STRIPS METHOD FOR EVALUATING A.C. LOSSES IN SLOT PORTION OF ROEBEL BARS – ERRORS ANALYSIS

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This work deals with the additional losses minimization in the Roebel bar windings of high power synchronous generators. In order to solve this problem, in the paper is presented a strips-method that provides a high accuracy estimation of the elementary currents through the strand conductors. According to this method, the cross section of each strand in N parallel-strips with the slot basis was divided, so that the strip-current density could be considered as a constant. The aim of the paper is to analyze the computing-method errors and the influence of the strips number on these errors.

1. INTRODUCTION

Stator windings in large hydrogenerators use Roebel bars in which the strands (elementary conductors) are complete transposed in the slot portion by a variety of arrangements. In a normal bar, that have a 2π transposition, each strand has two crossovers, and, after passing through the slot portion, is in the same position relative to the other strands. Thus, each strand has the same mean depth in the slot, the same leakage reactance and the same voltage induced by the both main and leakage fluxes. However, in the endregions of the generator, leakage flux flowing through the bars produces voltage differences between the strands. Currents circulate between the strands in addition to the normal load current, and additional losses results.

Minimization of these additional losses is an important objective having as effect the increase of the efficiency of high power synchronous generator. The Roebel bar optimization problem supposes to find the number of the strands and the transposition angle in the slot portion; so that the bar loses have the minimum value.

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The calculation methods of losses in Roebel bars used at present are based largely on mutual impedances [1,2] which involve the most precise knowledge possible of the currents in the elementary conductors and of the distribution of these currents on the cross-sections. The method of the strips, presented in a previous work [3, 4], allows to calculate the currents and then the losses in the elementary conductors. All the utilized methods are based on certain hypotheses by means of which some errors are introduced. It is important to know the errors being made comparatively to the method considered to be the best.

2. THE BAR MODEL

The structure of a Roebel bar results from Fig.1. In Fig.1.a one can see the arrangement of the elementary conductors in two columns, numbered from 1 to \( m \) on a column. Fig.1.b presents the radial view and Fig.1.c the view of the axis of an elementary conductor in two different planes.

Fig. 1 – The Roebel bar structure.

Fig. 2 – The Roebel bar model: a) the actual structure; b) the idealized structure.
For calculation, this actual structure of the bar, given in Fig. 2.a, is replaced with an idealized bar whose elementary conductors are made of many sections with axes which are parallel to the slot basis and to the machine axis, as seen in Fig. 2 b.

One considers an elementary section defined by the vertical plans $Z$ and $Z+1$ from Fig. 2. This is divided by planes parallel with the slot basis. A family of $N$–strips is formed, of strip thickness $-h$. They are numbered from $n_{x}$ to $n_{y}$ for the section of level $\lambda$. The levels are numbered as one can see in Fig. 2.b. The number $N$ of strips is chosen so as to be able to consider that on the thickness $h$ the density of the electric current is constant, with an admissible error.

Fig. 3 – An elementary section.

3. THE CALCULUS OF THE CURRENTS

One chooses a $\Gamma$ – curve (Fig. 3) traced through the upper parts of two consecutive strips with the order numbers $\nu - 1$ and $\nu$. One performs the line integral along this curve of electric field intensity and obtains a relation between the currents of the two considered strips. The currents vary in a sinusoidal shape in time. In consequence, one can use complex quantities. One can calculate the $I_{c,\nu}$ current of the $\nu$ strip depending on the currents of the elementary conductors under the form:

$$I_{c,\nu} = I_{c,\nu} + I_{c,\nu} \cdot (1)$$

Here $I_{c,\nu}$ is the sum of the two currents in the neighbor conductors in the same level $\lambda$, and $I_{c,\nu}$ is the sum of all the currents in the conductors placed between the
slot base and the $\lambda$ level. For $S_\nu$ and $T_\nu$ one considers the following system of relations:

$$
K_\nu = \frac{b_{\text{cu},0}}{b_{\text{cu},0,1}}; \quad B_\nu = \frac{j2\omega\mu}{\rho_{\text{cu}} b_{\text{cu}}};
$$

