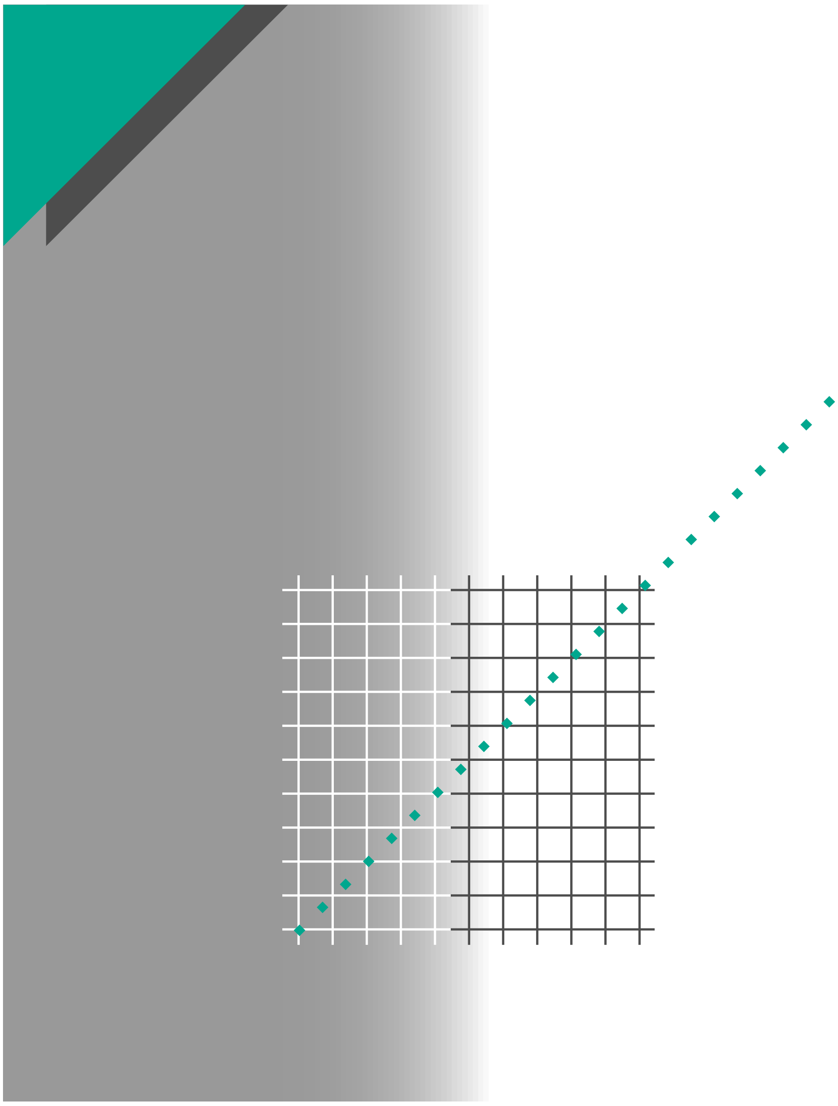
Collection Technique

Cahier technique n° 145

Thermal study of LV electric switchboards



C. Kilindjian

GROUPE SCHNEIDER

■ Merlin Gerin ■ Square D ■ Telemecanique

Cahiers Techniques are a collection of documents intended for engineers and technicians people in the industry who are looking for information in greater depth in order to complement that given in display product catalogues.

These Cahiers Techniques go beyond this stage and constitute pratical training tools.
They contain data allowing to design and implement electrical equipement, industrial electronics and electrical transmission and distribution.
Each Cahier Technique provides an in-depth study of a precise subject in the fields of electrical networks, protection devices, monitoring and control and industrial automation systems.

The latest publications can be downloaded on Internet from the Schneider server.
code: **http://www.schneiderelectric.com**
section: **mastering electrical power**

Please contact your Schneider representative if you want either a Cahier Technique or the list of available titles.

The « Cahiers Techniques » collection is part of the Groupe Schneider's « Collection Technique ».

Foreword
The author disclaims all responsibility further to incorrect use of information or diagrams reproduced in this document, and cannot be held responsible for any errors or oversights, or for the consequences of using information and diagrams contained in this document.

n° 145

Thermal study of LV electric switchboards

C. KILINDJIAN

After graduating as an engineer from the Ecole Supérieure d'Energie et des Matériaux of Orléans in 1986, he then joined Merlin Gerin in this same year as part of the Technical Section in the Low Voltage Switchboards unit.
Responsible for basic studies, he specialises in problems of heat exchanges and electrodynamic withstand in LV equipment.
He is currently working in the Anticipation departent of the Low Voltage Power Compartments SBS as an expert on thermal problems in LV circuit-breaker and equipment development.

E/CT 145 first issued, december 1997

Thermal study of LV electric switchboards

This «Cahier Technique» aims at furthering the understanding and mastery of the thermal problems encountered in LV electric switchboards.
After a brief review of standards and of thermal phenomena: conduction - radiation - convection, the author shows how LV cubicles can be modelled using modelling techniques normally reserved for other areas.
Modelling naturally leads to software to aid design of electrical cubicles equipped with switchgear.
The results are compared with real temperature measurements.
Finally, the methods and possibilities of the IEC 890 guide are described.

