Vol. 2(37), No. 1, 2017 DOI: 10.5277/PED170104

# FINITE-ELEMENT ANALYSIS OF ACCIDENTAL ENERGIZING OF AN OFF-LINE TURBOGENERATOR*

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**Abstract:** The computation of accidental energizing of an off-line turbogenerator has been conducted. Inadvertent energizing of a turbogenerator has become a particular issue in a power plant. The investigated case is three phase energizing. Great emphasis is placed on physical phenomena occurring in the rotor. The results of computations allow one to indicate the risks of damages of construction elements and can confirm the limits of the values set in dedicated protection devices.

**Keywords:** *turbogenerator, off-line inadvertent energizing, finite-element method, abnormal operation state*

## 1. INTRODUCTION

Over the years, several cases of inadvertent energizing of turbogenerators occurred. One of them was described in [1]. The main reason of accidental energizing is human error caused or contributed to the event. Further ones are operating errors, control circuit malfunctions, and breaker head flashovers [2, 3]. When a turbogenerator is energized while off-line at a standstill, it behaves as an induction motor and can be damaged within a few seconds. Steam or gas turbines can be damaged as well. The cost of appeared incident is not only the cost of repair construction elements or replacement of destroyed turbogenerator but the considerable cost of purchasing replacement power during the time when the unit is out-of-service.

Some connection designs allow one to provide flexibility to take out-of-service a single high voltage generator breaker and thereby a turbogenerator being off-line is isolated from the power system through an only open high voltage disconnect switch. There is many incidents in which high voltage disconnect switches are opened in order to provide the isolation between the turbogenerator and power system. Despite the fact that the interlocks are inserted between the generator breaker and disconnect switch to

*Manuscript received: January 26, 2017; accepted: March 25, 2017.

prevent accidental switch closure, the number of accidents coming from accidentally energized through this disconnect switch during off-line is not small [4].

The protection device used to detect accidental energizing is a voltage supervised overcurrent relay [4, 5]. This device utilizes voltage relays to supervise the output high-speed instantaneous phase overcurrent relays to provide inadvertent energizing protection. The overcurrent relays are automatically armed when the turbogenerator is off-line and remain armed while the turbogenerator is shut down. They are automatically removed from service when the unit is on line. The overcurrent relays are set to respond to current seen during an accidental energization. Undervoltage relays enable or disable current detectors through time delay relays. They are often set at 85% of rated terminal voltage and run the overcurrent tripping when voltage falls below the mentioned value when the turbogenerator is out-of-service. Additionally, they are equipped with a timer set with a sufficient delay (generally 2 s) to prevent overcurrent relays.

The goal of the performed research was to show phenomena existing in rotor damping bars during inadvertent three-phase energizing and showing the most vulnerable elements of the turbogenerator construction. During this analysis, great emphasis was placed on computations of electromagnetic torque, stator current amplitudes and showing the waves of physical quantities. Papers on such research are scarce because previous analyses of abnormal operation states of turbogenerators were performed by the circuit method without investigations of phenomena existing in the rotor. This article presents of the results of computation performed by the finite element method allowing investigation of the physical phenomena occurring in a turbogenerator rotor with satisfying accuracy [6–8].

## 2. INVESTIGATED TURBOGENERATOR

Main technical data of the investigated turbogenerator are given in Table 1. The computations were performed by using field-circuit model whose detailed description is presented in [12, 13]. The computations were performed by verified field-circuit model of turbogenerator which possesses field part reflecting the real distribution of stator and rotor windings as well as rotor wedges.

