Optimal Utilization of Power Buses for Photovoltaic Installations

Prof. Dr.-Ing. H.-P. Schmidt
University of applied science Amberg-Weiden
Electrical Engineering

Summary

In photovoltaic systems economic wiring can results in remarkable savings. A technique so far used in electrical systems of buildings and factories is the power bus with piercing contacts. A flat cable -the so called power bus - is installed as one single cable run. The electrical connections are carried out via plugs and sockets, which are clamped onto the flat cable. The electrical connection of the cores is done by piercing contacts. Multi core cables are used to reduce installation costs. With the application to photovoltaic systems the thermal overload limit is off special interest.
To asses the thermal overload an equivalent electrical network is derived, where effective thermal resistances are determined from analytical, FEM and FVM calculations. A FVM simulation is carried out for detailed studies of an specific operating condition.
Results from simulations are in good agreement with measurements for various operating conditions.

1. Introduction

To further enhance the economics of photovoltaic installations considerable savings can be achieved, if conventional wiring is replaced by a power bus with piercing technology to contact modules. A single multi-core cable with a relatively small cross section can be used to wire many modules.

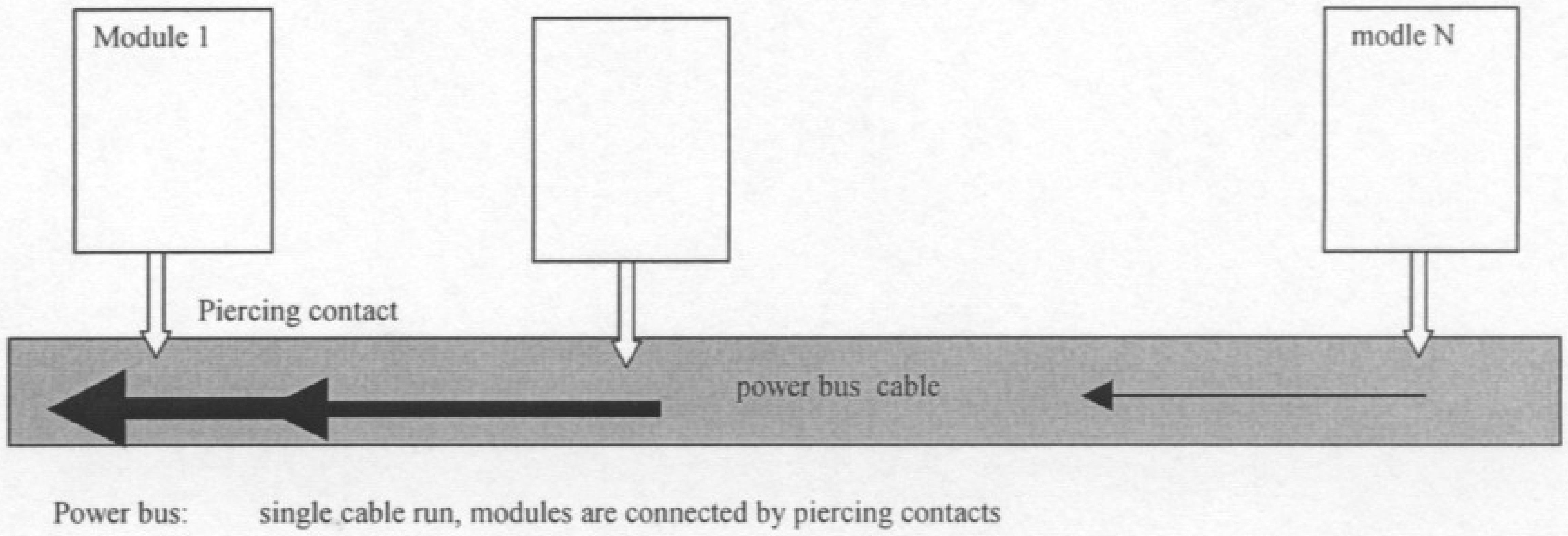


Fig.1 Schematic of an installation

Using a non standard cable the ampacity is to be determined for various laying and operating conditions. The maximum permissible current for a cable/line with respect to thermal overload is usually determined for a well-defined operational condition and then related to various actual conditions via [1] [2]

$$I_z = I_r \cdot \prod f_i$$

The "rated current" I_r is determined and correction factors f_i are applied to cover the relevant range of operational conditions. For optimal utilization actual operational conditions can be modelled in detail with numerical studies and appropriate corrections factors are determined.

In this study the lumped parameter (electrical equivalent circuit for heat transfer), the FEM (finite element method) and the FVM (finite volume method) are applied to determine the ampacity for various laying operational conditions.

2. Network approach

Modelling of heat flow with an electrical network requires appropriate simplifications, which are not always at hand. The parameters of concentrated elements are not always easily determined and the degree of detailing might be unclear. However, the resulting nonlinear circuit is solved with standard numerical procedures.

Firstly, a brief account of the network approach is given. Basic relations are deducted from the Poisson equation for charge conservation (steady state) and heat transfer (steady state) [1], [3],[4].
Time dependence is deducted from the network formulation and the time depended heat transfer equation. The basic equivalences and relations are:

Heat transfer		Network	
Temperature difference	ΔT	Voltage drop	ΔU
Heat flow	Φ	Current	I
Heat flux	ϕ	Current density	J
Thermal conductivity	λ	Elect. conductivity	σ
Thermal Resistance	R_{th}	Resistance	R
Thermal Capacity	C_{th}	Electrical Capacity	C
$\Delta T = R_{th}\,\Phi$		$\Delta U = R\,I$	
$\Phi = C_{th}\frac{\partial}{\partial t}\Delta T$		$I = C\frac{d}{dt}\Delta U$	

Convective and radiative heat transfer are modelled on the basis of an effective thermal resistance [3] ,[4],[5].