Contents

1 Introduction

1.1 Controlling thermal phenomena in LV cubicles

The new manufacturing methods developed in industry in recent years (just in time...) have brought a new notion to light: **industrial dependability**. This concept which covers two different aspects, safety of persons and equipment, and availability of electrical power, shows when it is applied to complex processes, the critical points whose operation must be thoroughly mastered.

The electric switchboard is one of these critical points.

Note that the problem is similar for major tertiary.
Formerly considered as a simple passing point, it has become the genuine nerve centre of electrical installations. The safety of the entire installation and thus of all industrial and tertiary activities relies on its dependability.

Mastery of its operation requires knowledge and control not only of the functioning of its components but also of the external influences to which they are subjected.

An electric switchboard is the combination of 4 basic elements:

- the envelope,
- the switchgear,
- the connections,
- the functions performing indication, control and processing of information.

Electric switchboards are increasingly technical and require a certain number of basic studies in order to master, in the design stage, the operating conditions of its components in a specific environment.
One area covered by such studies is the thermal aspects which form the subject matter of this «Cahier Technique».

2 Thermal problems in a switchboard

Three main reasons make thermal mastery increasingly vital. These reasons are:

- The tendency to place electrical equipment in envelopes (for safety purposes) which are increasingly made of insulating material (poor calory dissipation capacity).
- Progress of switchgear which includes more and more electronic components of increasingly compact size.
- The tendency to fill switchboards to their limit and an increasing bulk factor (ratio between the nominal current of the switchboard incoming circuit-breaker and the sum of nominal feeder currents. This factor is also known as the diversity factor).

2.1 Causes, effects and solutions

The temperature of an electrical device is the result of:

- the Joule effect ($P = R I^2$), i.e. of its withstand to current flow,
- ambient temperature.

Electrical switchgear is designed in accordance with manufacturing standards which define the maximum temperatures not to exceed to ensure safety of persons: temperature of case and of switching devices, maximum temperature deviation for terminals; this is verified by product certification tests.

As devices function in a wide variety of working conditions in switchboards, the causes of excessive temperature are numerous.

Table (see **Figure 1**) shows the main causes, their effects and the possible solutions.

Causes	Effects	Protection	Solutions		
External temperature too high	■ Switchboard internal temperature too high ■ Tripping of thermal releases ■ Ageing of electronics ■ Temperature of enclosure walls too high	■ Alarm ■ Automatic fan startup	■ Improve ventilation of room and/or switchboard	Can occur in some cases even when designed according to standard practice.	IEC439
High diversity factor. Installation possibilities exceeded.	■ Tripping of switchboard incoming protection ■ Switchboard internal temperature too high ■ Temperature of enclosure walls too high	■ Load shedding	■ Adequately sized switchboard		
Short-circuit or overload	■ Damaged conductors ■ Damaged insulated bar supports	■ Safety tripping	■ Adequately sized conductors. ■ Supports with good electrodynamic at high T°		IEC634
Loose connections	■ Device conductors destroyed	■ Uncertain upstream tripping	■ Tightness checks. ■ Temperature rise detection.	Mounting and maintenance problems	
Conductor cross-section too small	■ Conductors destroyed	■ None	■ Adequately sized conductors.	Installation design error	IEC898
Device derating error or incorrect positioning	■ Abnormal operation (tripping) ■ Premature ageing	■ Tripping or indication	■ Review choice of components and/or positioning. ■ Ventilation.	Error in choice or use of device	IEC947

***fig. 1**: thermal problems in terms of cause and effect.*

The problem in fact consists of ensuring, on switchboard design, that all its components will operate in temperature conditions that are less restrictive than those laid down by their construction standards. The scheduled current must obviously be able to flow through the connection switchgear (circuit-breakers, contactors, etc...) without any problem.

In addition to safety of persons and equipment, two other objectives must be considered:

- availability of electrical power (no untimely operation or failure to operate),
- lifetime of components.

In conclusion, the challenge consists of anticipating with a high degree of certainty the thermal operating state of the switchboard.

Three types of solutions can be identified:

- the panel builder's experience,
- the real tests for repetitive switchboards,
- the use of software which can determine, according to envelope characteristics, the current strength/temperature pair for each heat source (switchgear - conductors) (see paragraph 4), in accordance with their position and with the temperature of the surrounding air. It is obvious that a software validated by experience and tests is of great use as it allows comparative study of the many possible installation configurations and thus optimisation of the future switchboard as regards thermal aspects and... cost.

2.2 Taking stock of standards

Many standards cover the Low Voltage area, for example the NF C 15-100 for France which defines the rules to be complied with for all LV installations.
As regards definition and design of LV devices and assemblies, the following can be referred to respectively:

- Switchgear standards, e.g. IEC 947.
- The IEC 439 standard for LV cubicles (assemblies). The IEC 439 international standard is divided into three parts:
  - IEC 439.1 which contains the rules for type tested assemblies and for partially type tested assemblies,
  - IEC 439.2 which defines the rules for prefabricated ducts,
  - The IEC 439.3 draft standard which covers LV switchgear assemblies installed in places accessible to untrained persons.