$$
A_\nu = \frac{3K_\nu}{3-B_\nu}; \quad D_\nu = -\frac{3B_\nu}{3-B_\nu};
$$

$$
C_\nu = (A_\nu - D_\nu)C_{\nu-1} - D_\nu \sum_{k=n_\nu}^{n-2} C_k;
$$

$$
E_\nu = (A_\nu - D_\nu)E_{\nu-1} - D_\nu \left( \sum_{k=n_\nu}^{n-2} E_k - 1 \right);
$$

$$(2)$$

$$C_i = 1; \quad E_i = 0;$$

$$C_{xy} = \sum_{i=1}^{N} C_i; \quad E_{xy} = \sum_{i=1}^{N} E_i;$$

$$S_\nu = \frac{C_\nu}{C_{xy}}; \quad T_\nu = S_\nu E_{xy} - E_\nu.$$

In these relations:

- $\mu$ is the magnetic permeability of the conductor material (virtually equal with the magnetic permeability of the vacuum environment $-\mu_0$);
- $b_{\text{cu}}$ – the width of the conducting cross section of an elementary conductor in the $\nu$ strip;
- $b_{\nu}$ – the width of the rectangular slot;
- $j$ is the imaginary unity.

The bar ends are treated similarly as the slot portion. One then chooses a closed curve $\Gamma_1$ traced through the first strips of the two successive elementary conductors $\xi$ and $\xi+1$. This curve is closed at the two bar ends by connections of the elementary conductors which are in number of $2m$. Another line integral of the electric field intensity along this curve was calculated, by means of which a relation between the currents of the elementary conductors was established. Thus are obtained $2m-1$ relations between the elementary currents. One also takes into account the fact that the sum of all the elementary currents is always equal with the current of the bar. Consequently:

$$
\sum_{\xi=1}^{2m-1} G(\xi, \xi) L_{\xi} = U_{\text{erc}} (\xi); \quad \xi = 1, 2, ..., 2m.
$$

(3)

The $G$ coefficients can all be calculated depending on geometrical dimensions and of material constants, all known, and $U$ is the electromotive force from the elementary conductor induced by the radial magnetic fields. The system
contains \(2m\) equations, with \(2m\) unknown variables and therefore the currents in the elementary conductors can be determined.

Now one can calculate the currents of every strip for any elementary conductor and one obtain for the \(v\) strip of the elementary conductor \(\xi^v\):

\[
I_{v,\xi^v} = \frac{P_{\xi^v}}{P_{\Sigma N}} I_\xi + \frac{B}{2} \left[ \left( U_{v,\xi^v} - \frac{P_{\xi^v}}{P_{\Sigma N}} U_{\Sigma N} \right) L_\xi + \left( V_{v,\xi^v} - \frac{P_{\xi^v}}{P_{\Sigma N}} U_{\Sigma N} \right) L_\xi \right],
\]

(4)

where, generally \(K_{v} = \frac{b_{cu,v}}{b_{cu,1}}\). At elementary hollow conductors of rectangular form there are only two dimensions \(b_{m1}\) and \(b_{m2}\). Considering \(K = \frac{b_{cu,2}}{b_{cu,1}}\) the following relations are obtained:

\[
P_{\xi^v} = K_1 \cdot K_2 \cdot \ldots \cdot K_v; \quad P_{\Sigma N} = \sum_{v=1}^{N} P_{\xi^v};
\]

\[
S_{\Sigma 0} = \sum_{v=1}^{N} S_{\xi^v}; \quad T_{\Sigma 0} = \sum_{v=1}^{N} T_{\xi^v};
\]

\[
S_{\Sigma \Sigma 0} = \sum_{v=1}^{N} S_{\Sigma \xi^v}; \quad T_{\Sigma \Sigma 0} = \sum_{v=1}^{N} T_{\Sigma \xi^v};
\]

\[
U_{u} = K \left( S_{\Sigma \Sigma 0} - \frac{2}{3} S_{\Sigma 0} \right); \quad V_{u} = K \left( u - 1 + T_{\Sigma \Sigma 0} - \frac{2}{3} T_{\Sigma 0} \right);
\]

\[
U_{\Sigma N} = \sum_{v=2}^{N} U_{\xi^v}; \quad V_{\Sigma N} = \sum_{v=2}^{N} V_{\xi^v},
\]

and in a similar way for the winding ends (air portion of the bar).

