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Influence of stator damper winding on magnetic and vibroacoustic parameters of turbogenerators

Abstract. *The increase of the load in modern turbogenerators causes higher local heating, higher magnetic leakage, increased forces of the electromagnetic origin and the increased acoustic noise level. Stator damper winding is an active cage-shaped constructive element positioned at the outer stator core diameter. Presented numerical calculations show that the stator damper winding can influence on the decrease of acoustic noise, electromagnetic forces between stator package and frame and additional losses.*

Streszczenie. *Zwiększanie obciążenia turbogeneratorów powoduje podwyższenie lokalnej temperatury, zwiększenie strumienia rozproszenia oraz zwiększenie poziomu szumów akustycznych. Uzwojenia tłumiące stojana jest dodatkowym elementem umieszczanym na zewnątrz rdzenia stojana. Zaprezentowano obliczenia numeryczne pokazujące jak to uzwojenie może wpływać na zmniejsznie szumów akustycznych oraz sił elektromagnetycznych między pakietem stojana a kadłubem. (**Wpływ uzwojenia tłumiącego stojana na magnetyczne i wiobroakustyczne parametry turbogeneratora**)*

Keywords: turbogenerators, numerical calculation, stator damper winding, acoustic noise
Słowa kluczowe: turbogenerator, szu my akustyczne, stojan..

Introduction

This paper treats two-pole and four-pole high-power turbogenerators. Constructive characteristics of turbogenerators [1], which determine their specifics compared with other rotation machines are:

- Cylindrical rotor body made in one piece from massive forging with open slots for the rotor windings;
- Concentric excitation rotor winding placed in the slots distributed across the rotor diameter;
- Rotor caps pulled over the rotor heads and leant on the rotor body
- Constant air gap;
- Big salience of the stator winding heads as a consequence of the winding pitch that equals approximately a half or a fourth of the stator diameter circle;
- Active parts of the stator are near the constructive parts of the frame.

Those constructive characteristics influence on the parameters of a turbogenerator as well as on the specific load in particular parts of the machine.

Development of modern turbogenerators is progressing in two main directions:

- Designs of air-cooled turbogenerators with rated powers as high as possible;
- Adoption of new limitations of rated powers, especially with four-pole turbogeneraters dedicated for nuclear power plants.

The problem of increasing specific magnetic loads in the same volume and at the same rotation speed can be solved in the following ways:

- With the application of materials with improved electromagnetic, mechanical and thermal characteristics;
- Application of new constructive elements;
    - A more accurate calculation of characteristic dimensions and optimization of the geometry.

The main purpose of this paper is to present an analysis of the influence of the stator damper winding at the electromagnetic parameters of turbogenerators, as well as its influence on the electromagnetic generation of the audible noise.

Stator damper winding

Stator damper winding is a new constructive element, and it was successfully applied in several designs of synchronous generators [2,3]. The effects of its application may be analyzed only with the application of numerical methods in the calculation [4]. It is placed along the stator diameter in appropriate slots, similarly to the cage of an induction machine. Electrically, there is a complete analogy. Constructively, it is in fact a mechanical fastening of the package in the frame. Stator package is in the generator frame fastened using bars, which are most commonly built in the form of dovetail. Bars are fastened to the rods, which are, depending on the type of construction, part of the frame or a corset. For more powerful turbogenerators, special technically demanding and expensive designs of the package elastic fastening in the frame are applied (elastic bars, special suspension, and similar). The cross-section of a bar, and their overall number is determined in mechanical calculation according to the maximal mechanical loading that may occur in the case of sudden two-phase short circuit.

These bars have to be made of a conductive material if they are used as the stator damper winding bars as well. Suitable material is the aluminum, which also have the favorable mechanical properties. For a complete damper winding (a cage), the bars are at the ends connected with a short-circuital ring. The choice of the cross-section is not forced by the electrical loading, i.e. with the current density across the cross section of the bars; however the choice of the number of the stator damper winding bars may influence the intensity and harmonic content of the electromagnetic force acting between package and the frame.

