Alexey. ADALEV[1], Nikolay KOROVKIN[1], Mikhail ROYTGARTS[2], Andrew SMIRNOV[2]

Saint-Petersburg State Polytechnical University (1), Factory Electrosila of the OJSC Power Machines (2)

doi:10.15199/48.2015.06.09

Calculation of circulating currents in the stator bars of turbogenerators

***Abstract**. A method of calculation of circulating currents and power loss in the stator bars of turbogenerators is presented. The method allows to create the model of a stator bar taking into account an arbitrary transposition of elementary strands in the slot and end zones of the bar. Two- and four-column regular types of transposition have been involved in the computer program realizing the method. Some preliminary calculation results for the turbogenerators of 160 and 220 MW have been obtained.*

***Streszczenie.** W artykule przedstawiono metodę obliczania prądów cyrkulacyjnych i straty mocy w prętach turbogeneratorów. Metoda pozwala stworzyć model pręta stojana, biorąc pod uwagę dowolną transpozycję elementarnych przewodów w żłobku i strefie końcowej pręta. Dwu- i czterokolumnowe regularne typy transpozycji zostały włączone w program komputerowy, który realizuje prezentowaną metodę. Przedstawiono wstępne wyniki obliczeń dla turbogeneratorów 160 i 220 MW . (**Obliczenia prądów cyrkulacyjnych w prętach stojanów turbogeneratorów**)*

Key words: circulating currents, stator bars, turbogenerator
Słowa kluczowe: prądy cyrkulacyjne, pręty stojana, turbogenerator

Introduction

Stator winding bars of large generators are built from a large number of insulated strands with a small rectangular cross section. Different magnetic flux linkages with the strands cause circulating currents (or eddy currents) flowing through the strands and giving great heat emission. Transposition (twisting) of the strands along the bar (that gives so called Roebel bar) reduces circulating currents and power loss in the bar significantly as compared to a massive bar. Searching of a proper transposition law is a problem of a great importance that is discussed by many researchers involving all amount of different calculation techniques: from approximate analytical ones to computationally expensive 3D FEM models, see e.g. [1-3].

Solution impediments and calculation technique

The most of calculation techniques treat a Roebel bar as a circuit equivalent of the strands system. The equivalent circuit for the system of three strands (as example) is presented in Fig. 1. Here the parameters L_i and M_{ij} are self and mutual inductances of the strands, R_i are ohmic resistance of the strands, E_{is} and E_{ie} are electromotive forces (EMFs) induced in the slot and end parts of the strands by magnetic fields produced by the rotor and the other stator bars.

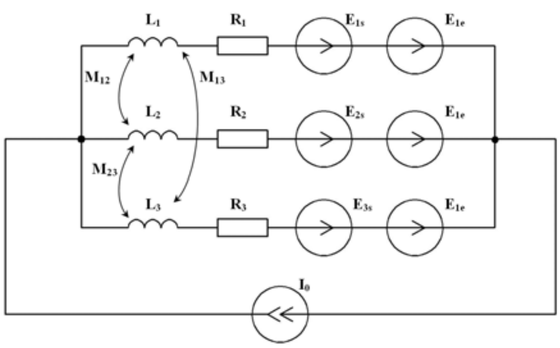

Fig. 1 Equivalent circuit for the stator bar consisting of three strands (example)

The current source I_0 creates the rated current through the bar that finally spreads among the strands according to differences in their impedances. The solution of the problem is obtained in the complex domain, therefore the strands parameters R, L, M are treated as constants, whereas E_s, E_e, and I_0 are sinusoidal time-functions.

The difficulty of the solution is that just several volts induced in the strands loops produce large circulating currents. At that voltage across the bar approaches several hundred volts and those loop contributions can be lost due to methodological or computational errors. Figure 2 illustrates amplitudes of the external EMFs in the strands (caused by the rotor and the other bars). Numeration of the strands of the four-column bottom bar is shown in the left part. Central diagram of Fig. 2 shows EMF in the slot part of the bar (3700 mm long). Right diagram of the figure shows EMF induced in the forward-bent part of the end zone (1065 mm long). It can be seen that both the segments produce maximum loop (differential) EMF of about 2-2.5 V though contribution of the end segment to a strand EMF is two orders lower than that of the regular segment.

Similar situation is with the inductive parameters of the strands. For example, maximal difference in the strands' inductances of the bottom bar of the 220 MW turbogenerator is about 5% (see Fig. 3, left). As it can be seen in Fig. 3 (right), distribution of the current I_0 over the untransposed bar is extremely nonuniform (here the external EMFs E_s, E_e are not involved for study). This distribution can be treated as a superposition of the uniformly distributed current I_0 and circulating currents induced by the inherent field of the bar. It should be mentioned that the most pronounced contribution to the inductive parameters (and their differences) is given by regular part of the generator.

