# Influence of Skin- Proximity Effects on Hydro Generator Winding connections.

*(Diploma Thesis M. KLINGELE in collaboration with ALSTOM (Switzerland) Ltd. Hydro Generator Tech. Center., A. SCHWERY)*

The aim of this study was to determine the additional electrical losses in the serial and terminal connections of large hydro generators. These losses are created by the skin and proximity effect caused by the currents in the conductors themselves and the field of the stator-winding overhang. Additional losses in this region can lead to local temperature rises (hot spots) that have to be avoided since temperatures in the winding connections must be lower than contractually guaranteed levels.

Hydro power plants contribute to a huge part of the world electrical energy production. This part varies depending on local climatic, geographic but also political conditions. Nowadays new hydro power plants are rarely built in traditional industrial areas like the USA, Europe or Japan. Today the growing market is located in the ascending industrial countries in Asia above all in China and India. All main suppliers of large hydro generators do their best to be present in these countries and face tough market conditions and heavy competition.

To succeed in these markets companies must guarantee high product quality and continue to invest in R&D in order to make the design of the generators even more robust and reliable. The reduction of electric losses is part of this work.

A minimum efficiency of the generator must be guaranteed and is besides the selling price the main criteria for the comparison between offers from competitors. Exceeding the guaranteed losses is contractually penalised. As an example, a 66 MVA hydro generator with a rated efficiency of 98.5% and a power factor of 0.9 produces losses of 890 kW. Exceeding the guaranteed losses by 2% results in liquidated damages of 125’000 Euros.

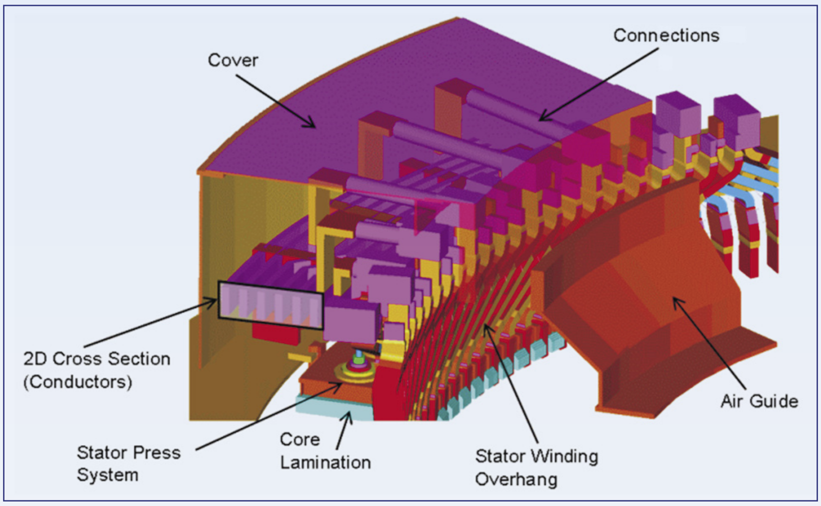

*Figure 1: Three dimensional representation of the stator end region.*

In hydro power plants salient pole synchronous machines are used to convert the mechanical energy of the water turbine into electrical energy. This type of machine is excited with a concentrated winding (pole coil) located on each pole. The stator winding of a three-phase synchronous machine is designed as a two-layer winding. The single stator bars are connected together to form coils. These natural connections are made at the bar ends via the so-called clips directly from the top layer to the bottom layer. The resulting natural groups of coils are connected by serial connections to form parallel circuits. Finally these parallel circuits are connected to the terminal boxes (high voltage and neutral terminal box) with the terminal connections. All connections are usually arranged on one side, the so-called connection side. Due to the limited space in the stator winding end region the connections are placed close to each other as shown in Figure 1 and Figure 2.