The part particularly of interest to us for LV switchboards is IEC 439.1 edited in 1985.
In the European context, this standard acts as a structural framework for most national standards (British Standard, NF C, VDE...) whose contents are a fairly accurate copy of the text of the IEC standard in which differences correspond rather to the country's specific practices than to questioning of fundamental points of the IEC standard.
In France this is the case of the NF C 63-410 standard.
The main contribution of this standard has been a more accurate definition of two notions aiming at increased safety. These notions are:

- That of Totally Tested Assemblies, **TTA** (type tested assembly) or of Partially Type Tested Assemblies, **PTTA**.
- The notion of forms (see **fig. 2**).

Without going into detail, we can say that the **TTA** correspond to products that are completely defined and frozen both as regards their components (exact drawings of each component) and manufacturing (assembly guide...) and which have to meet **type tests** (temperature rise, short-circuit, continuity of frames...) laid down by the standard.

The **PTTA** correspond to assemblies whose basic structure is a TTA to which one or more modifications have been made which must be validated either by calculation or by a specific test.

The notion of **forms** corresponds to a precise definition of the degrees of separation that can be found in a switchboard and which increase protection of persons by inaccessibility to live parts (busbars...). Four types of forms can be identified ranging from total absence of separation (form 1) to complete partitioning of the various switchboard elements (form 4).
It should be noted that these partitions obviously greatly affect the thermal behaviour of these assemblies.

The IEC standard also defines the temperature rise test to be verified on assemblies.
It stipulates the conditions and temperature rise limits (paragraph 8.2.1. of the standard) that must not be exceeded by the assembly components.

- Test conditions:
  - the assembly must be set out as in normal usage,
  - the current corresponding to the rated value is distributed in the various devices allowing for a diversity factor (Kd) varying according to the number of main circuits

2 ⩽ number of feeders ⩽ 3 Kd = 0.9
4 ⩽ number of feeders ⩽ 5 Kd = 0.8
6 ⩽ number of feeders ⩽ 9 Kd = 0.7
number of feeders ⩾ 10 Kd = 0.6

  - thermal stabilisation is reached if the temperature variation does not exceed 1°C/h.

The cross-sections of the conductors connected to the devices must conform with the standard.

- the T° measurements are performed using thermocouples
- the reference ambient temperature is 35 °C

- Temperature rise limits

Compared with ambient temperature, the following temperature limits must not be exceeded:

- 70 K for terminals connecting external conductors,
- 25 K for manual control devices,
- 30 K or 40 K for accessible or inaccessible external metal surfaces,
- specific values for built-in components and for insulators touching the conductors.

As concerns standardisation, a technical guide for the predetermination of these temperature rises is also available (IEC 890). However it requires validation by a number of tests as it does not have standard status.
It provides correct results for simple configurations (envelope with few partitions, evenly distributed hear sources...). A presentation of this method is proposed in paragraph 7 together with a comparison with our «cubicle» designer approach.

