# Computations of Losses and Temperatures in the Core Ends of a High Voltage Turbo-generator

**Yujing Liu† and Stig Hjärne***

**Abstract -** The work described in this paper is to investigate the additional iron losses and consequent temperatures in core ends of a turbo-generator wound with high voltage cables. Electromagnetic calculations are made with 3D FE models, which include the lamination material with anisotropic properties both in magnetic permeability and electric conductivity. The models also include the geometry of the stator teeth and eventually the axial steps designated to reduce the core end losses. The 3D model of the rotor consists of field windings with straight in-slot parts and end windings. The thermal models are simplified into two dimensions and include the heat sources dumped from the 3D electromagnetic solutions. The influences of power factor on additional iron losses are studied for this cable wound machine and conventional machines. The calculation results show that the additional iron losses can be reduced to about 15% by introducing some small steps around the airgap corner of core ends.

**Keywords:** 3D, eddy currents, end-region, iron losses, temperature, high voltage, cable wound, turbo-generator

## 1. Introduction

### 1.1 Background

The tolerance to high voltage provides *Powerformer*, cable wound generators, the possibility to be directly connected to high voltage power network without step-up transformers. The thick insulation around the copper core in the cables is the key part.

On the other hand, however, the cable insulation that is made from plastic material PEX cannot stand the similar temperature as the insulation materials in conventional machines. As the temperature in PEX rises to higher than 90°C, the property of the insulation of PEX is getting worse. The material will be ageing quickly.

The criterion of temperature in the available cables for design practice is 70°C. The temperature rise in the stator due to all the losses is not allowed to be higher than 40°C. While in conventional generators, the stator temperature rise in principle can be 120°C with high-class insulation. It is very clear that the limitation of temperature in a cable wound generator is extremely strict.

The first turbo-generator made by *ABB Generation* (now *Alstom Power*) is installed at Eskilstuna, Sweden. The rotor structure is almost the same as conventional two-pole turbo-generators.

In order to get low temperature rise in the stator, water-cooling is applied in the stator core by arranging a number of water tubes axially through the stator core. The heat from the copper losses in the cables (stator windings) is transferred to the stator core through the PEX and then to the cooling water through the plastic water tubes.

### 1.2 Risk of overheating and design limitations

To avoid locally overheating in the end-region caused by a small amount of additional iron losses is critical in design this type of machines. Concerning heat transfer, the existing structure has some clear drawbacks.

1. Temperature tolerance of the cable insulation: around 70 °C is very strong limitation for design of a large-scale generator.
2. The designed air gap flux density is 1.05T, which is 10 ~ 15 % higher than a conventional machine. This higher flux density will lead to higher losses in the end region by 20 ~ 30 %.
3. No air convection on the end surface of the stator lamination: the supporting bodies for the water tubes are attached on the stator core end. There exists only heat conduction from the core ends. Furthermore, the composite material for the supporting body has very low heat conductivity.
4. Low heat conductivity of the water tubes: This leads to a big temperature gradient in the water tubes and the filling material. It acts as a heat isolation layer.

This paper was received the best paper award from ICEMS 2005, which held in Nanjing, China from Sep. 27 to Sep. 29, 2005

† Corresponding Author: Department of Power Technology, ABB AB, Corporate Research, 721 78 Västerås, Sweden(yujing.liu@se.abb.com)

* Department of Turbo-generator, Alstom Power, 721 76 Västerås, Sweden

Received November 10, 2005 ; Accepted November 21, 2005

### 1.3 Tasks for 3D FE analysis

The tasks described in the paper include:

1. to investigate the additional iron losses due to the end effects (axial flux);
2. to calculate temperatures for stator tooth;
3. to propose approaches to reduce the losses down to an acceptable level if they are too high in the original design.

### 1.4 Machine data

The machine is a 2-pole, 3-phase, cable wound turbo-generator. The rotor has the same structure as conventional machines. Rated data: apparent power = 42 MVA; rated stator voltage = 136 kV; rated stator phase current = 178 A; frequency =50 Hz; rated power factor = 0.93; rated rotor current = 1100 A.