Determination of Parameters

For simple geometries heat conduction can be modelled easily, since thermal resistances are calculated just like electrical resistances. It is important to note that these resistances are calculated under the assumption of isothermal surfaces, this may not hold for real world applications and may lead to erroneous results. For layers the well known relations results:

$$\Delta T_g = T_0 - T_u = R_{thg} \cdot \Phi; \quad R_{thg} = \frac{1}{A}\frac{d_1}{\lambda_1} + \frac{1}{A}\frac{d_2}{\lambda_2} + \frac{1}{A}\frac{d_3}{\lambda_3}$$

Likewise are cylindrical geometries easily accessible and are widely applied to ampacity calculations [5],[6]:

$$R_{th} = \frac{1}{2\pi L \cdot \lambda} \ln\left(\frac{d_a}{d_i}\right)$$

The geometry of the flat cable consists of insulated copper wires which are embedded in the cable as shown in the following sketch.

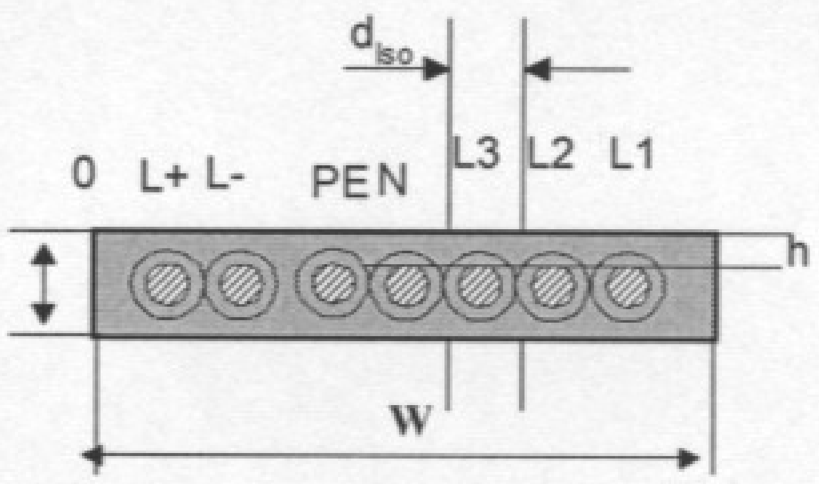


Fig. 3 Schematic sketch of the flat cable
Cores are designated as in standard AC-application, in photovoltaic installations designation changes)

Assuming a constant temperature at the surface one can approximate the thermal resistance. (E.g. four loaded cores). The heat from the core L2 will pass the layer of the width d_{iso} and the approximate thickness of h. The thickness h may be corrected, since the heat is applied from the cylindrical surface of the conductor with the radius r_L. Taking into account that half the heat is conducted upwards and downwards one might approximate the resistance by:

$$R_{th\_iso} = \frac{1}{2}\frac{h(1 + r_L/2)}{d_{iso} L \cdot \lambda}$$

L denotes the length of the cable.

More excat values might be found by FEM calculations. The heat transfer equation can be solved with FEM for an arbitrary geometry with high accuracy.

$$\frac{\partial}{\partial x}\left(\lambda(x,y)\frac{\partial}{\partial x}(T(x,y))\right) + \frac{\partial}{\partial y}\left(\lambda(x,y)\frac{\partial}{\partial y}(T(x,y))\right) = -s(x,y)$$

s denotes the source term i.e ohmic heating λ denots the thermal conductivity

From the solution i.e. the temperature field, the thermal resitance can calculated by the ratio of temperaturs to applied power. i.e $\Delta T= R_{th}\,\Phi$

The solution is shown for three cores loaded. The assumption that heat flows only in up- and downwards is retained quite well for the middle core. The thermal resistance calculated from the basic relation: is in good agreement with the analytical approximation, deviations are smaller than 3%.