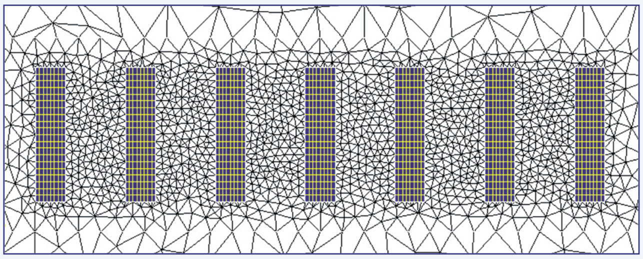

*Figure 2: Cross section of the meshed conductors surrounded by air (indicate the conductors in Figure 1).*

The conductors are sources of copper losses ($I^2.R$) and additional losses. Due to the complexity of the geometry, the additional losses were up to now only evaluated using formulas based on simplified considerations. Additional losses can be split into:

- losses due to the skin effect,
- losses due to the proximity effect.

Different shapes and arrangements of the conductors have been analyzed in order to establish design criteria. For this purpose the losses in the conductors were evaluated using magneto dynamic FEM simulations based on the commercial software package Flux (2D). The description of the FEM geometry is done considering the following additional influences:

- magnetic material of the stator frame and case parts,
- clamping system of the stator core lamination,
- currents in the stator winding overhangs.

The results of the computation were represented in simple graphics allowing the design engineers an efficient utilization.

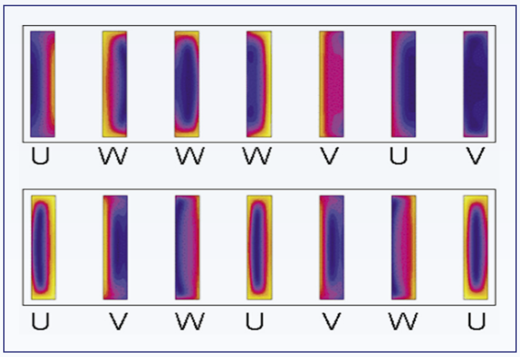

*Figure 3: Current density distribution for two different cases of phase arrangement.*

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## 3D geometry and corresponding 2D model

A three dimensional model of a stator section is shown in Figure 1. Containing the metallic parts such as the stator frame, air-guides and the clamping system of the stator core are shown. A FEM model of the cross section of the conductors without the frame and the stator-winding overhang is displayed in Figure 2. The distribution of the stator bars corresponding to one phase in the stator slots forms a repetitive pattern on a part of the circumference. Within this repetitive section the distribution is not regular. Consequently depending on the considered position of the 2D model on the circumference of the stator, different phase arrangements of the connecting conductors are possible.

Figure 3 shows for example the computed current density distribution in the conductors for two different phase arrangements corresponding to two different positions on the circumference of the machine. Regarding the generated losses the upper phase arrangement is the worst case and the lower phase arrangement the best case for all phase arrangements of the considered machine.

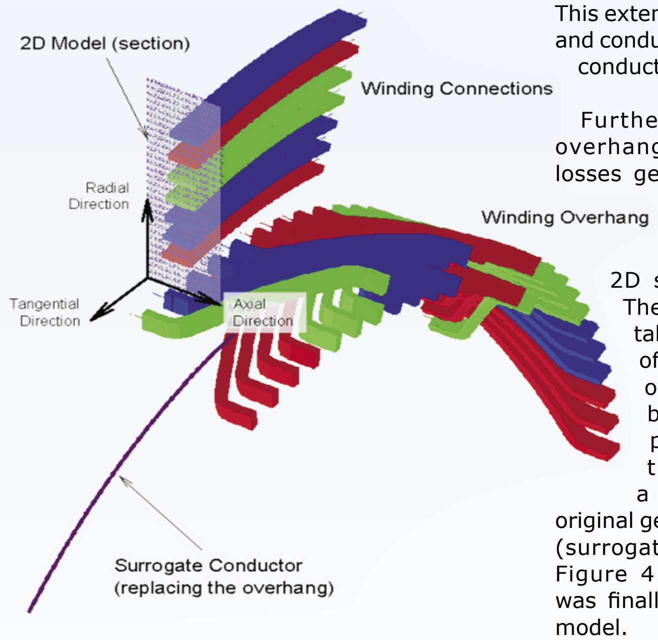

*Figure 4: 3D model for calculating the field components caused by the stator winding overhang*