Considering a constant current density on the cross section of the strip, one determines the losses in the strip. Adding the losses from all the strips, for all the sections, one obtains the losses in the entire bar.

4. ERRORS ANALYSIS

In this way it is possible to determine the precision or the error with which the calculation is performed by means of the strips method. We know from electro-technique the specifically case in which in a rectangular slot of \(b_s\) width one places \(m\) rectangular elementary conductors, of the same width as the one of the slot, all carrying by the same current; these elementary conductors have the height \(h_q\) and a length equal with the length of the slot. The increasing coefficient of the electric resistance in alternative current \((k_r)\) is defined as the ratio between the losses in
alternative current \((P_{cu})\) and the losses \((P_{c0})\) caused by a continuous current of the same intensity. For the presented case, this coefficient has the expression [5]:

\[
k_r = \varphi(\xi) + \frac{m^2 - 1}{3} \cdot \psi(\xi)
\]  

\[
\xi = \alpha \cdot h; \quad \alpha = \sqrt{\frac{\mu_0}{2 \rho_{cu}}}; \quad \omega = 2\pi f;
\]

\[
\varphi(\xi) = \xi \cdot \frac{\text{sh}2\xi + \sin 2\xi}{\text{ch}2\xi - \cos 2\xi}; \quad \psi(\xi) = 2\xi \cdot \frac{\text{sh}\xi - \sin \xi}{\text{ch}\xi + \cos \xi}.
\]

In these relations, \(\rho_{cu}\) is the electric resistivity of the conducting material, and \(f\) is the frequency of the alternative current, of sinusoidal shape, which carries the conductors.

In the following numerical example, two calculation methods of electric resistance increasing coefficient were considered. For the same slot and for the same dimensions, one calculate firstly \(k_{r1}\) by means of the strips method and then \(k_r\) using the relation (6).

In this case, the calculation error is:

\[
\varepsilon_r = \frac{k_{r1}}{k_r} - 1.
\]

This error depends on \(m\), on \(h\), respectively \(N\).

![Fig. 4 – Errors distributions versus elementary conductors number at different strips number.](image-url)
In order to obtain numerical values, one considers an actual case with the following data:
- width of the rectangular slot $b_c = 25 \text{ mm}$;
- height of a column of elementary conductors $HP = 66.33 \text{ mm}$;
- the thickness of the insulation of the elementary conductor is neglected;
- the width of an elementary conductor in the Roebel bar $b_{cu} = 12.5 \text{ mm}$;
- the axial length of the slot (the length of iron core) $L = 1.75 \text{ m}$;
- the number of elementary conductors per column is considered to vary between $2 \div 70$.

It is found that the error varies with respect to $m$ both as value and as a sign. The variations decrease with the increase of $N$, respectively with the decrease of $h$. An important diminution of the error $\varepsilon_r$ is obtained with the increase of $N$ as shown in Table 1.

<table>
<thead>
<tr>
<th>$N$</th>
<th>$2 \times 10^5$</th>
<th>$2 \times 10^6$</th>
<th>$2 \times 10^7$</th>
<th>$2 \times 10^8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_r$</td>
<td>$&lt; 10^{-3}$</td>
<td>$&lt; 10^{-4}$</td>
<td>$&lt; 10^{-5}$</td>
<td>$&lt; 10^{-6}$</td>
</tr>
</tbody>
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The distribution of the errors depending on $m$ at four different values of $N$ is given in Fig. 4.

5. CONCLUSIONS

The results presented show that the strips method is entirely useful and has an error depending on the thickness of the strip. One can consider initially for $N$ the value of $10^5$, and then one finalizes the calculation with $N = 10^7$. One must take into account that the calculation time is practically proportional to $N$. For instance, at $N = 2 \times 10^5$ and $m = 70$, the computing time is approximately 1 minute. For $N = 2 \times 10^8$ the computing time increases to 9 hours (using PC of general use of 1.7 GHz). Fig. 4 clearly shows the way in which it is recommended to choose $N$.

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REFERENCES