Equivalent circuits of stator damper winding

Parameters of a generator in some particular regime of the operation are analytically calculated using equivalent circuits of the generator [5,6]. They are shown for two axes, the direct-one *d*-axis) and for the quadrature axis (*q*-axis) using Park equations. Fig. 1 shows equivalent circuit of a generator with stator damper winding for the no-load condition in the direct axis, since exciter winding is placed and works only in that axis. The circuit elements show that regardless of the knowledge of the exciter and damper winding parameters (given with r_f, $x_{\sigma f}$, r_k, $x_{\sigma k}$) and magnetic conductivity of the air gap (given with x_m), it is not possible to calculate resistance of the iron r_{Fe} accurately enough.

To present the problem more clearly, it is necessary to start with the equivalent circuit of the stator damper winding depicted with the Fig. 2.

Network impedance is consisted of resistances ($r_{\text{št}}$ and r_{pr}), leakage reactance ($x_{\text{št}}$ and x_{pr}) of the bars and the short-circuital ring, and the mutual inductance M_{net} given with the magnetic flux linkage in other contours when the electric current flows only through one contour of the cage.

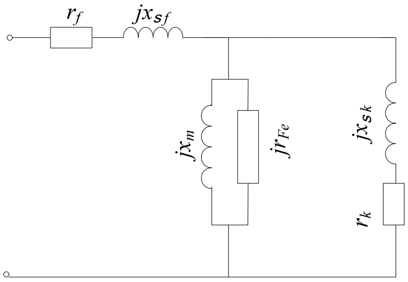

Fig. 1. Equivalent circuit of stator damper winding in *d*-axis

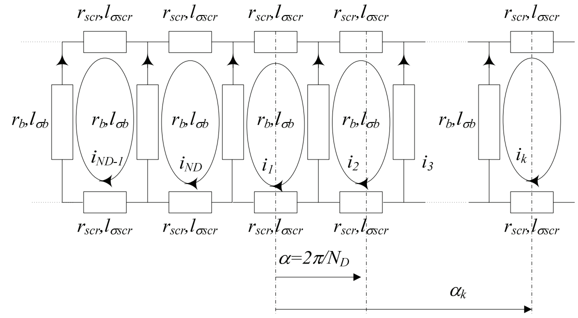

Fig. 2. Network of equivalent impedances of the damper winding

In Fig. 2. r_{scr} and $l_{\sigma scr}$ denote resistance and leakage inductance of the short-circuital ring; r_b and $l_{\sigma b}$ denote resistance and leakage inductance of the damper winding bars; i_1 – i_{ND} denote currents in circuits of N_D damper winding bars; $\alpha_k=k\cdot\alpha$ denote angles between a pole's line of symmetry and the line of symmetry of the *k*-th circuit.

The unknown variable that is to be solved in order to calculate the currents in the bars is the flux linkage of a particular contour. For the *k*-th contour we may write [1]:

$$0 = 2r_{scr}i_k + r_b(i_{(k-1)b} - i_{kb}) + \frac{d\psi_k}{dt} \tag{1}$$

Relation between current in bar and current in short-circuit ring is:

$$i_b = i_{scr}\, 2\sin\frac{p\pi}{N_D}\,. \tag{2}$$

The system of the matrix equations for the network depicted with the Fig.2 is, using the fact that the flux is linked with the currents sources of the exciter winding:

$$0 = \boldsymbol{R}_k\boldsymbol{i}_k + \frac{d\boldsymbol{\psi}_k}{dt} \tag{3a}$$

$$\boldsymbol{\psi}_k = \boldsymbol{L}_k i_k + \boldsymbol{L}_{kf}\boldsymbol{i}_f \tag{3b}$$

where $\boldsymbol{\Psi_k}$ denotes the vector of the cage flux linkage, $\boldsymbol{R_k}$ is the matrix of the resistances of the stator cage winding, $\boldsymbol{L_k}$ is the matrix of the inductances of the stator cage winding, $\boldsymbol{i_k}$ is the vector of the cage currents, $\boldsymbol{L_{kf}}$ is the matrix of the mutual inductances of the rotor winding and stator cage, $\boldsymbol{i_f}$ is the vector of the exciter currents.