## 2. Electromagnetic Model

### 2.1 Definition of the physical problem

In this paper all the calculations of the additional losses are made for steady state operations of the generator. It is time harmonic application for electromagnetic problem. All the electromagnetic values vary sinusoidally with time.

Only the fundamentals of the stator currents are taken into account. It means that other time harmonic components in the currents are ignored.

The sinusoidally time varying currents create the varying magnetic field and induces eddy currents and causes additional iron losses in conducting materials. In the stator laminations, the insulation of sheets breaks down the axial path of the eddy currents. But the axial component of the flux induces eddy currents in radial-circumferential plane, in which the electric conductivity is in the same level as normal iron.

Especially in the end region of the machine, the axial component of the flux density may be very high (in some cases up to 1.0T) locally. In consequence, the induced eddy currents cause high losses and overheating.

### 2.2 Eddy current fields and magnetic vector potential

In conducting materials of the 3D electromagnetic model, magnetic vector potential $\vec{A}$ and electric scalar potential $V$ are used. The following potential equation is applied in those materials.

$$\nabla \times \frac{1}{\mu} \nabla \times \vec{A} = -\sigma \frac{\partial \vec{A}}{\partial t} - \sigma \nabla V \qquad (1)$$

In the air, where excitation currents exist, the reduced magnetic scalar potential is used. In the magnetic materials without eddy currents and excitation currents, the total magnetic scalar potential is used.

Using this combination of the magnetic potentials gives better accuracy and fewer unknowns of the FE problem.

### 2.3 3D FEM and software

It is clear that in this problem the most important values are distributed in three dimensions. In order to understand and solve the problem, a 3D model is required. It is interesting to discuss a little about the cases to choose between 2D and 3D models. In a 3D model we describe the physical model as it is because most of the real applications are geometrically in three dimensions. But in a 2D model we must firstly simplify the real application to a 2D model.

This simplification process very much depends on our experience and our primary understanding about the physical phenomena of the applications [1].

When the application is a little more complicated, we must introduce some kind of correction factors or equivalent coefficients to consider the simplifications. These factors are very often case-dependent. Theoretically the three dimensionally distributed physical quantities cannot be expressed correctly by those collective factors if the geometry is complicated.

Furthermore, the complexity of the three dimensional application often make it difficult or even impossible to check those factors are reasonably chosen. Therefore the progress from a 2D model to a 3D model is not only a matter of accuracy, but also the matter of correctness.

Based on this point of view, it will not be so surprise that we often take hours to understand a new 3D result because it is so different from our earlier understanding (imagination) on the phenomenon.

In order to solve the 3D problem, a commercial program *OPERA-3D*, which includes pre-processor, post-processor and solver *ELEKTRA* for eddy current tasks.

The modeling is parameterized with the help of user subroutines in the Built-in Command Language. Changing model becomes very easy by changing the value of related parameters in the input file or in case of necessary modifying concerned subroutines.

Several dozen of subroutines in the built-in command language are used to create the model and analyze results. Directly creating such a complicated model in an interactive way with the menu functions of the program is almost impossible. Even though the software vendor does not directly recommend this approach, it has been used in ABB for many applications in several years. The practice shows that the approach is very important for us to be able to solve our tasks - complicated geometry in the electrical machines.

## 2.4 Model creating

Considering the limitations from both the speed and the memory of the computer, only a quarter of the machine is included in the model (shown in Fig. 1). Using this simplification makes it possible to include the more detailed geometry in the model.

The current density both in the stator windings and the rotor windings is assumed to be uniform in the conductors and calculated from the total current, number of turns and overall area of the cross section of a coil.

For the stator winding (cables) only the straight parts are included because of the assumption that the contributions from the curve (circumferential) parts are relatively small. In the rotor winding, the straight parts and the curve parts of a coil are included. Two out of the fourteen coils have less cross sections but same current density as other coils.

## 2.5 Geometry of the model

A limited length of the machine is modeled because the fields after this length are almost two dimensional except the radial cooling ducts. This length is chosen as 250 mm from the rotor core end.