Table 1. Main technical data of the investigated turbogenerator

| Parameter | Value |
|---|---|
| Rated apparent power, MV·A | 500 |
| Rated terminal voltage, kV | 21 |
| Rated armature current, kA | 13.75 |
| Rated power factor | 0.80 |
| Rated field current, kA | 4.5 |
| Number of poles | 2 |
| Rated torque, MNm | 1.273 |

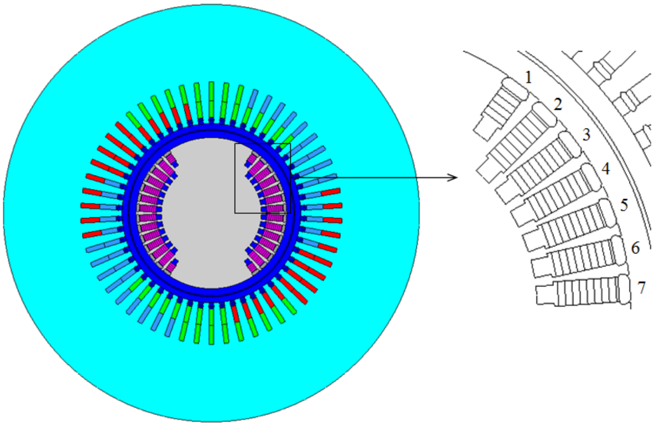


Fig. 1. Field part of the turbogenerator model with visible numeration of rotor wedges

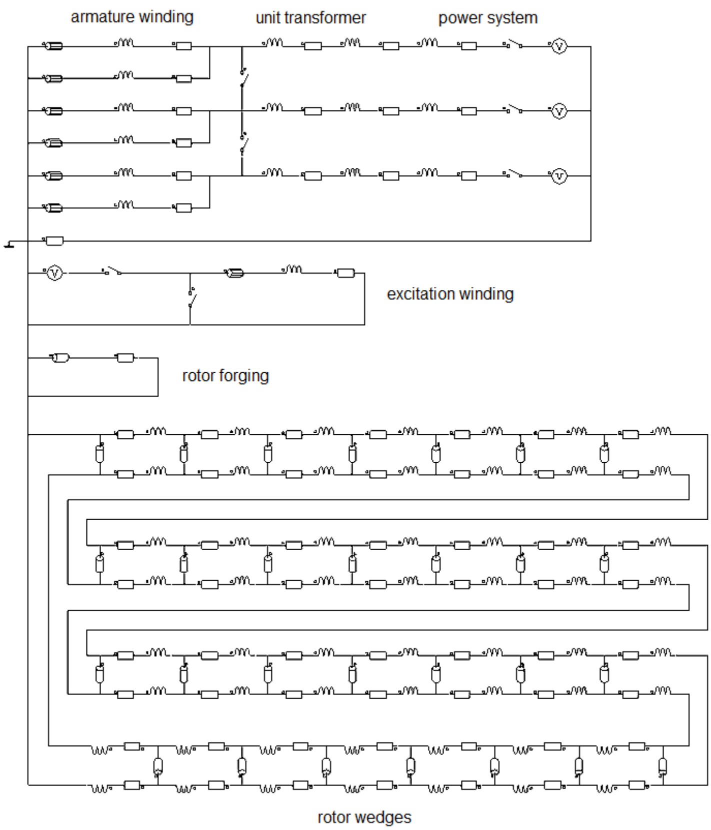


Fig. 2. Circuit part of the turbogenerator model

Circuit part contents the elements reflecting the windings and circuits existing in the field model and resistances and inductances which are the part of end-winding connections. The view of field model with visible numeration of rotor wedges is seen in Fig. 1. Rotor wedges and rotor forging represent the damping bars in this machine type.

The circuit model (Fig. 2) is expanded by the step-up transformer reactance and the grid reactance computed for the strong power system (SkQ″ = 15000 MVA) in order to reflect the real voltage drop. In the investigation there is assumed that the turbogenerator is connected to strong power system in order to reflect the worst case while stator currents are the highest in comparison with weak power system. The weak power system forces higher voltage drop and lower current which does not exceed rated value and thereby lower negative effect of appeared negative sequence of stator current. Assumed moment of inertia of a turbine and an exciter is 5 times higher than moment of inertia of turbogenerator rotor.

## 2. RESULTS OF COMPUTATION

Inadvertent energizing of the turbogenerator is simulated as a start, similarly as in the case of the induction motor. Three stator phases are supplied from the power system in order to research the worst case. The initial rotor speed equals zero, whereas field winding is opened. The simulation begins at $t = 0$ s. During the simulation, the turbine control system and excitation regulation are neglected in order to focus only on physical phenomena occurring in the turbogenerator during investigated abnormal operation state to present the worst case.