Flux linkage of any current contour can be calculated using flux density across one slot pitch of the damper winding. In the space of the *k*-th contour this angle spans from α_k to α_{k+1} :

$$\psi_k = r \cdot L_i \sum_{n=1,n_B} \int_{\alpha_k+\omega t}^{\alpha_{k+1}+\omega t} \hat{B}\cos(m_n\theta + \theta_{0n} - \omega_{tn}t)d\theta \tag{4}$$

where φ_r denotes flux linkage of the *k*-th contour, *r* is the diameter of the cage, L_i is ideal length of the machine, ω is the synchronous angular velocity, *m* is the spatial order of harmonics, n_B is overall order of the flux density harmonics, $\hat{B}$ is the magnitude of the flux density in the air gap adapted to the penetration depth of the wave, θ_{0n} is the initial phase angle of the *n*-th harmonic, ω_{tn} is angular velocity of the wave expressed using spatial wave order and fundamental frequency.

The flux linkage Ψ_k can be determined for a known flux density *B*. With known parameters of the equivalent circuit of the active resistances and leakage inductances, the induced voltages and currents in the branches of the network shown with the Fig. 2 are calculated. The calculation can be performed accurately enough for the rotor damper winding, since the magnetic flux density in the air gap is known and dominant, e.g. the network branch with the resistance of the iron in the equivalent circuit shown with Fig.1 can easily be neglected.

The branch with the resistance R_{fe} cannot be neglected for the cage at the outer diameter of the stator. This means that the classical analytical procedure cannot be applied for the accurately enough determination of the flux linkage Ψ_k between two bars of the damper winding with the angles α_k i α_{k+1}.

It follows that for the stator damper winding only numerical methods [4] are capable to accurately determine the field and the flux linkage ψ_k at the outer diamater of the stator. Moreover, the equivalent circuits can be used only to for the calculation of the average currents in the damper winding bars, while a dynamical 2D simulation can be applied for the determination of the shape and the intensity of a current in each bar of the damper winding.

Numerical model for the calculation of the stator damper winding influence

The model of the turbogenerator used in calculation considers the bars of the stator damper winding as a whole with the frame. Between stator frame and stator yoke there is an air gap. This is real since an air gap exists between the insulated stator sheets of stator core and the stator damper winding bars and the frame. Separation of these two complex bodies allowed us to calculate forces. The material quality of each active turbogenerator part and its geometry is taken into account in 2D FEM models, which do not include the parameters of end winding parts. All numerical calculations were performed in software package MAGNET Infolytica. These parts are modeled in MAGNET as the external circuit linked to the 2D solid model, and lumped-parameter values for the leakage reactance and the active resistance of the end windings and short-circuital ring were added. For that purpose, the parameters r_{scr} and $l_{\sigma scr}$ of the network shown in Fig. 2 were calculated using analytical formulae [6]. In a real model, the air gap between package and the frame is very small in the regions between the package and the bars (in packaging tolerance below 0,5 mm). The corset practically rests on the package, and its weight is measured in tons for high power turbogenerators. For transition from the magnetically conductive medium into the air, the air gap thickness and the quality of the material on the opposite side of the air gap - in such a case, the frame, have a relatively small influence to the leakages. In the same time, values of the flux linkage in the frame and the losses caused this way are closely related to the value of magnetic flux density in the stator yoke, distance between the frame and the package, and with the presence of a damper winding, what shall be presented in more details later.

Fig. 3 shows magnetic flux density of a two-pole generator with the damper winding bars disconnected.