Straight tooth edges are used in the model because of the complexity of the curved tooth edges in the real machine due to the round surface of cables. The holes for water-cooling are not included in the electromagnetic model either.

In the pre-processor of the used program, the geometry is described as layers (in extrusion direction) and domains (in base plane). Each layer may have its own domains. The detailed handling is not the topic of the paper and not included here.

The model can be also created with solid objects and their combinations in the latest version of the software.

# 3. Electromagnetic Results

## 3.1 Eddy currents and iron losses

Eddy currents distributions on the stator tooth where the eddy currents reach their maximum at that time moment are shown in Fig. 2. It is the modified design with ten small steps at the core ends. The small steps close to the airgap are approximated with a sloped line in the calculation.

The color shading indicates the magnitude of the eddy current density. The sizes of cones indicate as well the magnitude of the eddy current density at certain locations. The directions of the cones indicate the direction of the eddy currents.

Every stator tooth will experience the similar distributions of the eddy currents but at different time moments

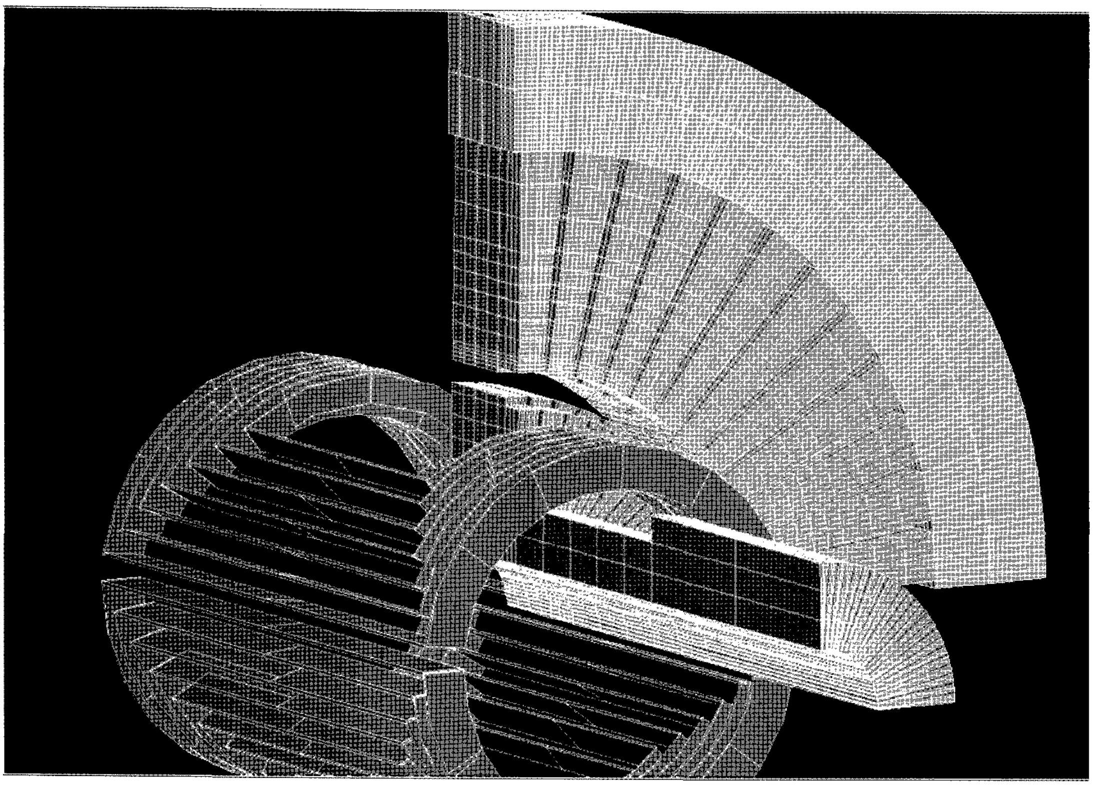


**Fig. 1** Electromagnetic model with field winding

because of the rotating fields in the machine.