On-line energizing the turbogenerator to power system causes that it behaves as an induction motor. Flowing alternating current through the stator winding creates a magnetic flux coupled with the magnetic flux coming from the current inducted in rotor conductive parts (rotor wedges and rotor forging). Interaction between these fluxes contributes to an appearance of asynchronous torque sufficient to move the turbine-generator shaft from standstill and therefore the rotor starts to rotate and accelerates. The direction of rotation is the same as during normal generating operation. At the first moment, the electromagnetic torque reaches value of 1.5 TN whereas after ca. 1 s it decreases and stabilizes at a constant level of 0.15 TN. The high value of the electromagnetic torque and its oscillation frequency close to the grid frequency can lead to a considerable torsional moment which can damage the turbine-generator shaft, bearings, clutch and fan blades. Beside this, during the accelerating process, the rotor velocity can reach the resonance speed. The waves of rotor velocity and electromagnetic force are presented in Figs. 3 and 4, respectively.

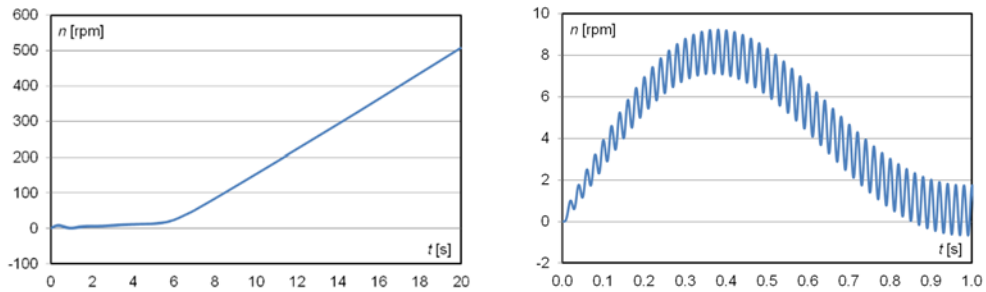


Fig. 3. Rotor velocity

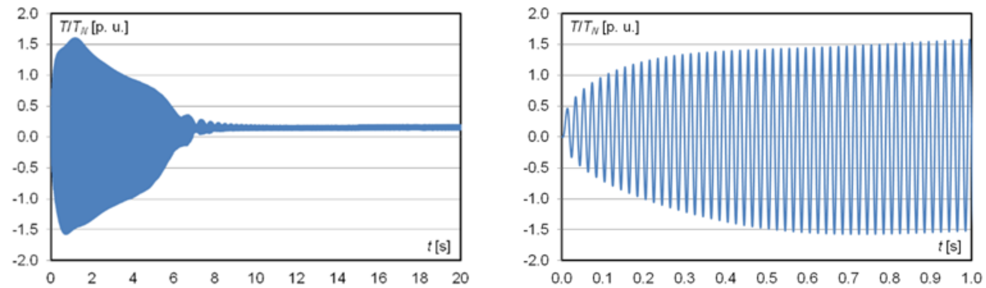


Fig. 4. Electromagnetic torque

The computed voltages at the turbogenerator terminals are equal to 0.6 USN and their waves are presented in Fig. 5. Obtained values of stator voltages are lower than the set value in undervoltage relay in the protection device, thus the simulation confirms the validity of assumptions. There is lack of the voltage oscillation. The computed maximum value of stator currents in the first period of the analyzed state equals 5.4$I_{SN}$ (Fig. 6). The obtained values of stator currents are higher than the set value in the overcurrent relay in the protection device thus the simulation confirms the validity of assumptions.