Therefore precision of the parameters of the circuit in Fig.1 should be rather high and contribution of the end zone field cannot be neglected. More precise calculation of the magnetic field in the end zone of a turbogenerator marks out the technique proposed in the present paper being compared to the other ones. On the whole two different FEM model are used to determine the parameters of the equivalent circuit as described below.

Since the most pronounced contribution to the parameters (and therefore their difference) gives the slot zone of the generator, a detailed two-dimensional plane model revealing a cross section of the generator slot zone is used for calculation of the strands' inductive parameters (L_i, M_{ij}) and electromotive forces E_{is}. The inductive parameters characterize the EMF induced by the intrinsic field of the bar, whereas the external EMF is induced by the magnetic field of the rotor and the other bars. The former

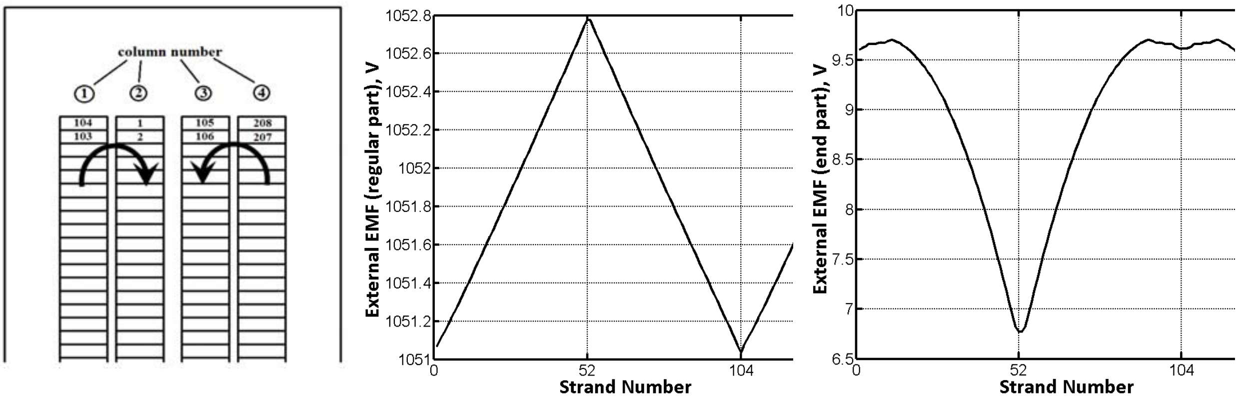

Fig.2 Amplitudes of the external EMF in the strands (untransposed bottom bar of the 220 MW turbogenerator)

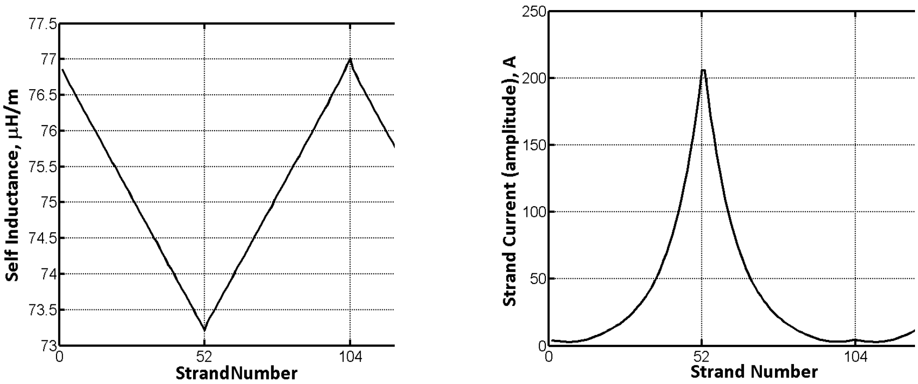

Fig. 3 Self inductances of the strands and contribution of the current source I_0 to the strands' currents (untransposed bottom bar of the 220 MW turbogenerator)