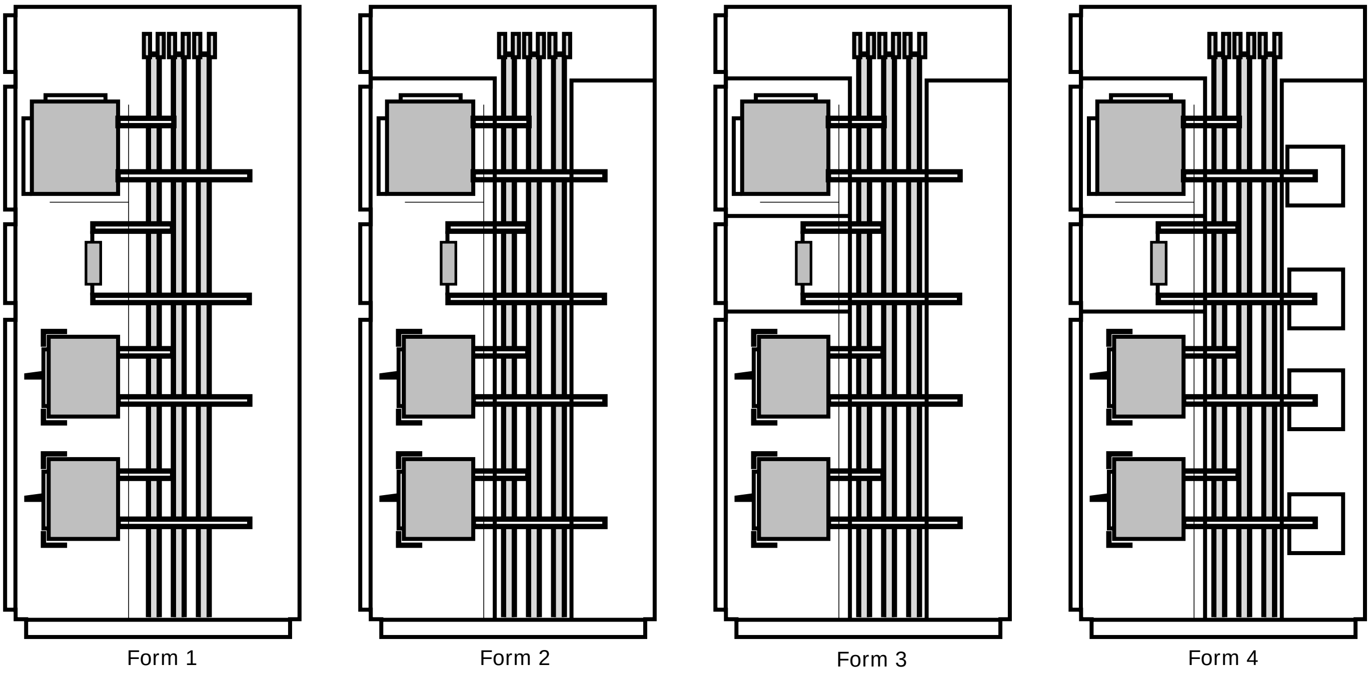

Form 1 Form 2 Form 3 Form 4

fig. 2: *various «forms» as in IEC 439-1/NF C 63-410 standards.*

3 Thermal behaviour of a LV electric switchboard

An electrical switchboard is a system made up of a fluid (air) and of solid bodies in which electric current flow is accompanied by energy losses causing the temperature to rise.
Progress towards thermal equilibrium involves the transfer of heat from live parts (devices, conductors....) where it is generated, to the parts in contact with the exterior which in turn transmit this heat to the surrounding atmosphere.

3.1 Brief review of the main thermal phenomena

The thermal behaviour of any system, including an electrical switchboard, can be described in terms of heat exchanges. Three types of phenomena are involved:

Conduction:

Transfer of heat inside solid bodies (see **fig. 3**). This phenomenon can be divided up into:

- Simple conduction where the body in question is not a source of thermal phenomena, e.g. conduction inside a wall.
- Live conduction where heat is created inside the body in question, e.g. a copper bar with an electric current flowing through it.

Calculations concerning the transmission of heat by conduction are based on Fourier's law which, for simple geometries, can be resumed by the equation:

$$\Phi_{i\,j} = \frac{\lambda S}{d}\left(T_i - T_j\right) \text{ where}$$

$\Phi_{i\,j}$: heat flux between two points i and j in W,
λ: thermal conductivity in W/m °C,
S: area of the heat exchange surface in m^2,
T_i, T_j: temperatures of the two points in °C,
d: distance between the two points in m,
λ is characteristic of the «conductive» medium. Its value depends on temperature but in most cases is considered as constant.

e.g. a few values of λ in W/m °C

Silver	$\lambda = 420$
Copper	$\lambda = 385$
Aluminium	$\lambda = 203$
Steel	$\lambda = 45$
Plastics	$\lambda = 0.2$
Concrete	$\lambda = 0.935$
Brick	$\lambda = 0.657$
Glass wool	$\lambda = 0.055$
Air (30 °C)	$\lambda = 0.026$

Radiation:

Transfer of heat between solid bodies separated by a medium of varying transparency (see **fig. 4**).

Such exchanges take place between the surfaces of any bodies facing one another and are represented by fairly complex relationships involving:

- The emission of the solid which, if considered to be an ideal black body, depends only on its temperature.
- The nature of the surface of the solid, expressed by its emissivity ε which reflects the relative ability of a surface to radiate energy as compared with that of an ideal black body under the same conditions.
- Reflection and absorption phenomena.

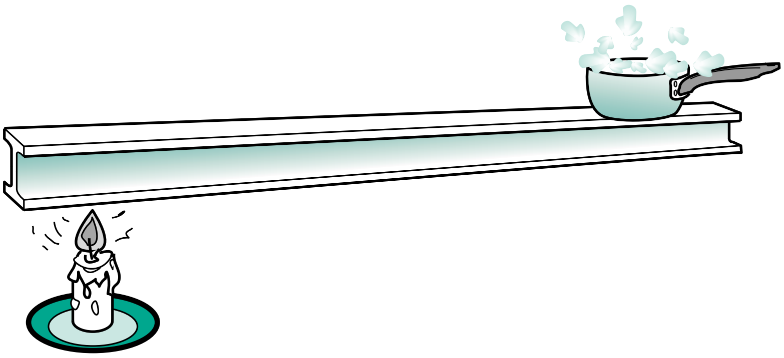


fig. 3: conduction.

- The disposition of these surfaces via form factors.

However in the special case where one surface (for example j) completely surrounds another surface (i) such that the ratio S_i / S_j is small, these expressions are simplified and we obtain:

$\Phi_i = \varepsilon_i \, \sigma \, S_i \left(T_i^4 - T_j^4\right)$ where
Φ: heat flux transferred through the surface i in W,
ε_i: emissivity of the surface i,
σ: Stefan-Boltzmann constant
(5.67032×10^{-8} W m^{-2} K^{-4}),
S_i: surface area in m^2,
T_i, T_j: temperature of opposite surfaces in K,

Convection:

The general term of convection in fact covers two different phenomena which are frequently treated together.

- Actual convection which corresponds to a transfer of heat between a solid body and a moving fluid. According to the origin of fluid movement, convection can be natural or forced (see **fig. 5**).