The total additional losses for this design are only 15% of those for another design without steps (almost rectangular core ends). This shows how important to use 3D FEM to improve the machine design, especially for new concept large-scale generators.

### 3.2 Influence of power factors

The turbo-generator may operate at different power factors depending on network requirements. Even though the stator currents of the machine are kept constant, with different power factors, the generator has different excitation currents and different load angles. Consequently, the additional iron losses will be different. In a conventional turbo-generator, with massive press plates, the additional iron losses in the end region change much with different power factors [2].

The reason is that in the over-excitation mode the cancellation between the magnetic fields from the stator currents and the magnetic fields from the rotor currents in the end parts of the stator core leads to lower additional losses compared with those in the under-excitation mode.

This cable wound machine has a special stator structure and much lower stator currents and deeper stator slot. The stator core in the end region has been modified to reduce the additional iron losses.

In order to compare the difference between this machine and a conventional machine, the influence of current sheet density is investigated. Two factors are introduced first:

$$k_J = \frac{J_{sn,E}}{J_{fn,E}} \quad \text{and} \quad k_A = \frac{A}{A_{n,E}} \tag{2}$$

Where $J_{sn,E}$ and $J_{fn,E}$ are eddy current densities induced by the rated stator currents and the rated field currents in machine *Eskilstuna*, respectively. $A$ and $A_{n,E}$ are the current sheet densities for a given stator currents and rated stator currents for machine *Eskilstuna*, respectively.

The iron loss density in the core can be expressed as

$$p = \rho \cdot J^2 \tag{3}$$

Where $\rho$ is the resistivity and $J$ is the eddy current density. Because the eddy currents are induced by both of the stator currents and the rotor currents, $J$ can be expressed as the phasor addition of two current densities:

$$J^2 = J_s^2 + J_f^2 + 2J_sJ_f\cos\psi \tag{4}$$

Where angle $\psi$ is the phase shift between the eddy current density by stator currents, $J_s$, and the eddy current density