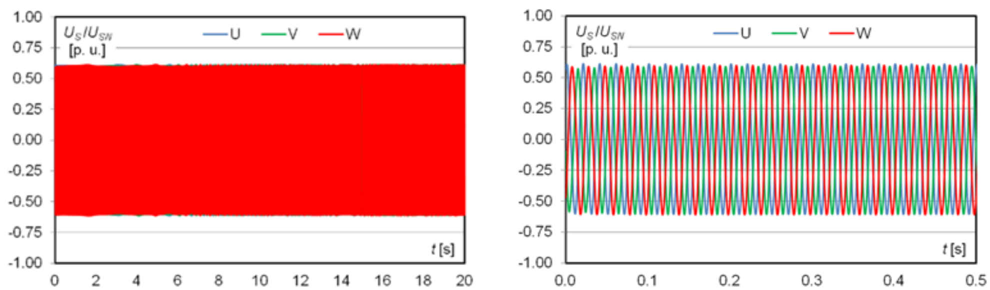


Fig. 5. Terminal voltage waves

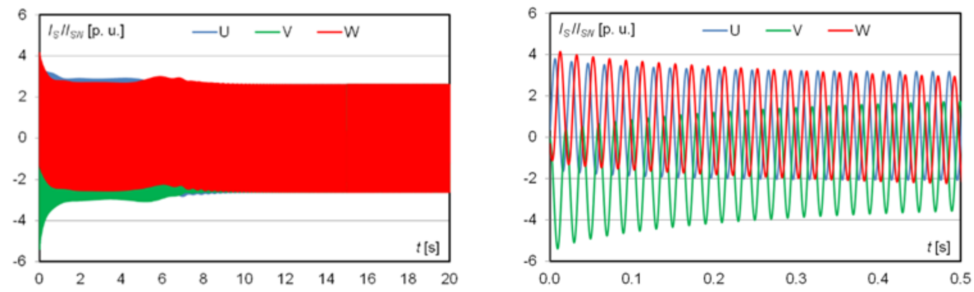


Fig. 6. Stator current waves

An off-line energizing turbogenerator for a long time leads to destabilization of the power system due to high absorption of active and reactive power. During this abnormal state, both absorbed active and reactive power are on constant levels and equal to $0.3P_N$ (ca. 120 MW) and $1.84Q_N$ (ca. 550 Mvar), respectively (Figs. 7a, b). Significant absorption of reactive power by the turbogenerator during inadvertent energizing can cause voltage drop in the power system. Absorbed reactive power is needed to magnetize the stator and rotor cores, whereas absorbed active power is utilized to cover losses in the windings.

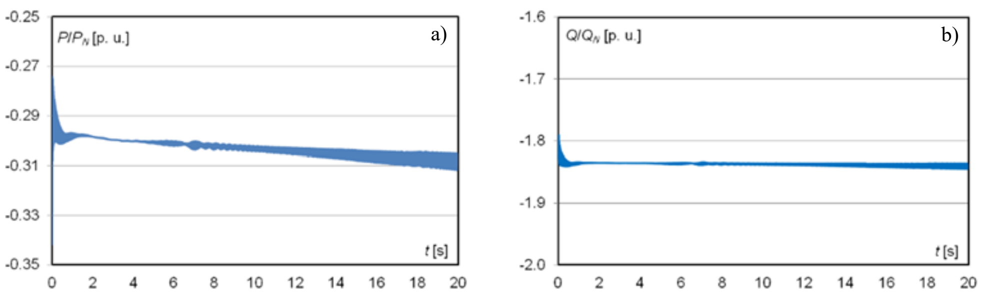


Fig. 7. Waves of absorbed active power (a), and absorbed reactive power (b) from the power system

When the turbogenerator is accidentally energized with three phase system voltage, the rotating flux appears at synchronous frequency and induces the current in the conductive parts of the rotor. The waves of currents in the chosen wedges are shown in Fig. 9. The most vulnerable construction element is wedge localized near to rotor big edge (wedge number 1 in the investigated turbogenerator, see Fig. 1) and the current wave existing in this wedge is presented in Fig. 8.

Induced huge magnitudes of currents in the rotor can cause rapid thermal heating in rotor wedges, rotor forging and retaining rings. Initially, these rotor currents possess the grid frequency but it decreases when the turbogenerator rotor speed increases due to induction motor action.

