Roebel Bar Model for Additional Losses Estimation in High Power Hydrogenerators

Toma DORDEA[1], Victor PROCA[2], Gheorghe MADESCU[1], Marius BIRIESCU[3], Marian GRECONICI[3], Marţian MOŢ[1], Ileana TORAC[1], Lucian OCOLIŞAN[1]

[1]*Romanian Academy, Timişoara Branch, Timişoara, Romania, tdordea@d109lin.upt.ro*
[2]ICMET*, Craiova, Romania, vproca@icmet.ro*
[3]*"Politehnica" University, Timişoara, Romania, biri@d109lin.upt.ro*

Abstract— **This paper deals with the additional losses estimation 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 present the basic elements of this approach.**

Index Terms— **electromagnetic analysis, induction generators, loss measurement, magnetic losses, resistance measurement.**

I. INTRODUCTION

Stator windings in large hydrogenerators use Roebel bars in which the strands (elementary conductors or subconductors) are complete transposed in the slot portion by a variety of arrangements. In a normal bar, that has 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 end-regions 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 copper losses result.

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 losses have the minimum value. In order to solve this optimization problem it is necessary to know all bar currents.

The calculation methods of losses in Roebel bars used at present are based largely on mutual impedances [1, 2] or finite elements method [3, 4, 5] 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 aim of this paper is to present an analytical model that provides a high accuracy estimation of the strand currents, taking into account all the magnetic fields that produce some copper losses.

II. THE ROEBEL BAR MODEL

The structure of a Roebel bar results from Fig.1. In this figure one can see the arrangement of the elementary conductors in two columns, numbered from 1 to m on a column.

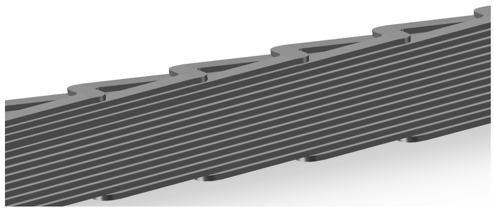

Fig. 1 The Roebel bar structure

In Fig. 2.a.) the case of a bar composed of 8 elementary conductors (m=4) placed on 2 columns is shown.

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

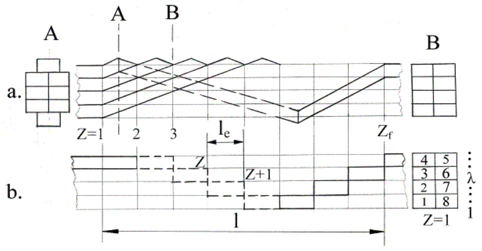

Fig. 2 The Roebel bar model
a) Actual structure; b) Idealized structure

One considers an elementary section defined by the vertical plans Z and Z+1 from Fig. 2. According to the proposed method (strip method), the elementary 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. A family of N–strips is formed, of strip thickness – h (Fig. 3). They are generally numbered from $n_{\lambda i}$ to $n_{\lambda f}$ for the section of level λ. 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.

This is the strips model that allows the analytical computation of strip currents and strand currents of the bar

[6, 7] in order to estimate the additional copper losses.

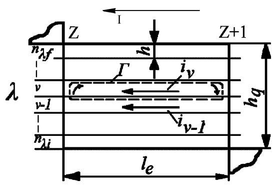

Fig. 3 An elementary section of layer λ

III. THE SLOT MAGNETIC FIELD

In the slot of an electric machine there are two kinds of magnetic fields. The two fields can generate additional losses in the copper conductors located in the slot.

Synchronous generators are generally high and very high power electric machines, with windings made of copper bars located in slots. If an alternating current flows through such bar, it generates a leakage field with lines closing transversely through the slot (Fig. 4).

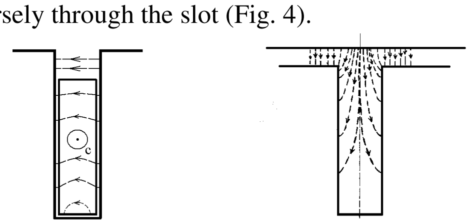

Fig. 4 The slot magnetic fields:
a) of inner current; b) and of external current

This leakage field, time-variable, induces in the bar eddy currents which determine an unevenly current distribution on the bar surface. Actually, it is found that the current density is lower close to the slot base (Fig. 5) and higher close to the slot opening (towards the air gap).

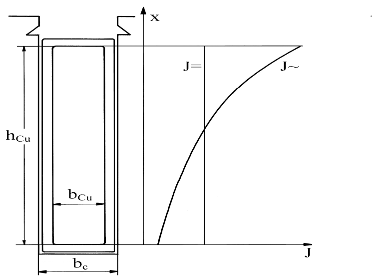

Fig. 5 Current density distribution in the bar

If three or many bar layers are in the slot, then similar distribution curves are got.