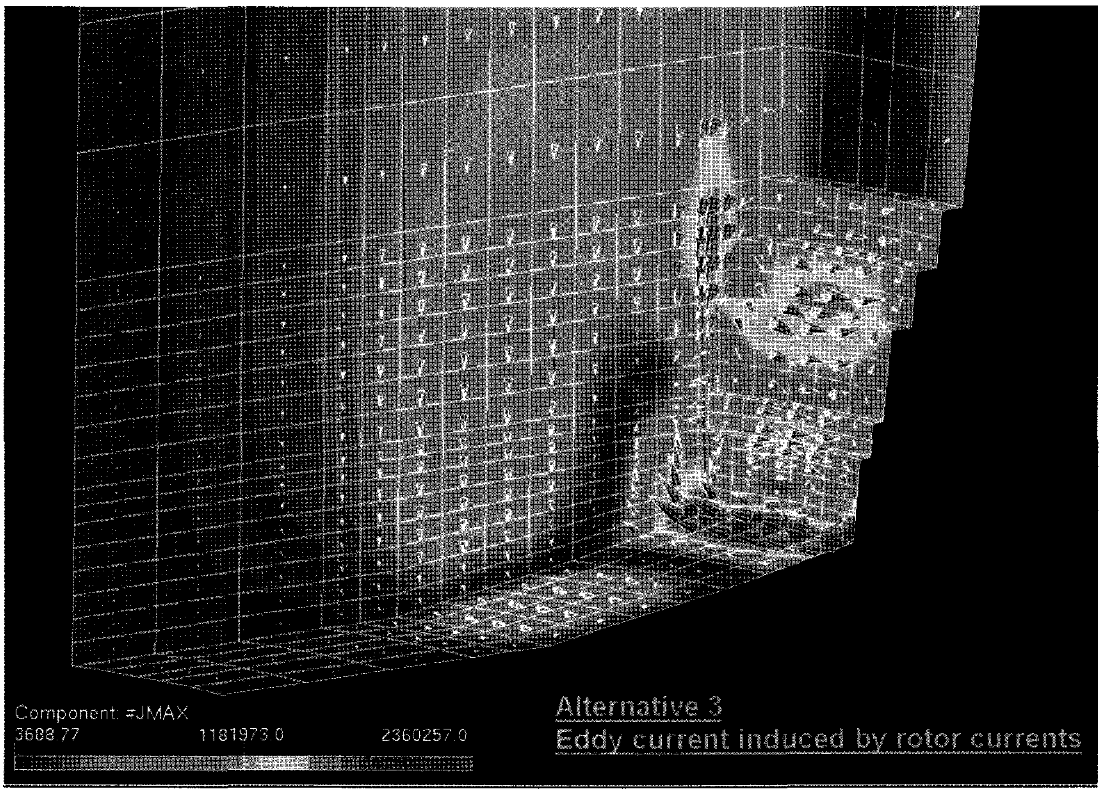



**Fig. 2** Eddy current vectors and density induced by rotor currents

by rotor currents $J_f$. The eddy current density by the rotor currents is expressed as:

$$J_f = J_{fn,E}\frac{I_f}{I_{fn,E}} = J_{f0,E}\left[1+k_A\frac{I_{f,E}-I_{f0,E}}{I_{f0,E}}\right] = J_{f0,E}S \quad (5)$$

And

$$S = 1+k_A\frac{I_{f,E}-I_{f0,E}}{I_{f0,E}} \quad (6)$$

Where, $I_{f,E}$ is the field current for this machine; $I_{f0,E}$ is the no-load value of $I_{f,E}$; $I_f$ is the corresponding field current to a given stator current; and $J_{f0,E}$ is the eddy current density induced by the no-load field current for this machine.

The eddy currents by the stator currents:

$$J_s = k_A J_{sn,E} = k_A k_J J_{fn,E} = k_A k_J J_{f0,E}\frac{I_{fn,E}}{I_{f0,E}} = J_{f0,E}T \quad (7)$$

Where

$$T = k_A k_J\frac{I_{fn,E}}{I_{f0,E}} \quad (8)$$

The loss density of the eddy currents for the no-load operation of is

$$p_0 = \rho\cdot J_{f0,E}{}^2 \quad (9)$$

The relative loss density of the additional iron losses for given stator currents:

$$p^* = \frac{p}{p_0} = S^2+T^2+2ST\cos\psi \quad (10)$$

In the above formulas in this section, all the materials have linear properties. The phase shift between the eddy currents is assumed to be same as that between the field current and the stator currents.

For different $k_A$, the relative additional iron loss density $p^*$ is calculated and shown in Fig. 4, where $k_A$= 1 is the curve for this machine (*Eskilstuna*). It shows the influence of cosφ on the additional iron losses for this machine is small.

Factor $k_A$= 2 or 3 means that the current sheet density or the stator currents increase 2 or 3 times from the values for this machine. The output power of the generator increases 2 or 3 times at the same time. The load angles for different cosφ are assumed to be same as those for this machine.

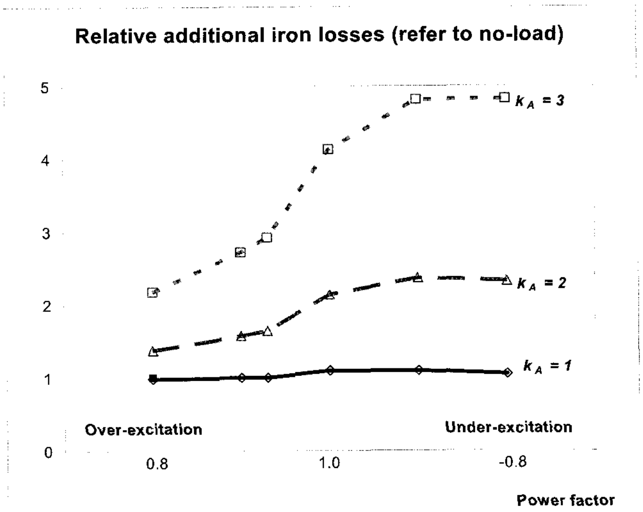



**Fig. 3** Relative additional iron losses with different power factors for different stator current loads

The curve with $k_A$= 3 shows the loss variation for a machine with higher current sheet density, which is the case for a conventional generator. The curve has similar pattern as those in the paper [2].