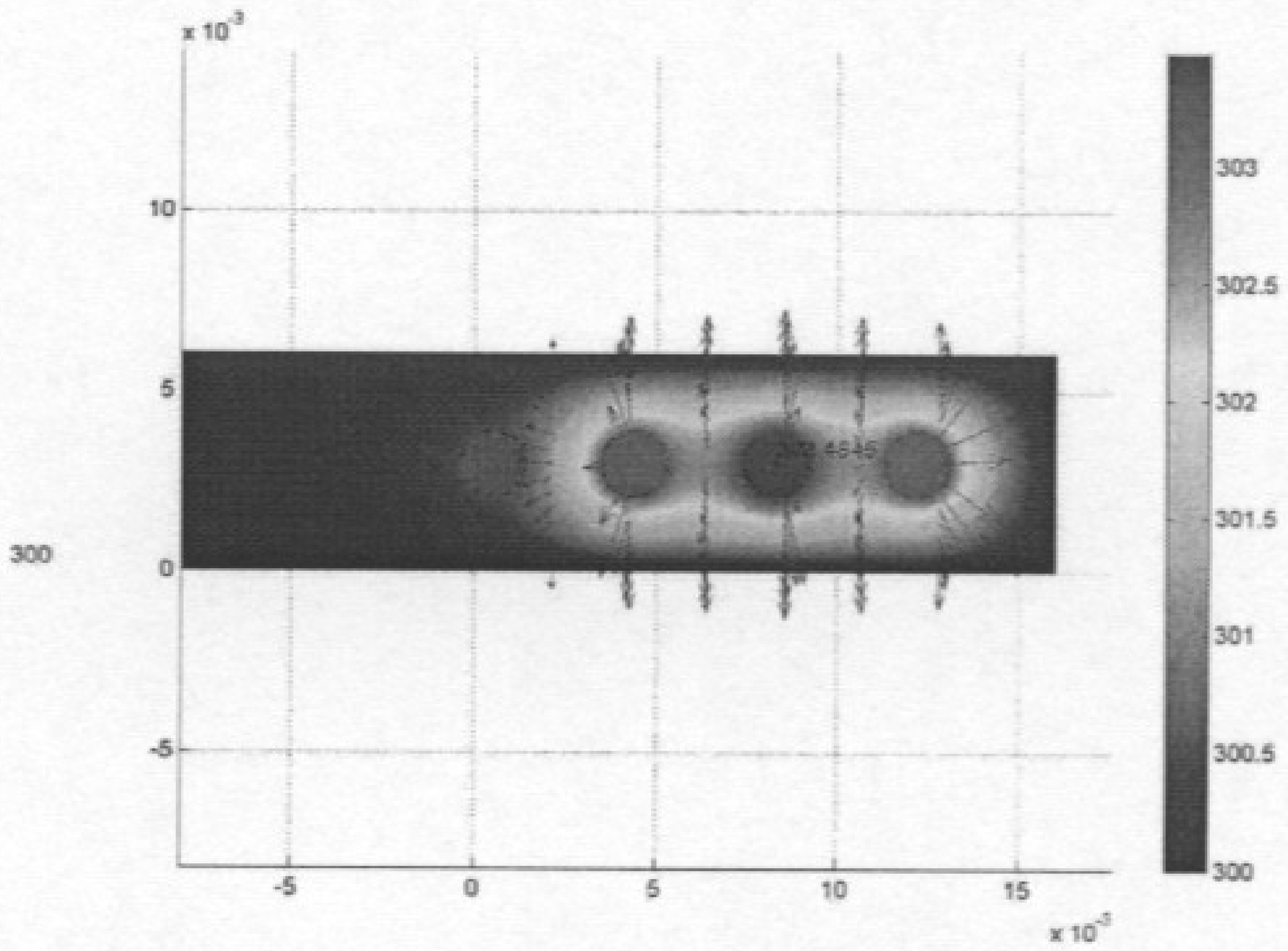


Fig. 4 Temperature distribution calculated via FEM. Arrows indicate heat flux

More complex are convective and radiative heat transfer. The thermal resistance for natural convection is given as

$$R_{th\_a} = \frac{1}{aA}$$

The heat transfer coefficient a may be determined via the boundary layer approach [3],[7].

$a = \frac{Nu \cdot \lambda}{L}$	heat transfer coefficient
$Nu = \left[0{,}825 + 0{,}325 Ra^{1/6}\right]^2$	Nusselt number
$Ra = Gr \cdot \Pr$	Rayleigh number
$\Pr = \frac{\eta c_p}{\lambda}$	Prandtl number
$Gr = \frac{g\beta \Delta T L L'^2}{\nu^2}$	Grasshof number

η viscosity, c_p thermal capacity, λthermal conductivity, β compressibilty, νviscosity, L length of surface, L' effective length

The according thermal resistance for the flat cable is given in the following graph.

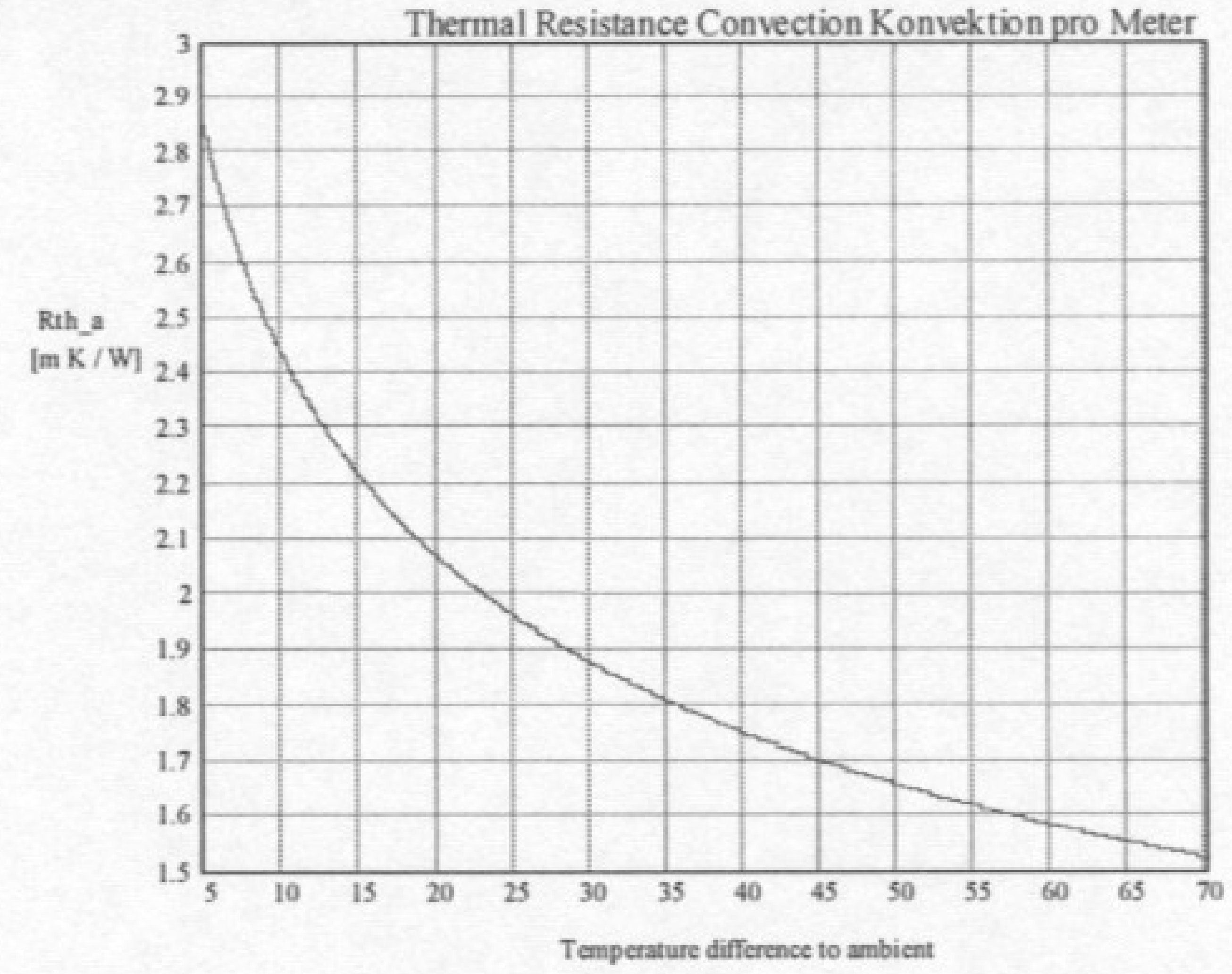


Fig. 5 Thermal resistance “free convection”