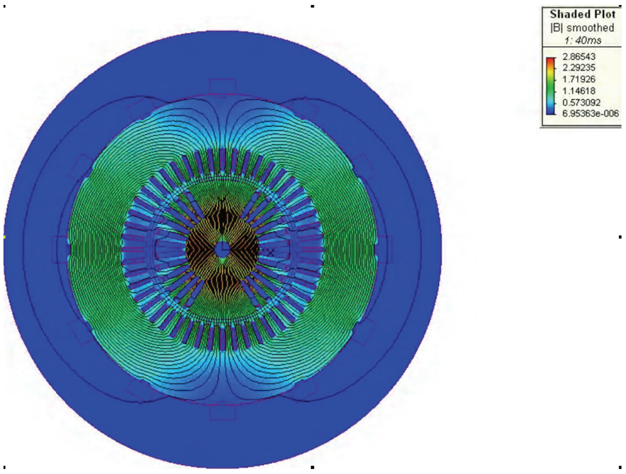

Fig. 3. Flux density of a two-pole generator with 48 stator slots and 12 disconnected damper winding bars (I_u=226 A)

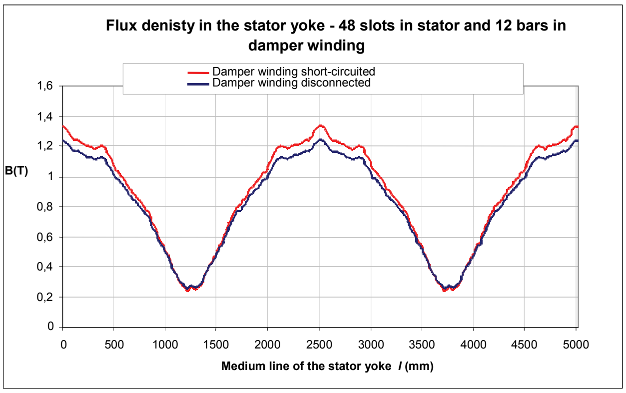

Fig. 4. Increase in the stator yoke's flux density with short-circuited damper winding

Fluxes and flux densities in stator winding yoke

The role of a stator damper winding, or its influence on the electromagnetic conditions in a turbogenerator can be divided in four fundamental groups:

- Decrease of the flux linkage in the stator frame
- Re-distribution of the flux into the area of smaller specific losses
- Decrease of the vibrations transferred from the package onto the frame and the noise of the electromagnetic origin – the stator damper winding serves as an elastic fixation of the package in the frame
- Decrease of the electromagnetic forces transferred in the generator foundation in the case of a sudden two-phase short circuit

The influence of the damper winding is analyzed in the models from the Table 1 for the following cases:

a) with the damper winding – short-circuited bars form the network depicted in Fig. 2

b) without the damper winding – the bars are disconnected

Fig. 4 compares the values of magnetic flux densities and fluxes at the medium line of the stator yoke and near the inner diameter of the frame, for a two-pole generator having 12 bars in the damper winding. For all the models, the exciter current is the same. Flux density in the frame is higher with disconnected damper winding because leakage flux is not pushed in the stator package as with the short-circuited damper winding (Fig. 5.) Similar conclusions are made for the models having 16 bars.

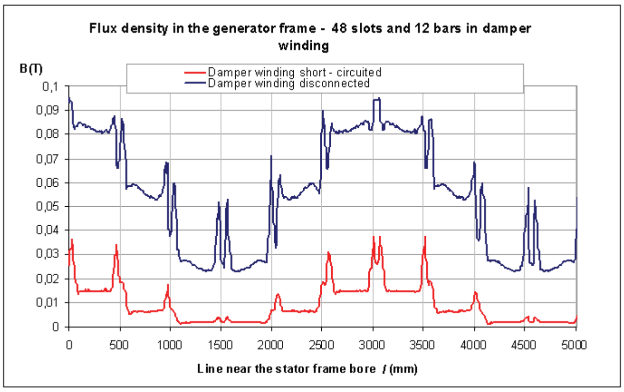

Fig. 5. Flux density in the frame is higher with disconnected damper winding

The calculations of a four-pole generator give the same relationships. In these models the air gap behind the frame package is significantly bigger since the simulated model was fastened by the corset. This caused absolute values of the flux linkages in the frame to be lesser, but the influence of the damper winding is similar. The exciter current was equal in all the calculations and settled on nominal excitation current of machine.