Because of this effect, the electrical resistance of the bars in alternating current (R_a) is several times higher than the electric resistance of the same bar in direct current (R_0):

$$R_a = k_{ra} \bullet R_0 \quad \text{where } k_{ra} > 1 \tag{1}$$

Consequently, in the alternating current generator winding, additional losses appear unavoidably.

For the computation of energetic parameters the lines of the leakage field from the slot are considered to be parallel to the slot base, i.e. perpendicular to the slot walls.

This field model is the basis for the computation of the current displacement effect, namely for the coefficient of increase of the bar electric resistance in alternating current (k_{ra}).

A slot where *m*-layers of rectangular bars are located is considered (Fig. 6).

Each layer has certain coefficient of electric resistance increase. By example, for the bar from the layer "*p*", the coefficient of resistance increase is [8]:

$$k_p = \varphi(\xi) + \frac{I_u\left(I_u + I_p\right)}{I_p^2}\Psi(\xi) \tag{2}$$

where the current I_p is the current from the considered layer, and I_u is the sum of the currents from all the layers located below the considered layer.

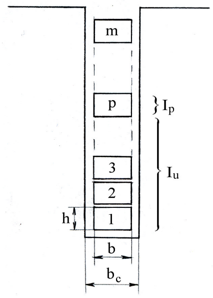

Fig. 6 Open slot with „M"- bars

If the same current flows through all the *m* – bars, an average value per slot of the coefficient (2) results [8]:

$$k_{ra} = \varphi(\xi) + \frac{m^2 - 1}{3}\Psi(\xi) \tag{3}$$

where the functions $\varphi(\xi)$ and $\Psi(\xi)$ have the well know expressions [8].

The problem of current displacement effect could be solved in this way also in the case when the bar is formed by many subconductors, connected in parallel.

The excitation field of a synchronous generator is generated by the current from the excitation winding, generally placed on the generator rotor. This magnetic field passes from rotor through air-gap into stator teeth, but enters also into the slot space, where the bars of stator winding are located (Fig. 7). It generates inner circulating currents through the bar subconductors, which are short-circuited at the ends, forming short-circuit loops. These currents cause additional losses in the stator winding, leading to the decrease of the electric energy conversion efficiency.

This magnetic field from the stator slot area was calculated, with view to determining the currents and additional losses in bars. For this purpose, in a previous paper [9] the conformal mapping method was used, in order to benefit from the advantages of the analytical methods for field computation.

The main results of the paper [9] in this paragraph are presented.

It is considered the numerical example in which the slot width b_c = 24 mm, the air-gap δ=5 mm and flux density $B_{\delta\max}$=1 T.

The magnetic field in the slot was calculated by analytical method (conformal mapping method) and by finite element method (FEM), at different depths (*y*=0.... -10 mm). Some computation results are presented in Fig. 8. Due to the symmetry of the magnetic field in the slot, the distribution curves of the magnetic field radial components were represented only on a half of the slot width (from the slot wall up to the slot axis)..

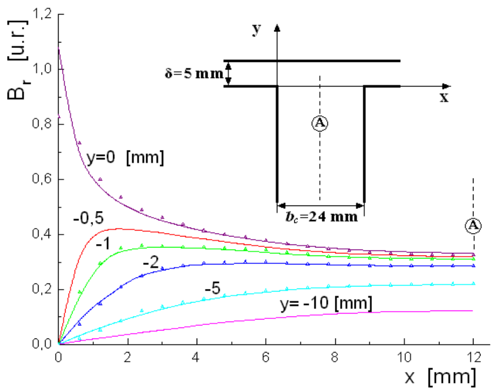

Fig. 8 Some curves of the flux density radial component across slot width direction: analytical method

On the basis of many computation examples, the following analytical relations of the radial magnetic field distribution in the slot width direction are proposed:

$$B_r(x) = B_{rm} \sin\left(\frac{x}{b_c}\pi\right), \text{ for } |y| \geq 2\delta$$

$$B_r(x) = B_{rm}\left(\sin\left(\frac{x}{b_c}\pi\right)\right)^{0,8} \text{ for } |y| \approx \frac{3}{2}\delta \tag{4}$$

$$B_r(x) = B_{rm}\left(\sin\left(\frac{x}{b_c}\pi\right)\right)^{0,5}, \text{ for } |y| \approx \delta .$$

Close to the air gap, when $|y| < \delta$, the distribution can be no more approximated by a sine curve; within these zones, the curves are like those ones calculated in Fig. 8 for $y = -2$ mm, $y = -1$ mm, $y = -0.5$ mm.