These transfers are characterised by exchange coefficients h_i:
$\Phi_i = h_i \, S_i \left(T_f - T_i\right)$ where
Φ_i: heat flux at the surface S_i in W,
h_i: heat exchange coefficient in W/m^2 °C,
T_f, T_i: temperatures of the fluid and of the surface of the solid body in °C,

From a physical viewpoint, the problem of heat exchange by convection is closed related to a fluid mechanics problem.

However from a practical viewpoint it can be tackled «simply» using heat exchange coefficients with expressions involving:

  - parameters describing the type of fluid flow (velocity, etc.),
  - the physical properties of the fluid (thermal conductivity, dynamic viscosity, thermal capacity, density, etc.).

They are often combined in the form of dimensionless numbers or characteristics (Nusselt, Prandtl, Reynolds, Grasshof numbers...).

For example: expression of the heat exchange coefficient for natural convection and a simple geometry: flat vertical plate of height L with a uniform temperature distribution

$h = \dfrac{Nu \, \lambda}{Dh}$ where
Nu: Nusselt number,
$Nu = 0.53 \, (Gr \, Pr)^{0.25}$
where Gr and Pr are the Grasshof and Prandtl numbers respectively, functions of the physical properties of the fluid and of the temperature difference between the fluid and the heat exchange surface,
λ: thermal conductivity of the fluid (W/m °C),
Dh: characteristic dimension (m).
In most cases Dh corresponds to the largest dimension of the solid body in contact with the moving fluid, in this case L.

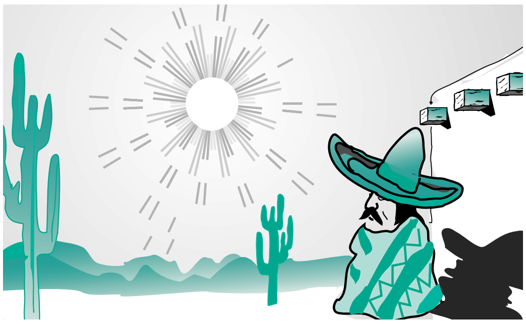


__fig. 4__: radiation.

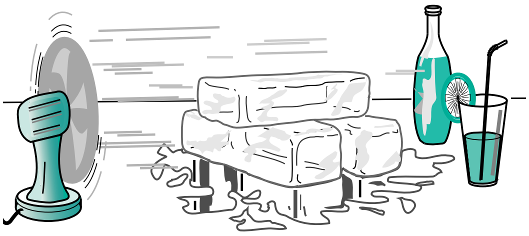


__fig. 5__: convection.

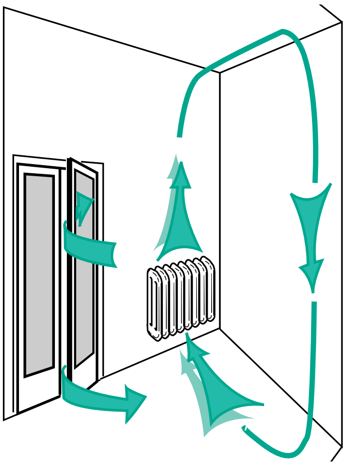


__fig. 6:__ convection currents.

NB: Note that the heat exchange coefficient depends on the temperature difference raised to a power of 0.25, hence:

$h = K(\Delta t)^{0.25}$

- **convection currents** which transfer heat through a fluid by the actual movement of the fluid. This explains, for example, the temperature gradient observed between the top and the bottom of a volume of a closed fluid subjected to heating.

The movement of air between two volumes is characterised by mass flowrates which are functions of flow cross-sections and flow velocities (see **fig. 6**).

Heat transfer is represented by:

$$\Phi_{i\,j} = \overset{\circ}{M}\,cp\left(T_i - T_j\right)$$

where

$\Phi_{i\,j}$: heat flux exchanged between i and j in W,

$\overset{\circ}{M}$: mass flowrate in kg/s,

cp: heat capacity of the fluid in J/kg °C,

T_i, T_j: temperature of the fluid in volumes i and j (°C).

NB: heat transfer is imposed by the direction of flow.

Expression of fluid velocity: in the case of natural convection, the fluid is set in motion between points i and j by the variation of its density with temperature.
Velocity is thus assumed proportional to these variations, i.e. a function of the difference in temperature between i and j.

$$V_{i\,j} = \text{Constant}\sqrt{\frac{\Delta\rho}{\rho}\,g\,D_{i\,j}} \quad \text{where}$$

$\Delta\rho/\rho$: relative variation of density,

g: acceleration due to gravity in m/s^2,

$D_{i\,j}$: distance between the two points i and j in m.

Moreover, if the fluid in question is assumed to have a perfect gas behaviour, then:

$$\Delta\rho/\rho = \beta\left(T_i - T_j\right) \text{ hence}$$

$$V_{i\,j} = \text{Constant}\sqrt{\beta\left(T_i - T_j\right)g\,D_{i\,j}}$$

where $\beta = \dfrac{1}{\left(T_i + T_j\right)/2}$ (case of perfect gases)

T_i, T_j: temperature of fluid in K

These formulae correspond to ascending or descending fluid volume movements.
In the case of fluid movement near a wall, the problem is both thermal and hydraulic and can be solved analytically in some cases (laminar flow along a wall).
In this case the fluid velocity along the wall has a similar expression, i.e. it is proportional to a temperature difference (fluid-wall).
See page 25 for a review of the definition of °C, K and °F.