Likewise the thermal resistance for radiation is temperature depended. The simplest model [3], [7]leads to

$$R_{th\_s} = \frac{1}{A\varepsilon\sigma(T+T_u)\cdot(T^2+T^2{}_u)}$$

With one core carrying current the equivalent circuit for steady state conditions is shown below. This models a cable “free in air”.

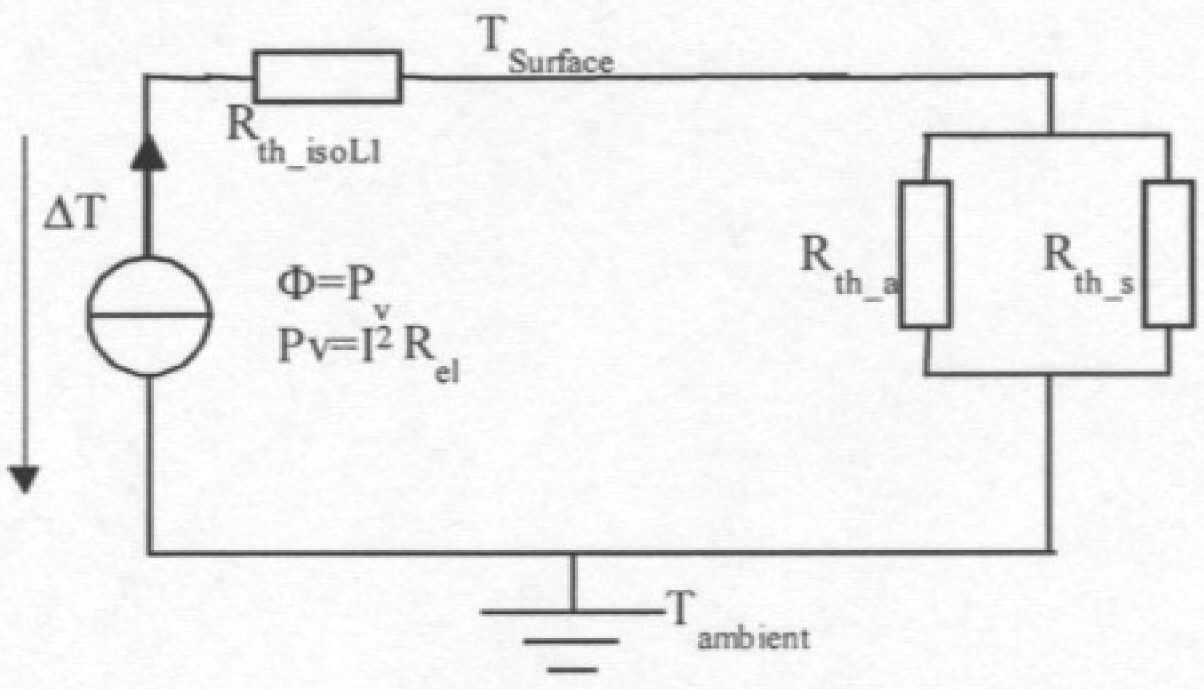


Fig. 6 Equivalent circuit for one loaded core

With more cores loaded this may be expanded to:

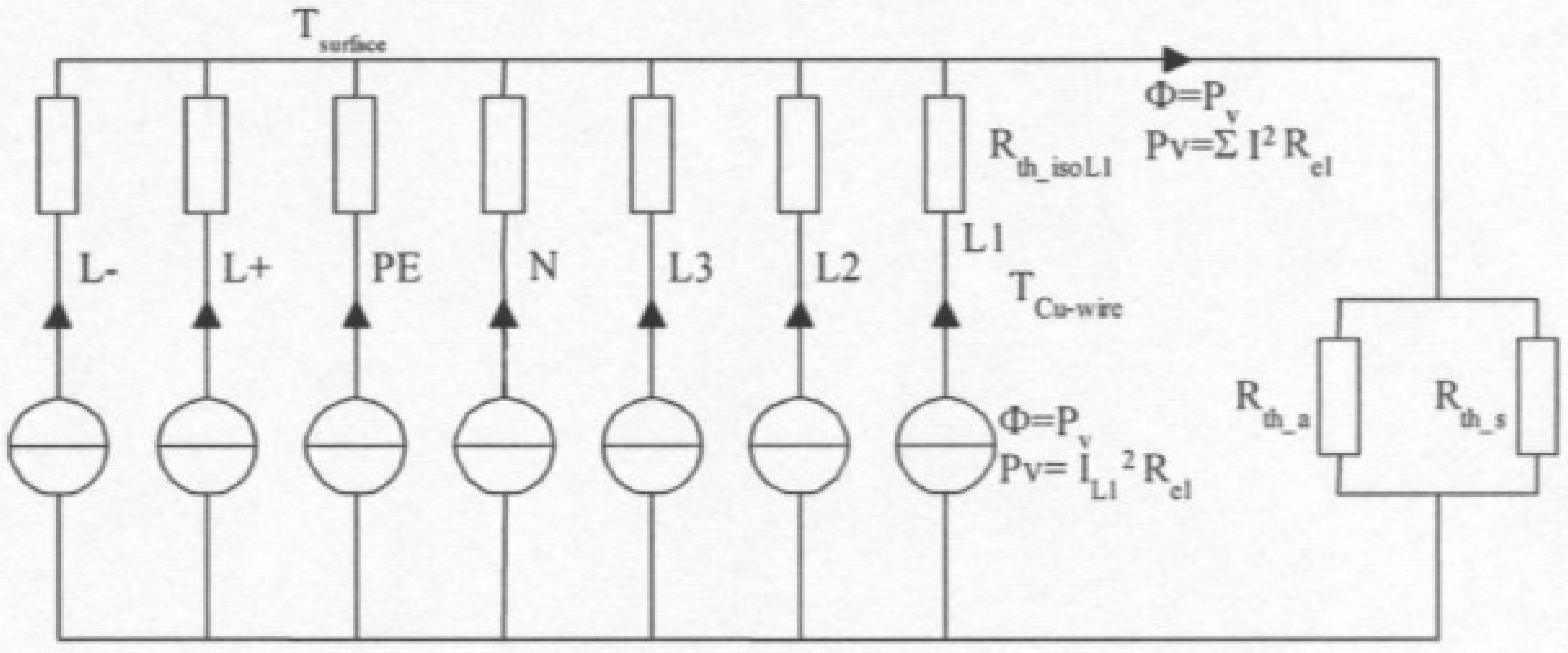


Fig. 7 Equivalent circuit with 7 loaded cores

The current sources model the temperature depended power losses of each core. The surface temperature is calculated from

$$\Delta T_{FL} = \Phi_{ges} \cdot \frac{R_{th\_a} R_{th\_s}}{R_{th\_a} + R_{th\_s}} = \sum I^2 \cdot R_{el}(T_L) \cdot \left(\frac{1}{R_{th\_a}(T_{FL}, T_u) + R_{th\_s}(T_{Fl}, T_u)} \right)^{-1}$$

While the temperature of the cores are calculated from

$$\Delta T_L = \left[p_L R_{th\_iso} + \left(\frac{1}{R_{th\_a}(T_{Fl}, T_u) + R_{th\_s}(T_{Fl}, T_u)} \right)^{-1} \right] \cdot \sum_i I_i^2 R_{el}(T_L)$$

Likewise the current can be determined from those equations when the maximum permissible temperatures of the cores are given.

$$\sum_i I_i^2 = \frac{\Delta T_{L\max}}{\left\{ p_L R_{th\_iso} + \left(\frac{1}{R_{th\_a}(T_{Fl}, T_u) + R_{th\_s}(T_{Fl}, T_u)} \right)^{-1} \right\} R_{el}(T_L)}$$

for $I_1 = I_2 = ... = I_N$

$$I = \frac{1}{\sqrt{N}} \sqrt{\frac{\Delta T_{L\max}}{\left\{ p_L R_{th\_iso} + \left(\frac{1}{R_{th\_a}(T_{Fl}, T_u) + R_{th\_s}(T_{Fl}, T_u)} \right)^{-1} \right\} R_{el}(T_L)}}$$

$$\Delta T_{L\max} = T_{L\max} - T_u$$

Considering different ambient conditions e.g. cable layings the effective resistances have to be determined again.

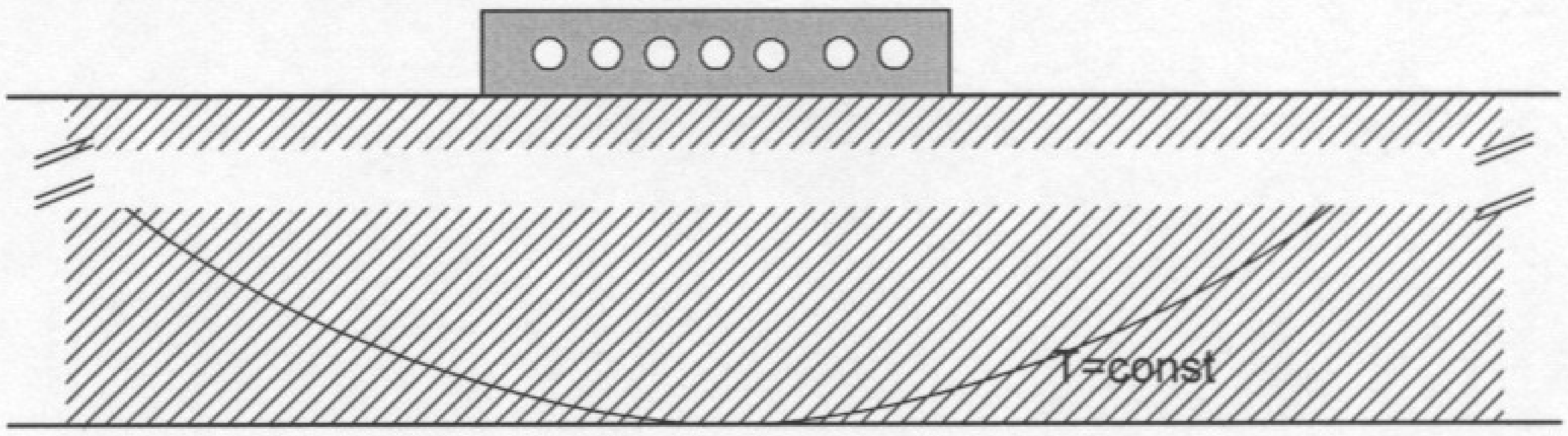


Fig. 8 Laying condition " on wall"

With one core carrying current and the cable fixed to a wall the following equivalent circuit results. A wall temperature at the surface of the cable and the temperature at the "free" surface are determined.