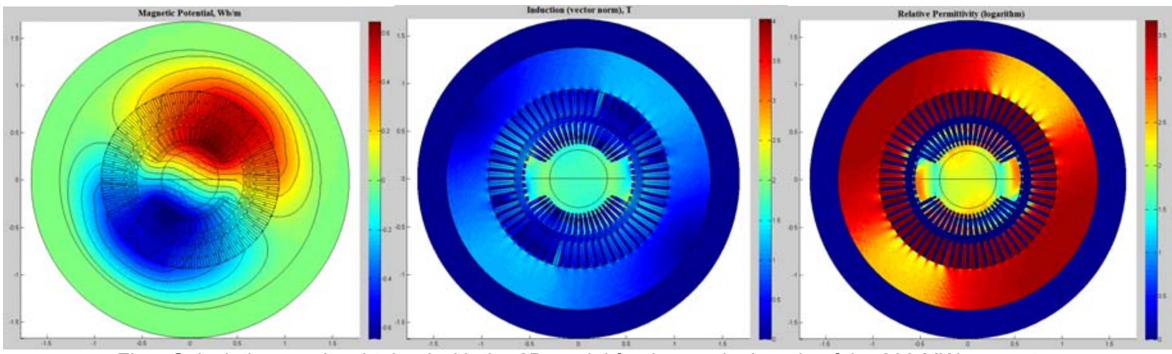

Fig.4 Calculation results obtained with the 2D model for the nominal mode of the 200 MW generator

EMF is considered to be dependent on both the strand position and strand currents, whereas the latter one depends only on the strand position. The 2D model is created in the conventional one-component vector potential formulation. When the inductive parameters and EMFs are determined, distribution of permittivity over the magnetic cores cross sections is preserved as in the nominal mode (see Fig.4).

Due to transposition of the strands, per-meter inductive parameters and slot EMFs (i.e. local contributions to the circuit parameters L_i, M_{ij}, and E_{is}) change along the bar. Associating the contributions' values to the position of a strand in the bar cross section and assuming the step-wise transposition, total parameters L_i, M_{ij}, and E_{is} can be obtained by proper integration (summation) of the per-meter values calculated in the plane 2D model for the initial positions of the strands. Since the above mentioned per-meter parameters do not depend on the transposition scheme, the discussed FEM problem can be solved only once. This allows to analyze several transposition schemes in short time (the discussed FEM problem is rather time consumptive for the great number of strands, that is usually 100-300).

The end zone electromotive forces E_{ie}, are assumed to be dependent only on the strand position and are calculated being induced in the end zone of the strands by the total magnetic field (including the field produced by the considered bar) in the nominal mode. This assumption is quite reasonable since the most part of the end segment of the bar locates in air where there the magnetic field is distributed smoother than in the slot zone. Besides, it is necessary to mention that the inductive parameters of the strands in the end zone (and consequently their differences) at least an order lower than that in the slot zone. So their contribution to the total inductive matrix is small.

The field distribution is obtained with the 2,5-dimensional model [4] that reveals a longitudinal section of a generator end zone in the cylindrical $\{r, z\}$ coordinates (see Fig.5). A mixed complex-variable formulation is used to obtain the distribution of the quasi-static magnetic field where the field components are considered to be sinusoidal both in time and along the angular coordinate. The end zone EMFs are calculated from the distribution of the magnetic field in the end zone of the generator for all the strands following their local positions in the bar in accordance to the given transposition scheme. EMFs are calculated by integration of the complex magnitudes of the magnetic induction components over the proper coil surface. Following this technique the EMF in Fig.2 (right) was obtained for the end part with z = 2390-2940 mm of the untransposed bottom bar.