3.2 Exchanges at switchboard level

The diagram below (see **fig. 7**) represents the elements making up the system studied: ambient air, enclosure, internal air and the various heat sources. This description of the switchboard thermal state shows that all the exchange phenomena described above must be taken into consideration and are all considerably inter-related.

For example:

■ The internal air temperature results:

□ from exchanges by convection between the internal air and the surfaces of the various devices, conductors and walls,

□ from the heat conveyed by the convective movements of air.

■ For the electrical devices in the switchboard, the heat generated by Joule effect is exchanged:

□ by convection between their heat exchange surfaces and the internal air,

□ by conduction with the bars and cables,

□ by radiation with the enclosure walls and the surfaces of the other devices.

The most important phenomena involved in overall behaviour are the convection phenomena.

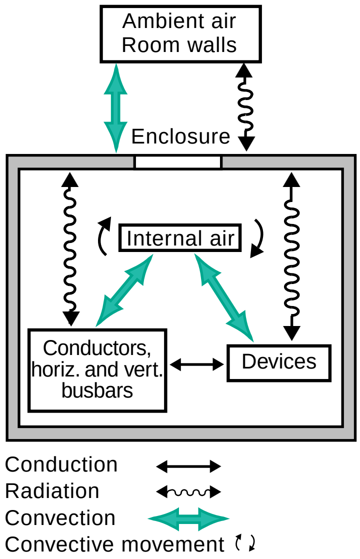


__fig. 7__: thermal behaviour of an enclosure.

4 Presentation of modelling

4.1 Principle

All the solution methods (e.g. Monte-Carlo, finite differences, finite elements) are based on a breakdown of the system to be modelled into elementary modules.

The chosen method, **nodal analysis**, is derived from a finite difference approach. Although conventional, this technique has the advantage of being able to represent thermal behaviour of a complex system while allowing for the interactions between the various parts or components of which it is made.

It can be used in a wide variety of applications, for instance to describe the behaviour of an artificial satellite, an electric motor, the climatic conditions inside a transformer substation or a building consisting of several rooms.

In theory this method consists of breaking up the system in question into various **isothermal volumes** known as **nodes**. Each node has a number of parameters, including a temperature, and, in some cases, a heat input independent of the heat exchanges. We then examine **couplings between nodes**, i.e. the various exchanges between volumes which will allow us to write our balance equations (conservation of energy and mass in the volume element attached to a specific node). This approach is in fact a spatial discretisation of the system and results in the definition of a **thermal network** with its nodes, capacities, heat sources and conductances expres-sing the various couplings between nodes (analogy of electrical and thermal phenomena): (see fig. 8).

We thus obtain a system of coupled equations, linear or non-linear, which will enable us to define a matrix, **the thermal admittance matrix**. We then have to specify the numerical values of the elements of this matrix which correspond to the **thermal conductances**.

Expression of conductances per type of exchange:

- Conduction: $G_{ij} = \lambda_i S_{ij} / D_{ij}$
- Radiation: $G_{ij} = \alpha \sigma \varepsilon S F_{ij} \left(T_i + T_j\right)\left(T_i^2 + T_j^2\right)$
- Convection: $G_{ij} = h_i S_{ij}$
- Convective movement: $G_{ij} = \overset{\circ}{M} cp$

Expression of heat flux equivalent to electric current:

$$I = \frac{1}{R}(\Delta U)$$

$\Phi_{ij} = G_{ij}\left(T_i - T_j\right)$ where

G_{ij}: energy flux between nodes i and j,

G_{ij}: conductance between i and j, dependent on the type of exchange considered,

T_i, T_j: temperatures associated with nodes i and j respectively.

As an example, let us model a room containing a heat source.

This system is broken down into 4 nodes:

1 for the internal air

2 for the walls (internal and external)

4 for the external ambient air

Nodal representation (simplified) (see fig. 9).

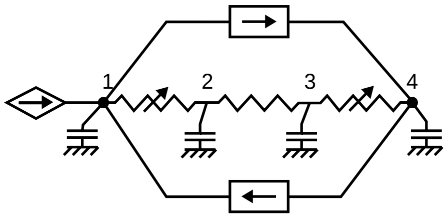
Equations expressing the heat fluxes for this simple system:

node 1:

$$Q_1 - h_{1.2} S_{1.2}\left(T_1 - T_2\right) + \overset{\circ}{M}_{4.1} cp\left(T_4 - T_1\right)$$
$$\overset{\circ}{M}_{1.4} cp\left(T_1 - T_4\right) = \rho_1 V_1 cp_1 \overset{\circ}{T}_1$$

Thermal quantities	Electrical quantities
Temperature	Potential
Thermal resistance	Electrical resistance
Heat flux $\Phi = G\left(T_2 - T_1\right)$	Current $I = \frac{1}{R}\left(U_2 - U_1\right)$
Thermal capacity	Electrical capacitance

fig. 8: Correspondence between thermal and electrical quantities.