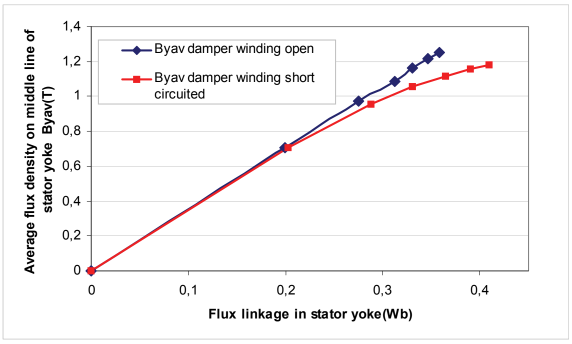

Fig. 6. No load magnetizing dependence in the middle of stator yoke for four pole generator with damper winding open and short circuited

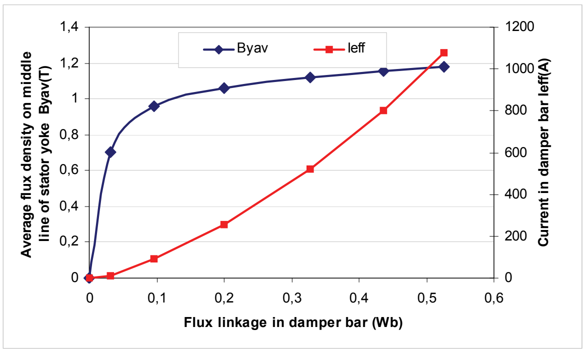

Fig. 7. Dependence of flux linkage and induced current in damper winding for different excitation current in four-pole generator

In the Figures 6 and 7, the dependence on different excitation current in field winding for parameters in stator yoke and stator damper winding is shown. When stator winding is short circuited for smaller value of excitation current the higher average flux density in yoke is induced. Due to linearization of function field density in stator yoke influence of air gap permanence can be reduced.

Forces between frame and the package and frequency spectrum

The unwanted acoustic radiation, or noise, generated by the electromagnetic origins is created in electric machines with the vibration of the stator package, caused by the magnetic forces. Radial vibration is present at the frequencies determined by the frequency spectrum of the exciting force, and its level is determined by the level of this exciting force and the mechanical properties of the stator package [7]. The sound pressure level in the free-field is finally determined by the vibration velocity, the efficiency of the machine as an acoustic emitter and its effective radiation area.

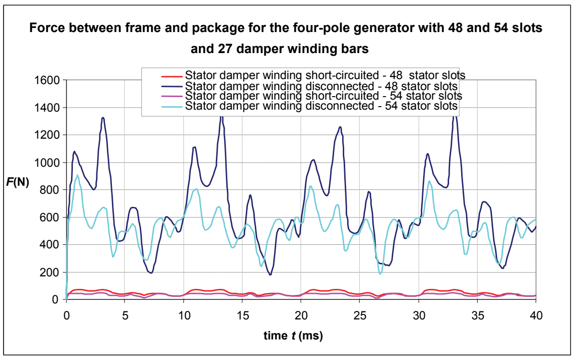

Fig. 8. Forces between frame and package of a four-pole generator in time-domain

Table 1. Force ratio

Δ (dB)	Pole number	Slot number	Damper winding bars
0,8	2	48	12
4,2	2	48	16
30,4	4	48	27
23,7	4	54	27

The frequency spectrum of this noise, determined by the frequency spectrum of the exciting force is specially interesting because of the frequency-dependent sensitivity of the human ear and a possible corresponding of the natural frequencies of the mechanical system and some of the harmonics in the exciting force. Fig. 8 depicts those forces in time-domain for a four-pole generator. To perform the frequency-analysis, a time-slot is chosen in all the examples shown, during from 20 ms to 40 ms. In these moments the transient effects are finished, and the force in the time-domain reaches the stationary state. The length of the examined time-slot is the period of the fundamental harmonic of the current, which equals 50 Hz. Because of the non-uniform sampling of the signal in the time-domain, the aforesaid signals were interpolated in programming system MATLAB to the uniform sampling at the frequency 2 kHz, using cubic spline interpolation. Using Discrete Fourier Transformation (DFT), the RMS spectrum of the forces was determined [8]. Since the interpolated force signal has 40 samples, the frequency resolution in two-side spectrum is 50 Hz, and the frequency of the highest presented harmonic is 950 Hz. Because of the logarithmic scale of the human hearing, the spectra were shown with the levels in the decibel scale, and the constant term was omitted since it does not contribute to the acoustic radiation.