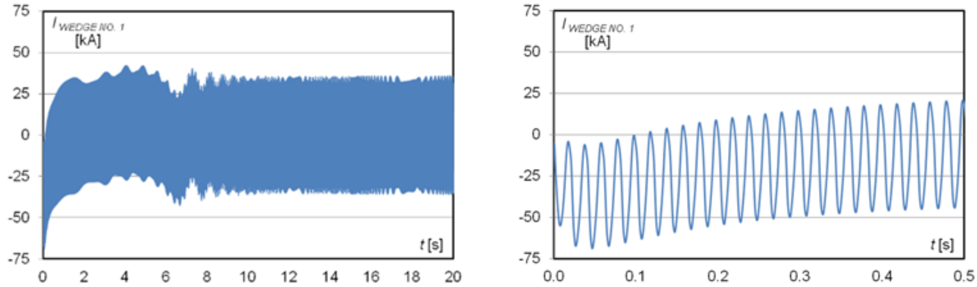


Fig. 8. Current wave in the rotor wedge No. 1 (localized near a big edge)

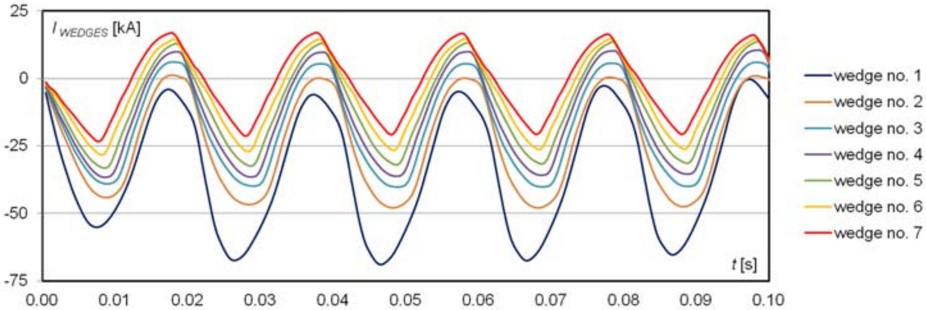


Fig. 9. Current waves in the rotor wedges

During inadvertent energizing of the turbogenerator, the field winding is opened and therefore voltage is induced on that. The wave of this voltage is shown in Fig. 10. Computed huge value of the field voltage can cause a surge.

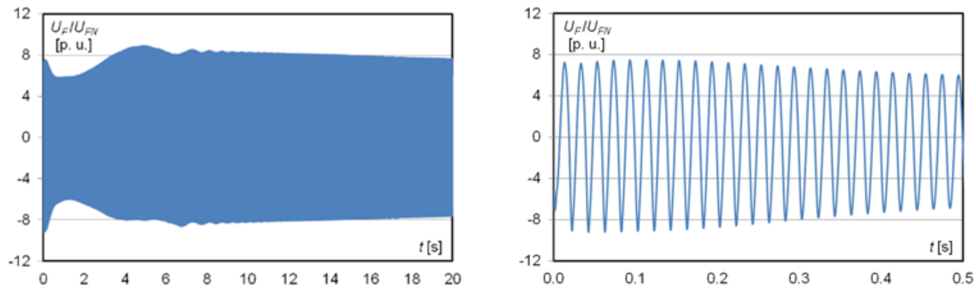


Fig. 10. Wave of inducted voltage on field winding

Flux lines for two rotor positions in direct and quadrature axes are presented in Figs. 11a, b, respectively, for first moment of inadvertent energizing. It can be seen that turbogenerator possesses inductive character in investigated abnormal operating state because windings resistance is negligible in comparison with reactance. The similar views of flux lines were noticed in case of sudden short circuit presented in [6]. At the first moment induced circulating currents in the conductive rotor parts do not allow penetrate inside the rotor – similar like in case of first period of sudden short circuit – subtransient state.