Nod 1 : internal air

Nos 2 and 3 : internal and external walls

Nod 4 : external ambient air

〰 represents exchanges by conduction

⇝ represents exchanges by convection

⊣→⊢ represents exchanges by displacement of air

◈ represents the input of heat in node 1

⏚ represents the heat capacity associated with each

fig. 9: Simplified nodal representation - modelling of a room.

node 2:

$$h_{1.2}\,S_{1.2}\left(T_1-T_2\right)-\frac{\lambda_2\,S_{2.3}}{d_{2.3}}\left(T_2-T_3\right)$$
$$=\;\rho_2\,V_2\,cp_2\,\dot{T}_2$$

node 3:

$$\frac{\lambda_2\,S_{2.3}}{d_{2.3}}\left(T_2-T_3\right)-h_{3.4}\,S_{3.4}\left(T_3-T_4\right)$$
$$=\;\rho_3\,V_3\,cp_3\,\dot{T}_3$$

node 4:

$$h_{3.4}\,S_{3.4}\left(T_3-T_4\right)+\dot{M}_{1.4}\,cp\left(T_1-T_4\right)$$
$$\dot{M}_{4.1}\,cp\left(T_4-T_1\right)\;=\;\rho_4\,V_4\,cp_4\,\dot{T}_4$$

NB: the terms T_i correspond to $\frac{d\,T_i}{d\,t}$.

Therefore they can be ignored when only the steady state with stabilised temperatures is considered.

Using these equations we then deduce the system of equations $[G][T]\;=\;[R]$ corresponding to:

$$\Phi_{i\,j}\;=\;G_{i\,j}\left(T_i-T_j\right)$$

where:
G: is the thermal admittance matrix
T : is the vector of unknown temperatures
R: is the vector of imposed conditions (heat sources Q1, temperature,...).

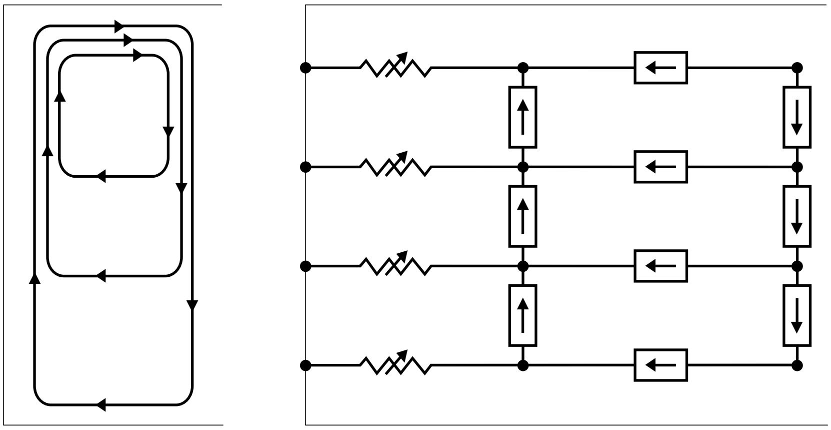
This type of approach has made it possible to establish calculation codes and regulations relating to thermal problems in buildings.

4.2 Modelling convection

As already mentioned in section 2, «convection» covers two phenomena which are treated together in most cases (exchanges between solid body and fluid and exchanges in the actual fluid).

Modelling of exchanges by convection must therefore by divided into two parts.

One part describes the mass flowrates (air movement) and the other the heat exchanges (heat exchange coefficient). The two parts are connected by the mass/thermal transfer dependencies (see **fig.10**).



Air movements

Corresponding nodal diagram showing the two aspects of convection

fig. 10: *mass and thermal modelling of convection.*

4.3 Application to LV enclosures

Two main types of enclosures can be identified for modelling purposes:

Non-partitioned enclosures

(boxes, cubicles...). In this case the nodal diagram, shown in **figure 11**, resembles the diagram in **figure 10**, with integration of the heat sources.

Highly partitioned enclosures with or without natural ventilation.

There are two possible modelling approaches:

- Each switchboard zone can be modelled as above and then these volumes are associated. However this results in overly large matrices bearing in mind that there can be a dozen zones to associate.

- A more global approach can be used without modelling the convection currents inside the various volumes and allowing only for air flows between zones (see **fig.12**).

These approaches have resulted in different software for each enclosure type. These programs are all structured in the same manner. Before describing in detail how to use the software (section 5), it is first necessary to further our knowledge of heat sources (busbars, devices) in order to determine the real operating currents of the devices installed in a switchboard.