In order to develop as general as possible analytical solutions, the radial component of the magnetic flux density (B_{rm}) in the slot axis and its distribution in the depth direction was analyzed further on.

By using many families of curves got by computation, also the MATHLAB facilities, an analytical relation for approximating the values of the magnetic field density in the slot axis was built under the following form, valid in any point from the slot axis:

$$B_{rm} = e^{-\alpha} B_{\delta\max} \tag{5}$$

where:

$$\alpha = m_m\left|\frac{y}{\delta}\right| + n_n \tag{6}$$

and:

$$m_m = \frac{38,39\left(\frac{b_c}{\delta}\right)^3 - 665,1\left(\frac{b_c}{\delta}\right)^2 + 6507\left(\frac{b_c}{\delta}\right)^1 + 1061}{\left(\frac{b_c}{\delta}\right)^3 + 909,4\left(\frac{b_c}{\delta}\right)^2 + 2654\left(\frac{b_c}{\delta}\right)^1 - 1246}$$

$$n_n = 0,0857\left(\frac{b_c}{\delta}\right)^1 + 0,3786 .$$

By using the approximate relation (5) the value of induction in the slot axis can be determined, avoiding the difficulties in using the conformal mapping relations. The relations (4) and (5) in the computing program for additional loses estimation was included.

IV. THE CALCULUS OF THE CURRENTS

One considers the elementary section belonging to the layer λ (Fig. 3). One chooses a Γ–curve traced through the upper parts of two consecutive strips with the order numbers υ-1 and υ. One performs the line integral along this curve of electric field strength and obtains a relation between the currents of the two considered strips. The currents through the strips υ and υ-1 are i_υ and $i_{\upsilon-1}$ respectively. The currents vary in a sinusoidal shape in time. In consequence, one can use complex quantities. One can calculate the $\underline{I}_{c\upsilon}$ current of the υ strip depending on the currents of the elementary conductors under the form:

$$\underline{I}_{c\nu} = \underline{S}_\nu \underline{I}_{c\lambda} + \underline{T}_\nu \underline{I}_{u\lambda} \tag{7}$$

Here $\underline{I}_{c\lambda}$ is the sum of the two currents in the neighbor conductors in the same layer λ, and $\underline{I}_{u\lambda}$ is the sum of all the currents in the conductors placed between the slot base and the λ-layer. For $\underline{S}_\upsilon$ and $\underline{T}_\upsilon$ one considers the following system of relations:

$$\begin{gathered}
K_\upsilon = \frac{b_{cu\upsilon}}{b_{cu,\upsilon-1}} ; \\
\underline{B}_\upsilon = j\frac{2\omega\mu\, h^2 b_{cu\upsilon}}{\rho_{cu} b_c} ; \\
\underline{C}_1 = 1 \;\; \underline{E}_1 = 0; \\
\underline{A}_\upsilon = \frac{3K_\upsilon}{3-\underline{B}_\upsilon} ; \\
\underline{D}_\upsilon = -\frac{3\underline{B}_\upsilon}{3-\underline{B}_\upsilon} \\
\underline{C}_\upsilon = \left(\underline{A}_\upsilon - \underline{D}_\upsilon\right)\underline{C}_{\upsilon-1} - \underline{D}_\upsilon \sum_{\varepsilon=n_{\lambda i}}^{\upsilon-2} \underline{C}_\varepsilon \\
\underline{E}_\upsilon = \left(\underline{A}_\upsilon - \underline{D}_\upsilon\right)\underline{E}_{\upsilon-1} - \underline{D}_\upsilon\left(\sum_{\varepsilon=n_{\lambda i}}^{\upsilon-2} \underline{E}_\varepsilon - 1\right) \\
\underline{C}_{\Sigma f} = \sum_{\upsilon=1}^{N} \underline{C}_\upsilon ; \\
\underline{E}_{\Sigma f} = \sum_{\upsilon=1}^{N} \underline{E}_\upsilon \\
\underline{S}_\upsilon = \frac{\underline{C}_\upsilon}{\underline{C}_{\Sigma f}} ; \\
\underline{T}_\upsilon = \underline{S}_\upsilon \underline{E}_{\Sigma f} - \underline{E}_\upsilon .
\end{gathered} \tag{8}$$

In these relations: μ is the magnetic permeability of the conductor material (virtually equal with the magnetic permeability of the vacuum environment – μ_0); $b_{cu\upsilon}$ – the width of the conducting cross section of an elementary conductor in the *υ* strip; b_c – the width of the rectangular slot; j – is the imaginary unity.