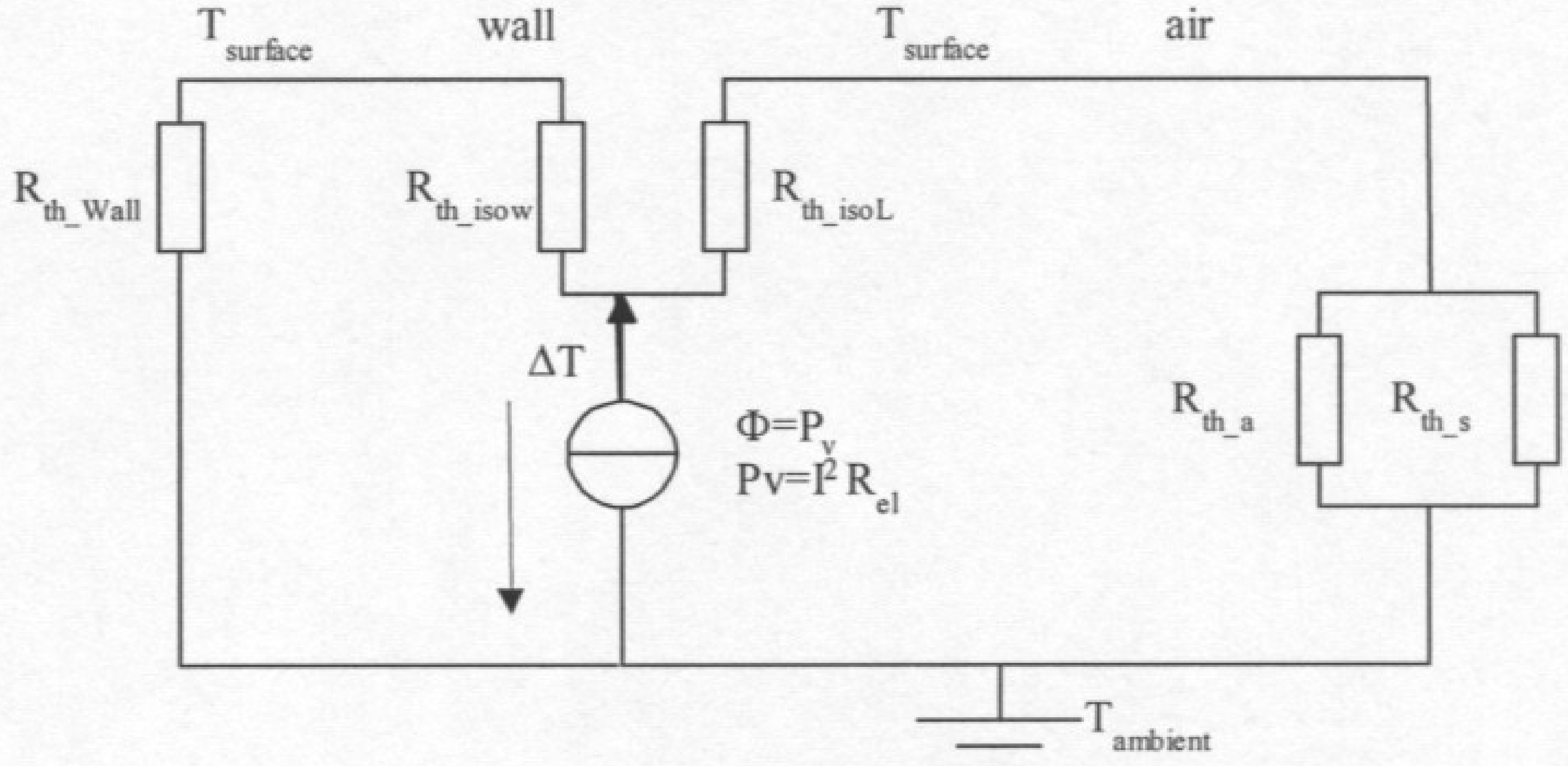
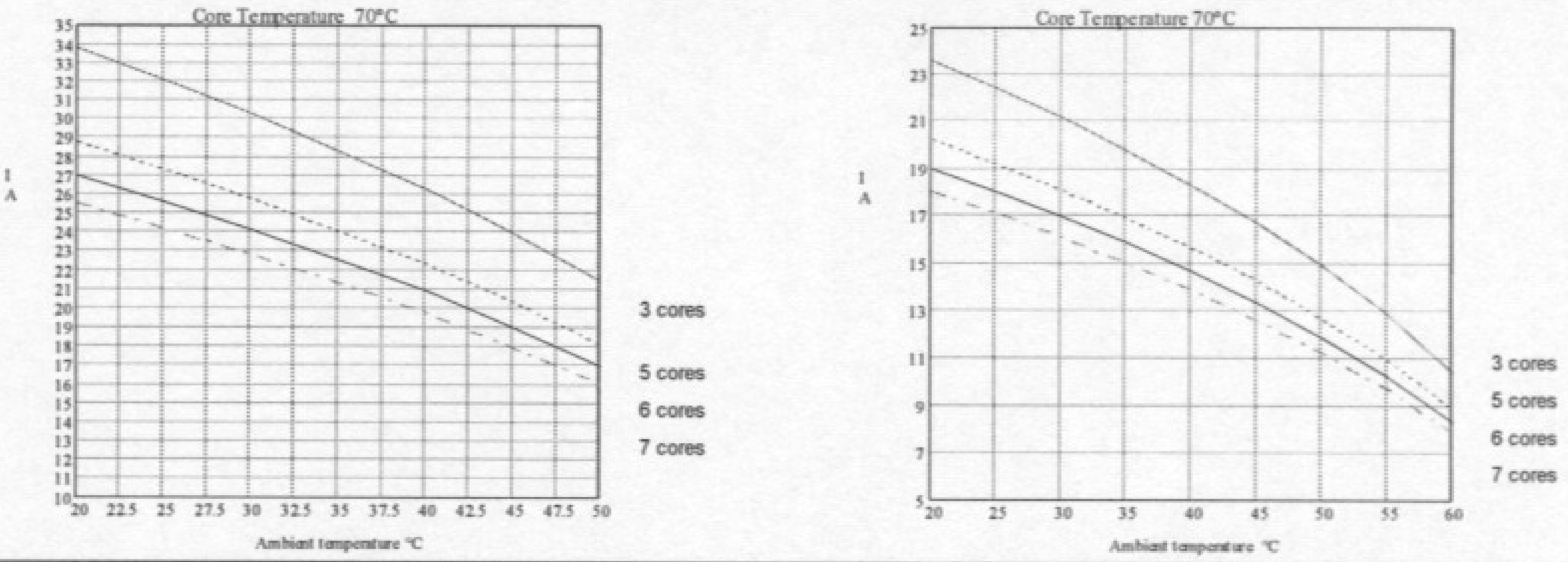