The loss factor kr is given by the ratio of the AC losses and the DC losses of the arrangement. In the case of an arrangement with n conductors, the average loss factor for the considered set of conductors is more significant.

$$k_{rAV} = \frac{\sum_{\nu=1}^{n} P_{AC\nu}}{n \cdot P_{DC}}$$

This formula is based on the assumption that each conductor leads the same RMS current |I1| = ... = |I2|. To compute the loss factor it is necessary to calculate the AC losses in all conductors considering the actual alternating currents in the model. The losses due to the direct current are $P_{DC} = R_{DC}.I^2$ , where the resistance is given by $R_{DC} = \rho_{Cu}.L/A$.L is the length, $\rho_{Cu}$ the resistivity of copper and A the cross section of the conductor.

The first calculations are performed on the basic model shown in Figure 2.We found out that it is necessary to check the influence of the conductive metallic parts in the vicinity of the conductors. The solid metallic parts can have an important influence on eddy currents generated by the end region fields. Therefore a detailed model considering the solid metallic parts was derived from the 3D-geometry (see Figure 1). This extended model contains magnetic and conducting parts located nearby the conductors.

Furthermore the stator-winding overhang has an influence on the losses generated in the connections. In the 2D FEM model only the influence of current components normal to the 2D section can be considered. Therefore it is only possible to take into account the influence of the currents in the winding overhang in a limited way. The basic idea to overcome this problem consists in replacing the winding overhang by a surrogate conductor. The original geometry and the simplification (surrogate conductor) are shown in Figure 4. This simplified geometry was finally considered in the 2D FEM model.

To be sure that the surrogate conductor has a similar influence in the area of interest, it was necessary to compare the field components generated by the winding overhang with those of the surrogate conductor. The components of interest are the axial and radial ones as these are the components creating the additional losses in the conductors, furthermore the tangential component can not be created by the chosen tangential surrogate conductor. A comparison of the radial field component of the original stator winding overhang and the radial field component of the surrogate conductor shows that the magnitude of the field component is the same with a slightly different distribution over the considered section. In order to establish these plots an internal ALSTOM tool was used permitting the computation of the magnetic field in the end part of a generator using the Biot-Savart method.

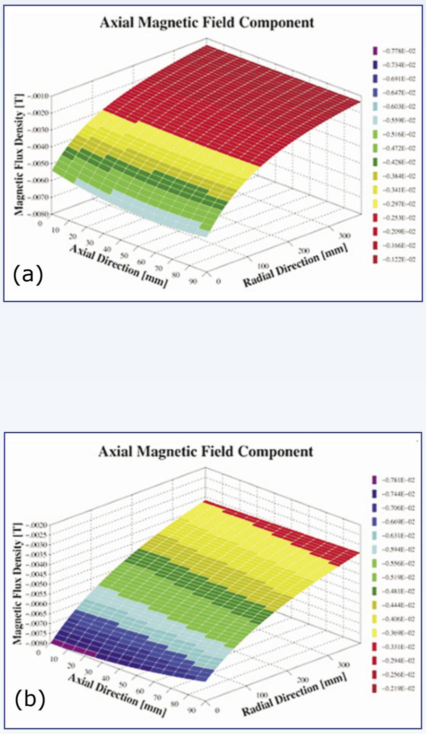

*Figure 5: Comparison of the axial magnetic field component for the original geometry (a) and for the surrogate conductor (b).*

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Finally Figure 6 shows the complete model including the metallic parts and the surrogate conductor. Compared to the initial model with conductors surrounded by air an increase of 10% of power dissipated in the connections was computed. The final simulations were based on this model, the influence of the stator winding overhang being not negligible.

## Computation results

The simulations were performed for different conductor shapes and separating distances in order to compare the average loss factors. Multiple simulations were carried out using FLUX2D's capability of single and multi parametric simulations. For this the alternating current losses were evaluated for a range of distances according to the space between the stator frame and the winding overhang. The results of the single parameterization can be displayed in a 2D curve.