The frequency analysis was also performed in the programming system MATLAB. For each of the examples, the ratio in decibels of the total power in all harmonic was calculated for the open damper winding vs. closed damper winding $\Delta = 10\log(P_{open\_winding} / P_{closed\_winding})$. These levels are systemized in Table I, and typical afore-mentioned spectra are depicted in Fig. 9. For the 4-pole generator and for the both examples shown, there is a visible decrease of the forces, as for the total RMS value of its pure alternating part, so for all of their harmonic components.

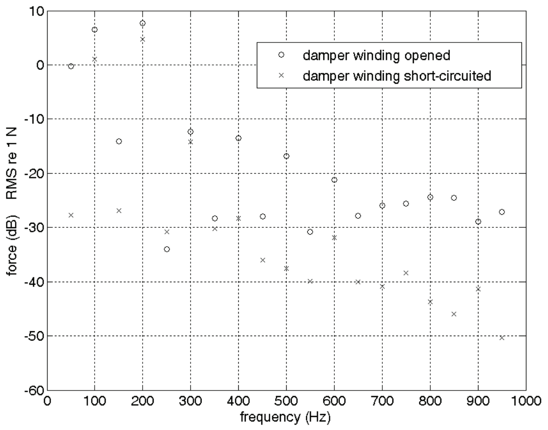

Fig. 9. DFT spectrum of the force for a two-pole machine with 48 slots and 16 damper winding bars

Increased exciter currents

In previous sections, all the calculations were performed form nominal exciter current. To further examine effect of the increased exciter current, the analysis was for the two-pole generator performed for exciter currents greater than its nominal value in no-load state (226 A). The results are summarized in Table 2, and show a significant increase in overall force level (the ratio Δ in dB has a negative sign).

Table 2. Force ratio for different exciter currents (two-pole generator)

Δ (dB)	Exciter current (A)	Pole number	Damper winding bars
-7,3	326	2	12
-12,4	426	2	12
-10,9	326	2	15
-17,6	426	2	15

Table 3. Force ration for different exciter currents (four-pole generator)

Δ (dB)	Exciter current (A)	Pole number	Damper winding bars
30,4	3375	4	27
20,6	3875	4	27
12,1	4875	4	27
5,8	5875	4	27

In the analysis of the four-pole generators, the above-mentioned negative effect is not present. The results are summarized in Table 3. It is also shown that with the saturation in the stator yoke the difference in the ratio Δ between open and whort-circuited damper winding is decreased. The calculations were performed for the nominal working point too. In this case the exciter current is 7895 A, and Δ equals 22.37 dB, i.e. the noise is decreased as well.

Conclusions

Presented numerical calculations show undoubtedly that the stator damper winding can influence on the decrease of audible noise, electromagnetic forces between stator package and frame and additional losses, all of that caused by preventing leakage in the stator package yoke. This decrease is quantizied in the paper using models of two standard turbogenerators, while the number of the stator damper winding bars was varying. Minimal number of the bars is determined by mechanical calculations of the stator package fastening. The decrease in mechanical forces, vibrations and audible noise may not occur for the analyzed two-pole model when dealing with the exciter currents increased above its nominal value. For the analyzed four-pole generator this effect is not present, and even in nominal regime of the operation the forces that cause audible noise of electromagnetic origin are decreased with the damper winding. In each individual case, the optimal number of damper winding bars should be carefully determined, and its effects should be examined using numerical simulations.

The obtained results are interesting for the mechanical behavior of the machines too, since the ideal cylinder is replaced by a real stator package, where the geometry and the number of slots play significant roles. The optimal number of the bars, as well as its pitch in the correlation with the number of the stator slots will be further researched.

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