Fig. 9 Equivalent circuit "cable on wall" one loaded core

The core temperature for N loaded cores is calculated from:

$$\Delta T_L = \left(\frac{1}{\frac{R_{th\_isoW}}{N} + R_{th\_wall}} + \frac{1}{\frac{R_{th\_isoL}}{N} + \frac{R_{th\_a}(T_{FL\_Luft}, T_u) \cdot R_{th\_S}(T_{FL\_Luft}, T_u)}{R_{th\_a}(T_{FL\_Luft}, T_u) + R_{th\_S}(T_{FL\_Luft}, T_u)}} \right)^{-1} \sum_{i=1}^{N} I_i^2 R_{el}(T_L)$$



Concrete wall | Thermal insulating wall

Fig. 10 Maximum current for 70°C permissible temperature

All of the results given are in good agreement to measurements by R. Graf [9]

Summary "lumped parameter" network:

Basic circuits can be used to determine explicitly the temperature and corresponding currents for a cable.

Nonlinear equations are to be solved, which is easily accomplished by standard numerical procedures. (E.g. Secant method with modifications according to Ridder, Mueller,….)

As more details are required a system of nonlinear equation is to be solved and appropriate thermal resistances have to be determined. This becomes a tedious task.

Since only the actually required temperatures, currents are determined no extra effort is needed for post processing.

With suitable simplifications maximum or average values are calculated.

3. Detailed Simulations for specific operating conditions The numerical solution of the underlying PDE

FEM

A different approach is a numerical solution of the PDE for the appropriate boundary conditions. The differential equation reads including subdomain boundary temperature T

$$\nabla \cdot \lambda \nabla T = h \cdot (T - T_{amb}) + c(T - T_{amb})^4 - S$$

The actual material properties are not at hand and have to be deducted from measurements. Here the temperature dependence may not be neglected. A sufficient fine mesh for a discrete formulation is to be used.

One shortcoming of standard FEM package is the difficulty in handling convection explicitly. Using a heat transfer coefficient does not allow for detailed calculations and results depend heavily of the actual value used.

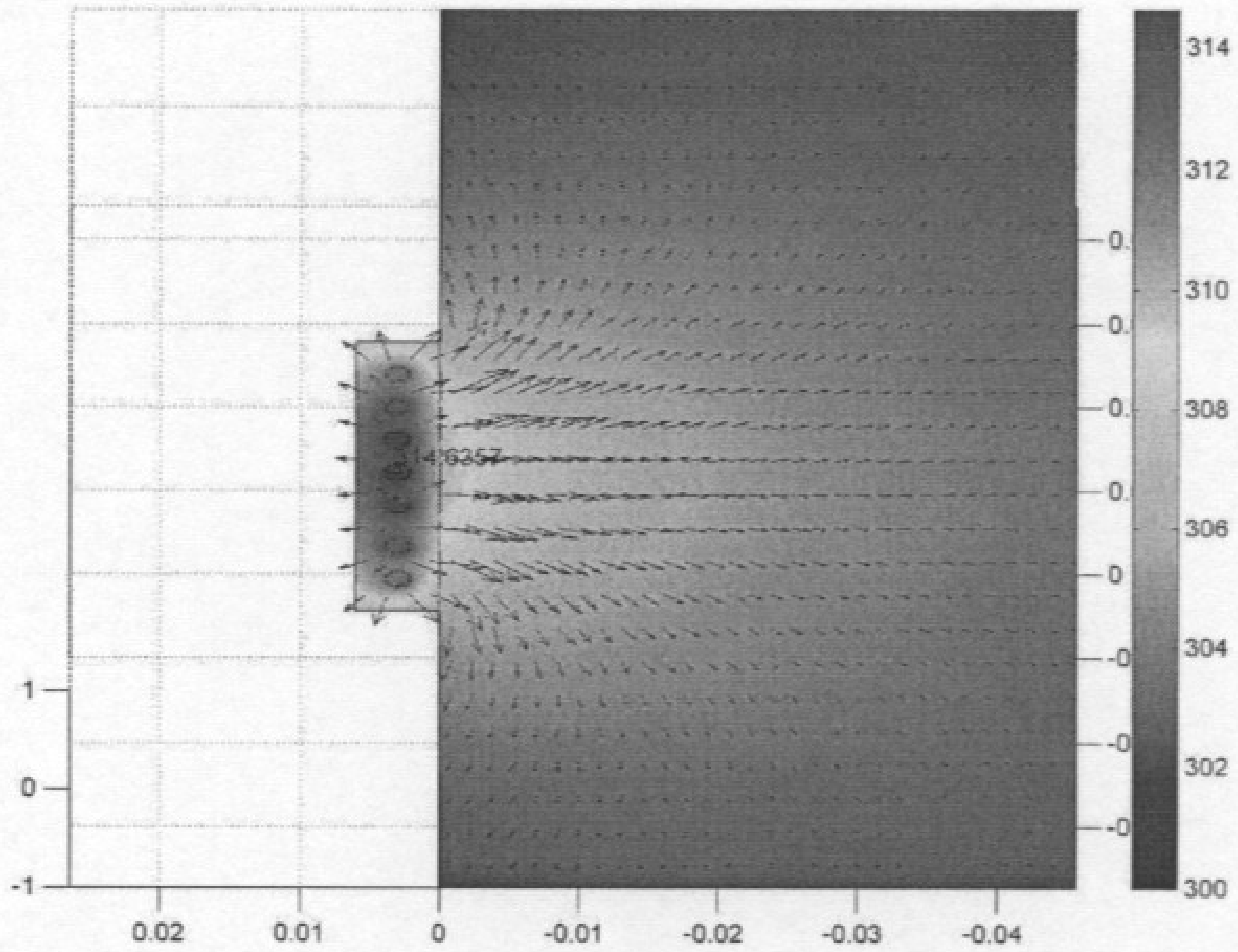


Fig. 11 FEM Calculation Cable with convection modeled (one side with heat transfer coefficient