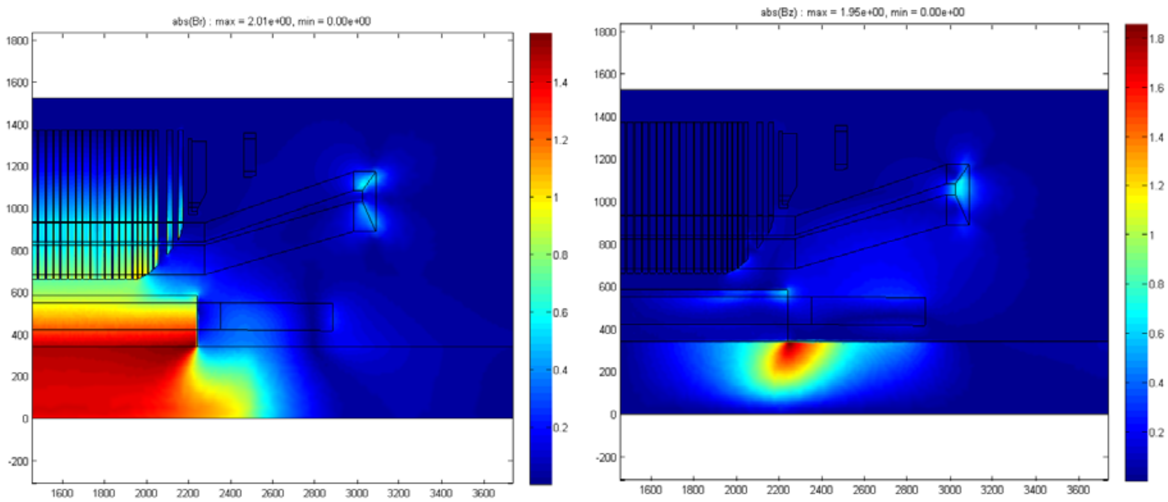

Fig.5 Calculation results obtained with the 2.5D model for the nominal mode of the 220 MW generator

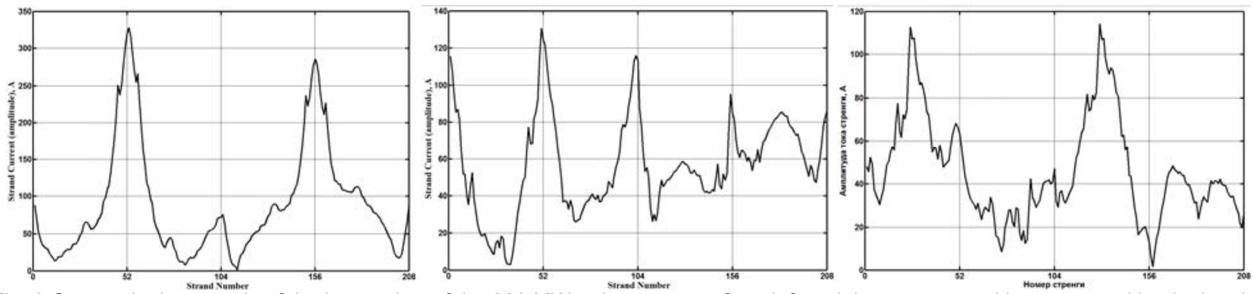
Fig. 6 Curents in the strands of the bottom bar of the 220 MW turbogenerator from left to right: no transposition, transposition in the slot zone 540°, transposition in the slot zone 540° and in each end zone 90°

Preliminary calculation results

Some preliminary results were obtained for 160 MW and 220 MW turbogenerators. Figure 6 illustrates distribution of the bar current over 208 strands comprising the bottom bar of the 220 MW generator in the case when all elements of the equivalent circuit are involved (as compared to Fig.3, right). Transposition parts: z = [-2158, 2158] mm in the slot zone and z = ±[2390, 2940] mm in the end zones. Transposition direction is in accordance with Fig.2 (left). The other parts of the bar are not transposed. Calculated loss are listed in Table 1.

Table 1. Calculation results for the bottom bar of the 220 MW turbogenerator

<table>
<tr><td rowspan="2">Transposition scheme: total angle (column pairs)</td><td>slot zone</td><td>none</td><td>540° (1-2|4-3)</td><td>540° (1-2|4-3)</td></tr>
<tr><td>end zones</td><td>none</td><td>none</td><td>90° (1-2|4-3)</td></tr>
<tr><td colspan="2">Total losses in the bar, kW</td><td>30.4</td><td>8.5</td><td>5.9</td></tr>
<tr><td colspan="2">Loss increment factor (AC/DC)</td><td>12.6</td><td>3.5</td><td>2.5</td></tr>
</table>

Preliminary results obtained have shown that the most significant effect gives transposition in the slot zone. However some additional decrement in the power loss (of about 30% for the case discussed in Table 1) can be obtained by using additional transposition in the end zone of the bar. It should be mentioned that such a decrement is observed not for any transposition in the slot zone. Actually by using the technique proposed in the paper some optimal combination of slot and end transpositions can be found to obtain the lowest power loss in the bar. This is a subject of the future work.

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Authors:

Assoc. Prof., PhD. Alexey Adalev and Prof., D. Sc. Nikolay Korovkin are with the Saint-Petersburg State Polytechnical University, Electromechanical Department, 29, Polytechnicheskaya str., 195251, Saint-Petersburg, Russia, phone: +7(812)5527572, e-mail: adalev@mail.ru; Deputy Chief Designer of Turbogenerators, Ass. Prof.,PhD. Mikhail Roytgarts and Engineer Andrew Smirnov are with the Factory Electrosila of the OJSC Power Machines,139, Moskovsky pr., 196105, Saint-Petersburg, Russia, phone: +7(812)6764200 ext.26536, e-mail: Roytgarts_MB @els.power-m.ru.