Flux densities for two rotor positions in direct and quadrature axes are presented in Figs. 12a, b, respectively. There are phenomena of magnetizing and demagnetizing of stator core. Demagnetization of stator core exists in direct axis and all flux lines penetrate to rotor surface on several millimeters and therefore strong saturation exists in this place, whereas in quadrature axis strong saturation exist in stator teeth.

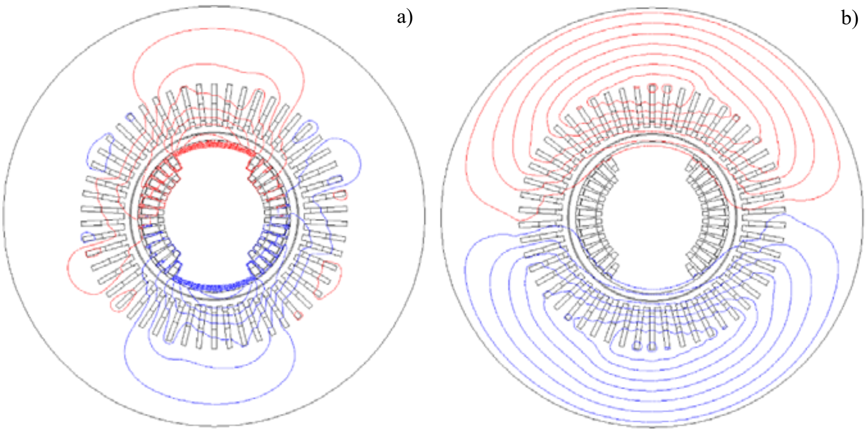


Fig. 11. Flux lines in direct (a) ($t$ = 0.02 s) and b) quadrature (b) ($t$ = 0.03 s) axes during inadvertent energizing

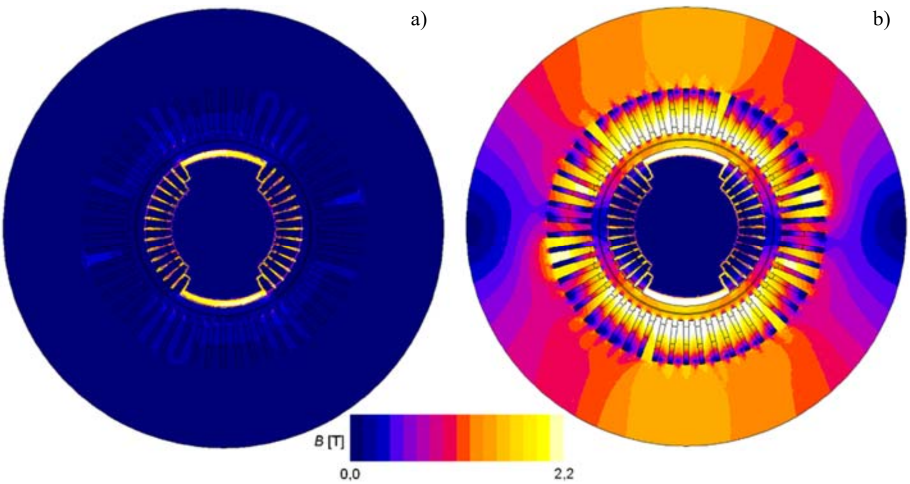


Fig. 12. Flux densities in direct (a) ($t$ = 0.02 s) and quadrature (b) ($t$ = 0.03 s) axes during inadvertent energizing

The induced currents in the conductive rotor parts occur up to several millimeters in rotor teeth and not deeper than ten of millimeters in the rotor big edge (in comparison, the rotor wedge height equals 22 mm). The higher depth of penetration of circulating current is noticed in the quadrature axis. Current densities in the rotor for direct and quadrature axes are shown in Figs. 13a, b, respectively.