The non linear navier stokes equation can only be handled with special algorithms and lead easily to excessive CPU-usage. The incompressible flow of natural convection is governed by the following PDE, where F denotes buoyancy forces and u velocity.

$$\begin{cases} -\eta \nabla^2 \mathbf{u} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} + \nabla p = \mathbf{F} \\ \nabla \cdot \mathbf{u} = 0 \end{cases}$$

FVM Simulation

The underlying PDE are the same, but no convective heat transfer coefficient is used. All of the conservation equations are solved simultaneously. I.e. energy, momentum and mass. The basic idea is to balance fluxes for small volumes.

The main advantage lies in the inherent better handling of convection. The so-called SIMPLE [9] –Scheme a semi implicit scheme with pressure correction (or alterations) is usually applied. This makes calculations of convective heat transfer feasible.

Still, computational requirement for 3-D simulations are considerable.

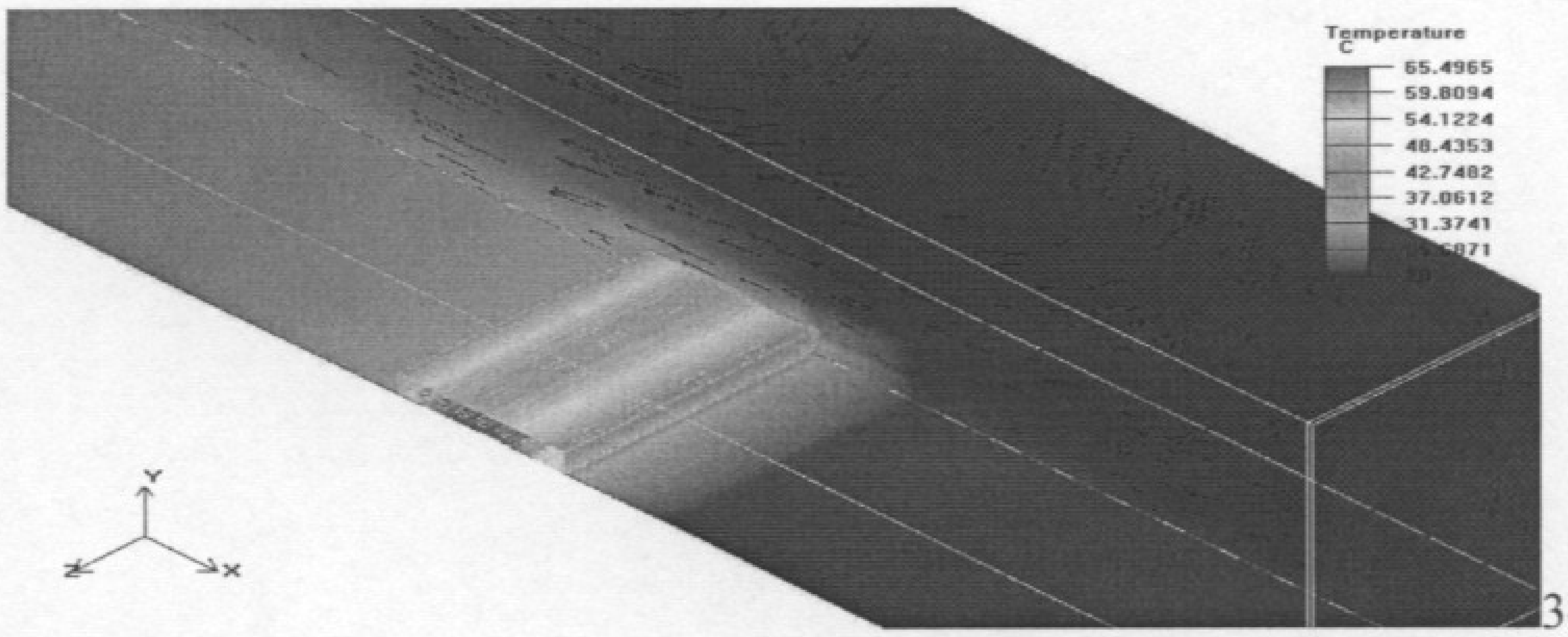


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Fig. 11 3- D FVM
Cable fixed to wall with an inclination of 45° with respect to buoyancy forces and flow restriction at the lower end.

Literature

[1] IEC 60287 Calculation of current ratings
287-1-1 Current rating equations

[2] VDE 0299- Teil 4 November 1998

[3] Wärmeübertragung, W. Walter, Vogel Buchverlag, Kamprath-Reihe, 4. Auflage, 1993

[4] Wärmeabfuhr in der Elektronik, M. Wutz, Vieweg,1991

[5] IEC 60287 287-2-1 Thermal resitance
Section 1 Calculation of thermal resistance

[6] IEC 60287 287-2-2 Thermal resitance ;
A method for calculating reductions factors.

[7] VDI Wärmeatlas

[8] R. Graf Optimal utilization of power busses
Master Theses FH Amberg Weiden

[9] Patankar, S. Heat Transfere and fluid flow, Hemisphere, NY