## 4. Thermal Model And Results

### 4.1 Thermal FE models

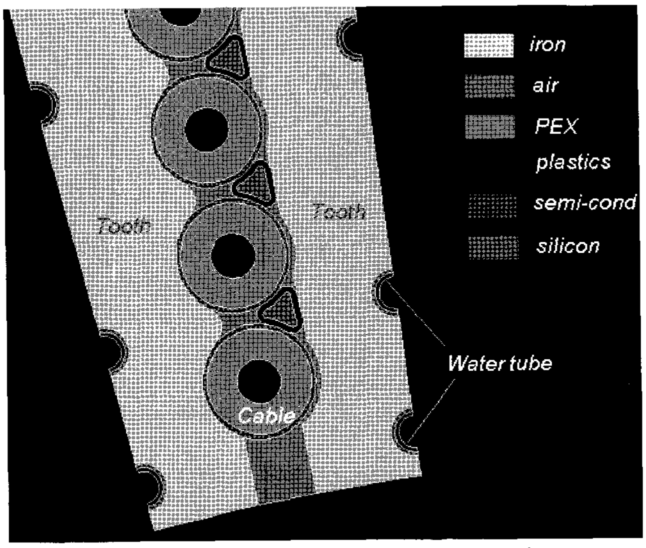



**Fig. 4** Materials for the thermal model

As described in the earlier section, the different insulation materials in cables, water tubes and other mechanical supporting insertions play important role in the heat transfer, especially in the slot parts.

All these detailed parts must be included in the thermal model in order to get correct temperature distributions. It is impossible to include all these details in a 3D model as the electromagnetic one used in the above section.

Because the temperature distribute symmetrically with tooth pitch, one slot is enough in the thermal model for this investigation (see Fig. 4). *Ace-thermal,* ABB made FE analysis program, is used to make the temperature calculations. It is a static thermal application.

### 4.2 Boundary conditions

The copper core in the cables has very high heat conductivity. The temperature change in axial direction in the copper is very little, approximately 0.5 °C. Therefore in the thermal model, the outer surface of copper is defined as a boundary instead of assigning material in the regions.

Considering the convective cooling on the inner surface of the stator, the boundary conditions (heat transfer coefficients and ambient temperature) used in the calculations are listed in Table 1.

**Table 1** Boundary Conditions For Thermal Model

| Boundary | Heat transfer coefficient(W/m$^2$) | Ambient temperature (°C) |
|---|---|---|
| Airgap | 200 | 38 |
| Water tubes | 10000 | 30 |
| Copper surface | 10000 | 65 |
| Other surface | 0 (isolation) | - |

### 4.3 Loss (source) density

The loss density in the thermal calculations comes from two kinds of previous electromagnetic computations: additional iron losses dumped from 3D results discussed in this paper and common iron losses calculated from the flux density distributions obtained in other 2D FE analysis (not discussed in this paper).

The 3D results include only the additional iron losses induced by the axial component of the flux density. The 2D results are used to determine the density of the common iron losses, which mainly depends on the square of flux density in the lamination. Even though the common iron losses consist of hysteresis losses, in-sheet eddy losses and access iron losses, a simplification is used here for calculating the density of the common losses in the lamination by:

$$p_{common} = 2.22B^2 \quad (11)$$

This formula is fitted out from the data table of the used electric sheets.

The density of the additional losses and the density of the common losses are locally added together to get the density of the total iron losses in the lamination. The density distribution of the total losses is used as source density in the thermal model.

### 4.4 Thermal results

Temperature calculations are made for different designs. For the designs with 4 steps and 10 steps in core ends, the temperature distributions are shown in Fig. 5 and Fig. 6. The cross section is axially located at 1 mm from the rotor ends.