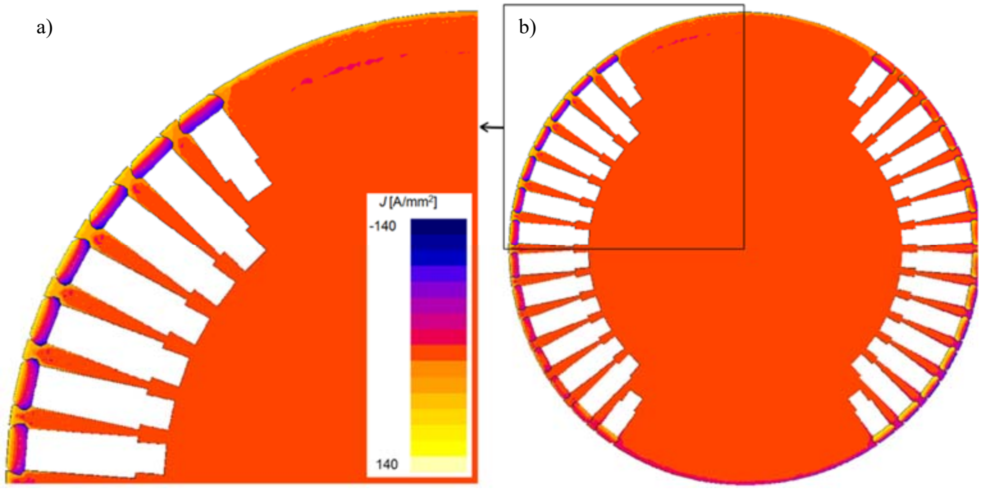


Fig. 13. Current densities in the conductive rotor parts in direct ($t$ = 0.02 s) (a) and quadrature (b) ($t$ = 0.03 s) axes during inadvertent energizing

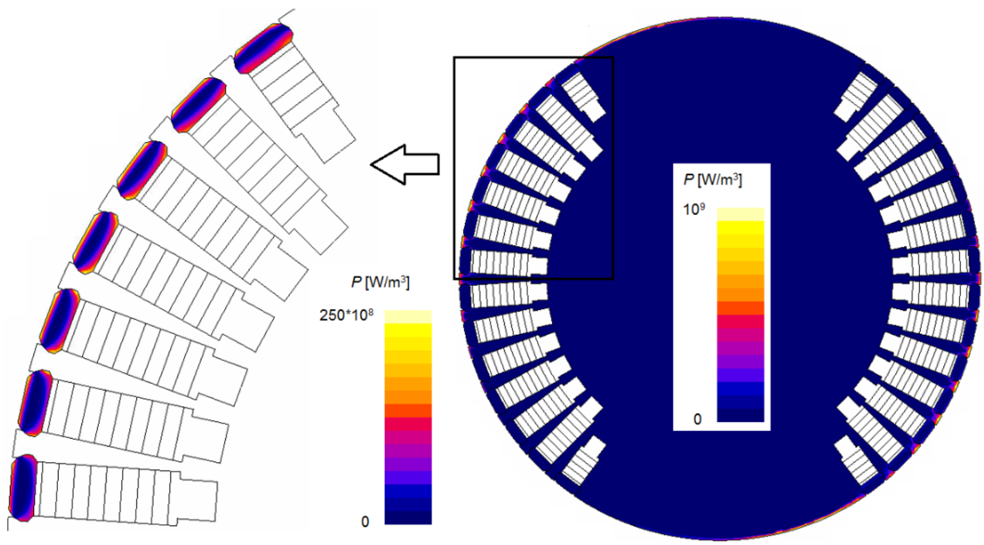


Fig. 14. Heat losses dissipation in the conductive rotor parts in direct axis during inadvertent energizing ($t$ = 0.02 s)