The bar ends are treated similarly as the slot portions.

One then chooses another closed curve Γ_1 traced through the first strips of the two successive subconductors ξ and ξ+1. This curve is closed at the two bar ends, where all the 2*m*-subconductors are short-circuited. A line integral of the electric field intensity along Γ_1-curve was calculated, by means of which a relation between the currents of the subconductors was established. Thus are obtained (2*m*-1) relations between the strand currents. One also takes into account the fact that the sum of all the strand currents is always equal with the current of the bar. Consequently:

$$\sum_{\varepsilon=1}^{2m-1} \underline{G}(\varepsilon,\xi)\underline{I}_\varepsilon = \underline{U}_{erc}(\xi), \quad \xi=1, 2,\ldots, 2m\text{-}1$$
$$\sum_{\varepsilon=1}^{2m} \underline{I}_\varepsilon = \underline{I} \tag{9}$$

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

Now one can calculate the currents of every strip for any strand conductor and one obtain for the υ strip of the elementary conductor ξ:

$$\begin{aligned} \underline{I}_{\upsilon,\xi} &= \frac{P_{r\upsilon}}{P_{r\Sigma N}}\underline{I}_\xi + \\ &+ \frac{B_1}{2}\left[\left(\underline{U}_\upsilon - \frac{P_{r\upsilon}}{P_{r\Sigma N}}\underline{U}_{\Sigma N}\right)\underline{I}_{c\lambda} + \right. \\ &+ \left.\left(\underline{V}_\upsilon - \frac{P_{r\upsilon}}{P_{r\Sigma N}}\underline{V}_{\Sigma N}\right)\underline{I}_{u\lambda}\right], \end{aligned} \tag{10}$$

where, generally $K_\upsilon = b_{cu,\upsilon} \,/\, b_{cu,\upsilon-1}$. At hollow strand conductors of rectangular form there are only two dimensions (b_{cu1} and b_{cu2}). Considering $K = b_{cu2} / b_{cu1}$ the following relations for the coefficients are obtained:

$$P_{r\upsilon} = K_1 \cdot K_2 \cdot \ldots \cdot K_\upsilon;$$
$$P_{r\Sigma N} = \sum_{\upsilon=1}^{N} P_{r\upsilon}$$
$$\underline{S}_{\Sigma\upsilon} = \sum_{\varepsilon=1}^{\upsilon} \underline{S}_\upsilon;$$
$$\underline{T}_{\Sigma\upsilon} = \sum_{\varepsilon=1}^{\upsilon} \underline{T}_\upsilon$$
$$\underline{S}_{\Sigma\Sigma\upsilon} = \sum_{\varepsilon=1}^{\upsilon} \underline{S}_{\Sigma\varepsilon}; \tag{11}$$
$$\underline{T}_{\Sigma\Sigma\upsilon} = \sum_{\varepsilon=1}^{\upsilon} \underline{T}_{\Sigma\varepsilon}$$
$$\underline{S}_{\Sigma\Sigma\Sigma\upsilon} = \sum_{\varepsilon=1}^{\upsilon} \underline{S}_{\Sigma\Sigma\varepsilon};$$
$$\underline{T}_{\Sigma\Sigma\Sigma\upsilon} = \sum_{\varepsilon=1}^{\upsilon} \underline{T}_{\Sigma\Sigma\varepsilon}$$
$$\underline{U}_\upsilon = K\left(\underline{S}_{\Sigma\Sigma\upsilon} - \frac{2}{3}\underline{S}_{\Sigma\upsilon}\right)$$
$$\underline{V}_\upsilon = K\left(\upsilon - 1 + \underline{T}_{\Sigma\Sigma\upsilon} - \frac{2}{3}\underline{T}_{\Sigma\upsilon}\right)$$
$$\underline{U}_{\Sigma N} = \sum_{\varepsilon=2}^{N} \underline{U}_\varepsilon;$$
$$\underline{V}_{\Sigma N} = \sum_{\varepsilon=2}^{N} \underline{V}_\varepsilon$$

and in a similar way for the ends winding.

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 elementary sections, one obtains the losses in the entire bar.

V. CONCLUSION

Based on the previously presented model, using such kind of relations, a computing program for both currents and additional loses estimations was developed. The influence of any input data (strands number, transposition angle, geometrical dimensions, material data) can be considered. The program allows a faster analysis of a bar structure and, if is necessary, can provide an optimal bar structure. The research work will be continued with an experimental model in order to validate this approach.

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