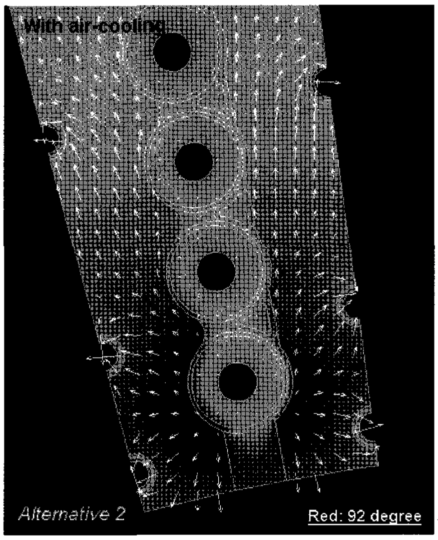



**Fig. 5** Temperature distributions for 4-steps design in cross section at 1 mm axially from the rotor end

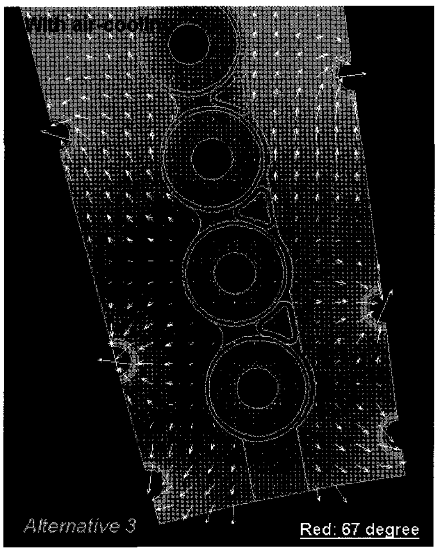



**Fig. 6** Temperature distributions for 10-steps design in cross section at 1 mm axially from the rotor end

The influence of axial heat conduction in the core is taken into account by calculating the problem in another plane, axial-circumferential (x-z) plane. The assumption in this case is no heat transfer in radial direction. It is roughly true at a special cross section. The maximum temperature in Fig. 6 may decrease from 67 °C to 63 °C due to this consideration.

## 5. Conclusions

3D FE analysis has been used to investigate the eddy currents and additional iron losses in stator core ends of a cable wound high voltage turbo-generator. The calculated detailed loss distributions allow us to improve the design. The final design with 10 small steps at core ends has only 15% additional losses in core ends compared with a rectangular core end design.

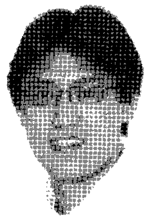
This improvement guarantees that the hotspot temperature is reduced to 63 °C, which is lower than 70 °C as design requirement for a cable wound machine.

The armature reaction of stator magnetic fields at load is relative low in the cable wound machine. That makes the machine to be different in two aspects from conventional machines. The first is the losses from the stator currents are much less than those from the rotor currents. The second is that the influence of cos φ on the additional iron losses is relatively small.

## References

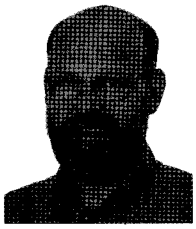
[1] G. K. M. Khan, "An integrated approach for the calculation of losses and temperatures in the end-region of large turbine generators," IEEE Trans.-EC, Vol. 5, No.1, March, 1990.

[2] T. H. Mason and P. D. Aylett, "Turbo-generator performance under exceptional operating conditions," IEE Paper No. 2849s, Jan., 1959.



**Yujing Liu**
He received B. Sc., M. Sc. and Ph.D. degrees in electrical engineering from Harbin Institute of Technology, Harbin, China, in 1982, 1985, and 1988, respectively. He has worked as associate professor in the area of electromagnetic computations, PM machine design, and other micro- and special machines.

Since 1996, he has worked in ABB Corporate Research, Västerås, Sweden. In addition to develop computational tools for machine analysis and design, he has made many investigations and studies on complex electromagnetic and thermal problems. His current interests include analysis, computations and simulations of electrical machines and drive systems.



**Stig Hjärne**
He has been employed by Alstom Power (ABB/ASEA) since his graduation 1970. Over the years he has been active within electrical design of turbo machines and the responsible person for the electrical design of Powerformer for turbo applications. He is nominated to senior technical specialist.