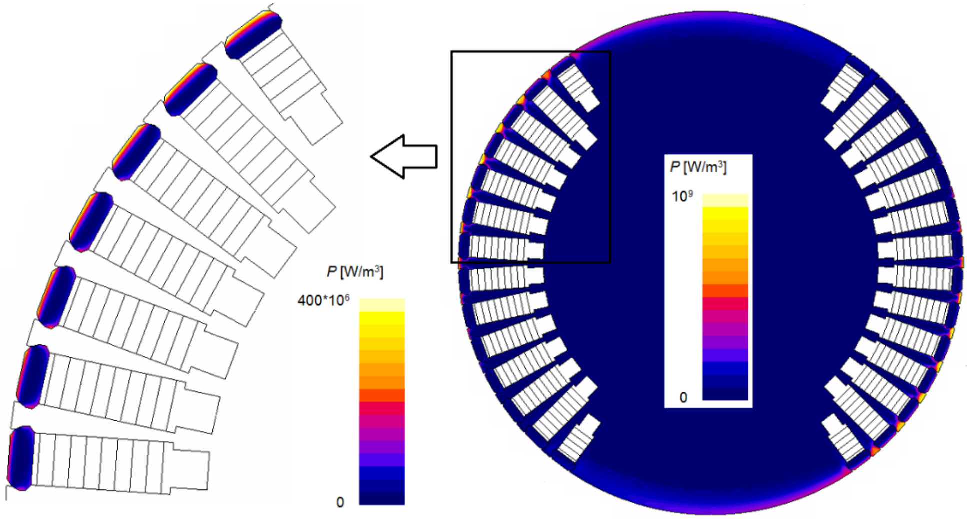


Fig. 15. Heat losses dissipation in the conductive rotor parts
in quadrature axis during inadvertent energizing ($t$ = 0.03 s)

Nowadays, it is believed that the failure of the coil winding due to high temperatures is unlikely since the currents induced in the forging of the rotor does not penetrate deeper than the height of the wedge and does not raise the temperature of field winding. Based on the distribution of current densities, there is impossible to clearly exclude overheating of the rotor winding. There is a possibility of mechanical damage as a result of the excitation winding falling fixing rings.

Based on the distribution of heat losses in rotor conductive parts (Figs. 14 and 15 for direct and quadrature axes) it could be possible to indicate the main sources of heat during inadvertent energizing. The largest heat sources come from rotor teeth of rotor forging. The densities of heat losses in these places are 2.5–4 times higher than in the rotor wedges.

## 3. DAMAGE DUE TO INADVERTENT ENERGIZING

An initial effect of inadvertent energizing a turbogenerator from standstill is rapid heating in iron paths near to the rotor surface. It results from lack of ventilation and cooling medium inside the machine off-line. The mentioned paths consist of the rotor wedges, rotor solid and retaining ring. The contact between these paths are points where exist huge temperatures due mainly to arcing. The arc heating can melt the metals and contribute to the weakening of the rotor wedges. If the tripping time is too long, it can contribute to failure.

There is a risk of damage of the field winding due to significant increase of temperature caused by huge value of induced circulating current in the rotor teeth on higher depth than the rotor wedge. Beside, this there is a risk of mechanical damage due to loss of wedge support.

The depth of current penetration is substantial less than the depth of the rotor winding (Fig. 13). Therefore, the damage of the rotor winding should not result from heating but rather from mechanical damage due to the loss of wedge support.

During the incident of inadvertent energizing, there is a risk that during acceleration, the turbogenerator reaches natural (torsional) frequencies. The computed rotor speed depends on the turbogenerator–turbine–exciter moment of inertia. Torsional torque can be very huge when the rotor speed corresponds to a natural frequency and can cause damage of the shaft. The huge stresses can lead to enormous vibration above the acceptable level, blade distortion, rubbing and finally can lead to turbine damage if the energizing source lasts so long.

In the case of lack of turning gear, the bearings on the shaft can be damaged due to insufficient lubrication because at standstill there is lack of the oil flow to the bearings.

## 4. CONCLUSIONS

The simulation of turbogenerator behavior in the power system by using the finite element method can confirm the risks occurring during inadvertent energizing reported elsewhere [1–5].

Inadvertent energizing of the turbogenerator can damage the machine if this abnormal operating state is not detected within a few seconds. Achieved results confirm set values in the protection device dedicated both overcurrent and undervoltage relays.

The most vulnerable element of the construction is the rotor wedge localized near to rotor big edge (wedge No. 1 in the investigated turbogenerator). The computed maximum density of the induced current in conductive rotor parts equals ca. 140 A/mm$^2$ (Figs. 13a, b), whereas the largest heat sources come from rotor teeth (Figs. 14 and 15).

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