For each shape different dimensions of the conductor cross section were investigated. Figure 7 shows the resulting loss factors for rectangular bars. Similar curves were computed for round and tubular conductors. These curves provide useful and condensed information for the optimisation of the connection arrangements and can be used by the designers without the necessity of further computations.

## Conclusion

The considered example shows that, for the computation of the additional losses in the connections, the influence of the winding overhang and the metallic parts cannot be neglected, an increase of 10% of the additional losses due to this influence was computed. Finally based on the modified model a series of computations were made. For different geometries curve arrays ready to be used by the design engineers for the optimisation of the connections were created.
With this work an easy to use and helpful guideline was established for the design engineer. The results together with the knowledge of the design engineer help to reduce the losses in the conductors, and avoid hot spots.

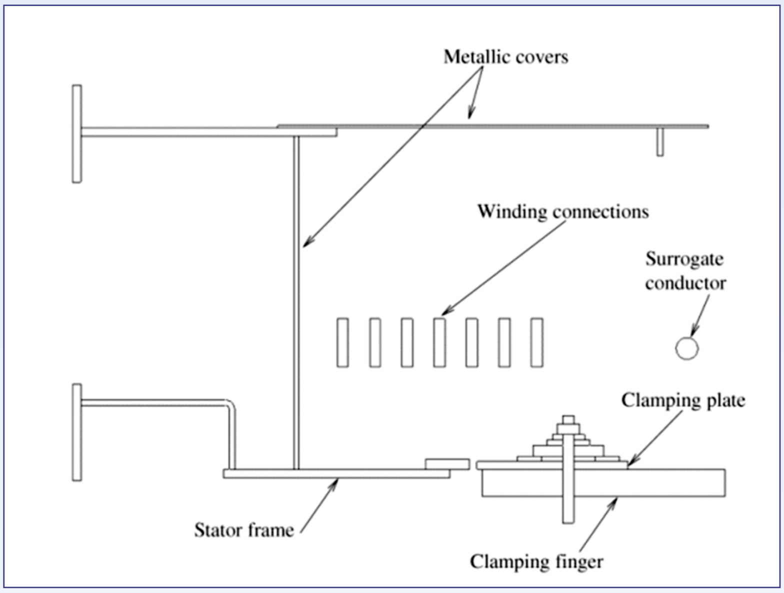

*Figure 6: Final model – Conductors considering the metallic parts and the Stator winding overhang.*

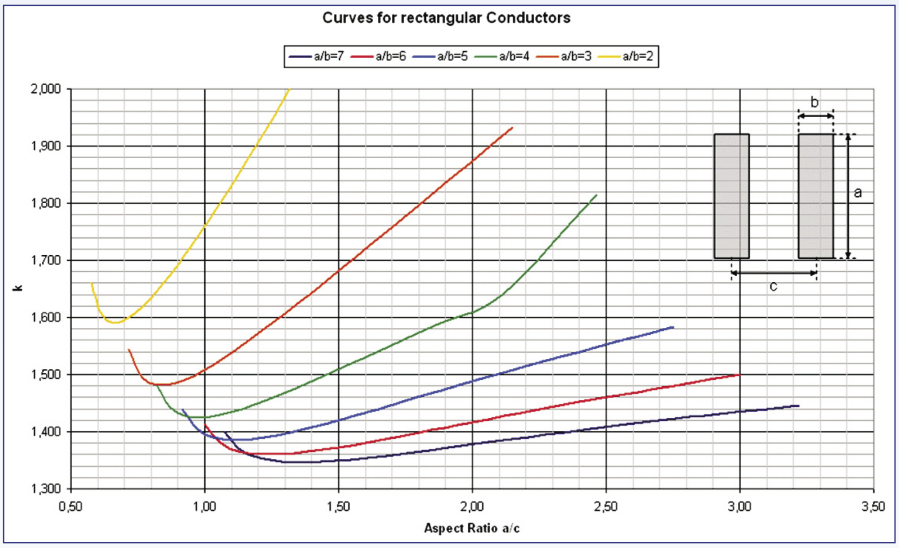

*Figure 7: Array of curves for rectangular conductors.*