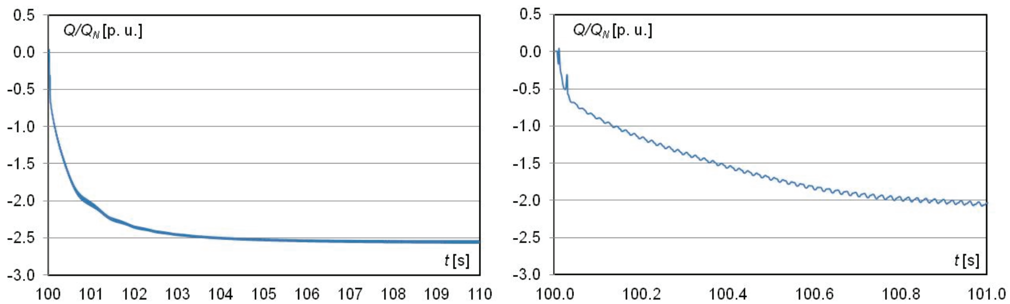

Fig. 11. Reactive power absorbed from the power system

3.2. SIMULATION RESULTS

The turbogenerator is designed to sustain the instantaneous stator currents and the shaft torques resulting from the three phase short circuit at the terminals. In this place, the different cases under study are presented in order to show the highest threats existing during faulty synchronization with inverse phase sequence. The calculation results are summarized in Table 2 for all the cases investigated.

Computed maximum instantaneous amplitude of electromagnetic torque equals $8.82T_N$ during faulty synchronization with inverse phase sequence. Whereas in the case of a sudden three phase short circuit at no-load at U_N, the maximum amplitude of electromagnetic torque equals $3.65T_N$. This means that the torque that appeared during faulty synchronization is 2.4 times higher. Additionally, a sudden three phase short circuit during rated operation condition was considered. This case is unrealistic because in the power plant the connection phases coming from the turbogenerator terminals which are connected to step-up transformer are isolated from each other. Even in this case the maximum amplitude of electromagnetic torque is lower than in the case of faulty synchronization being investigated and equals $8.31T_N$ despite the fact that the maximum amplitude of the stator current is the highest. The description of physical phenomena existing during sudden short circuit based on finite element method can be found in [9].

Table. 2. Instantaneous amplitudes of determined waveforms during the simulation

Cases under study		T_{MAX} [p.u.]	$U_{S\,MIN}$ [p.u.]	$I_{S\,MAX}$ [p.u.]	$I_{2\,MAX}$ [p.u.]	$I_{F\,MAX}$ [p.u.]	$I_{W7\,MAX}$ [kA]	P_{MAX} [p.u.]
1	Faulty synchronization with inverse phase sequence at U_N and slip = 0	8.82	0.23	10.10	4.46	2.62	152.84	0.23
2	Faulty synchronization with inverse phase sequence at $1.05U_N$ and slip = 0	9.32	0.21	9.88	3.17	2.69	154.93	1.18
3	Faulty synchronization with inverse phase sequence at U_N and n = 2996 rpm	9.05	0.20	10.71	5.04	2.66	158.15	0.22
4	Faulty synchronization with inverse phase sequence at U_N and n = 3004 rpm	8.81	0.23	10.42	4.27	2.62	154.51	0.49
5	Sudden three phase short circuit at no-load at U_N	3.65		6.03			88.75	
6	Sudden three phase short circuit at rated operation condition	8.31		11.82			129.18	

The rule in [10] presents the following synchronizing limits: breaker closing angle, generator side voltage relative to system and frequency difference. The latter two are taken into account during investigations. The computed results are included also in Table 2. The maximum voltage deviation is 5%, whereas this voltage cannot be lower than U_N in order to avoid the reactive power being absorbed by the turbogenerator. Therefore, the maximum acceptable voltage used equals $1.05U_N$. An increase of terminal voltage causes an increase of maximum electromagnetic torque and a decrease of maximum stator current amplitude.

Acceptable frequency difference is in the range from –0.067 to 0.067 Hz. It means that acceptable speed difference is ±4 rpm. There is an increase of stator current amplitudes for both lower and higher speed than synchronous speed. Whereas lower speed contributes to appearance of higher maximum electromagnetic torque.

The highest stator current amplitude and thereby the highest instantaneous negative sequence of stator current was recorded in the case of lower speed than synchronous speed. Higher negative sequence of stator current has an impact of induced current in the conductive parts of the rotor. There is a huge risk of the retaining ring damage.

4. CONCLUSIONS

The simulation study of turbogenerator behavior in the power system by using finite element method allows us to reflect the real physical phenomena existing inside the turbogenerator.

Faulty synchronization with inverse phase sequence causes an appearance of higher electromagnetic torque than in the case of a sudden short circuit and thereby huge mechanical stresses which can lead to the rotor shaft damage. The most vulnerable construction element is rotor wedge number 7 localized near to the rotor big edge. This conclusion is proper for all the cases investigated. Huge inducted currents in the conductive parts of the rotor which appear on account of stator current negative sequence can cause failure of the retaining ring.

The worst case is for $1.05U_N$ (2nd investigated case, Table 2) from the point of view of the mechanical stress. Whereas from the thermal point of view, the worst case is when speed is below synchronous speed (3rd case, Table 2).

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