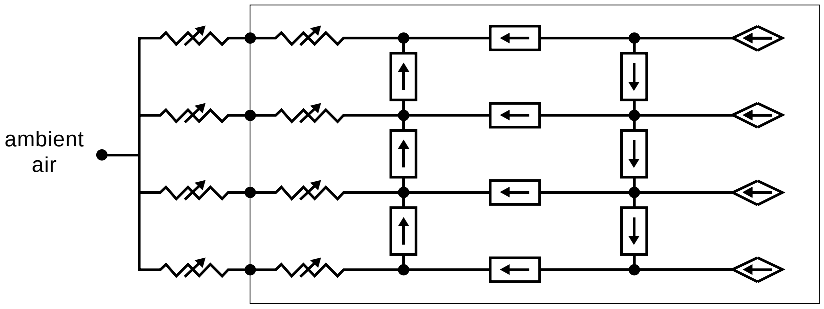


***fig.11**: Non-partitioned enclosures.*

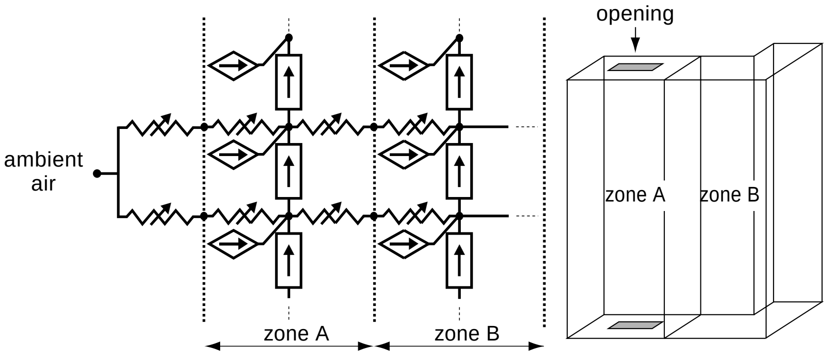


***fig.12**: case of a partitioned enclosure.*

5 Behaviour of heat sources and characteristics

The heat sources considered in modelling are busbars, connection conductors and electrical devices.
The latter are considered to be «black boxes» dissipating calories instead of model modes. In other words, rather than their operating temperature, we calculate the maximum current that they are able to convey for a given installation configuration so that they do not exceed their maximum operating temperature.

5.1 Busbars

Busbars are designed to satisfy two conditions:

- Sufficient capacity to convey the required rated current without inducing a temperature rise in the bars that could damage the insulators supporting them.
For example the bars can be sized so that they do not exceed a steady state temperature of 110 °C; this value is completely dependent on the type of insulating materials with which they are in contact, for example the supports. The table in **figure 13** gives a few busbar temperature values for an ambient temperature of 50 ° and 65 °C.

- Capacity to withstand a short-circuit current without serious bar deformation, rupture of insulator supports or excessive temperature rise. The second condition corresponds to a problem of electrodynamic forces and may be studied separately. However the first condition requires knowledge of the total of the currents flowing through the switchboard.

The temperature of the air surrounding the bars is of particular importance in order to size the bars accurately and ensure that they do not exceed a critical temperature mainly depending on the type of material used for the supports. Consequently, knowing the air temperature in the various switchboard zones, we can determine, at the end of the program, the temperature of the bars according to their characteristics (dimensions, forms, arrangements...) and thus validate their sizing.

NB: as regards calculation of heat flux, we consider that bars mainly dissipate power by convection and radiation with internal air.

Temp. near the bars (°C)	**Cross-section**	**Current (A)**	**Power loss (W)**	**Bar temperature (°C)**
50	1 b 100x5	1000	45	79
50	1 b 100x5	1500	107	109
50	3 b 100x5	1500	10	65
50	3 b 100x5	3400	61	110
65	1 b 100x5	1000	45	92
65	3 b 100x5	1500	11	80

fig.13: thermal values of a few busbars for different ambient air temperatures.

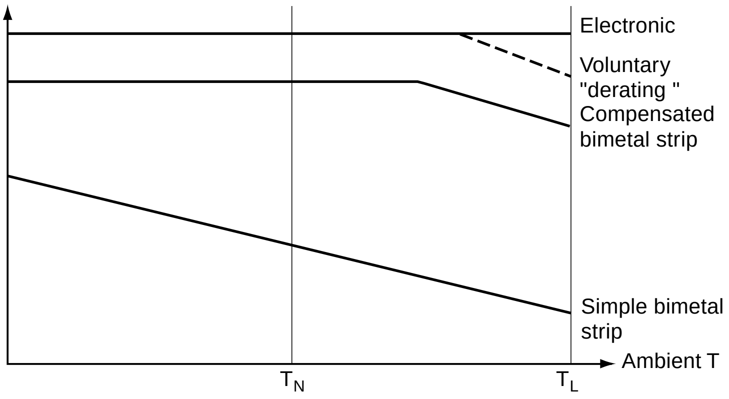
5.2 Switchgear devices

In power distribution cubicles, the switchgear devices used are mainly circuit-breakers. Together with the contactors and fuse-disconnectors, they dissipate heat when electric current flows through them.

The table in **figure 14** gives, as a general indication, a few power loss values per phase (per pole).
Note that the powers dissipated at a given In are of same order of magnitude for the different devices, although slightly lower for circuit-breakers as compared to fuse-disconnectors and even compared to contactors due to their hard but resistant contacts.

Circuit breakers				
I_n (A)	250	400	630	800
Pw - fixed	17.4	25	21	36
at I_n - withdrawable	23	35	54	58
Fuse-disconnectors				
I_n (A)	250	400	630	800
Pw at I_n	30	44	67	_
Contactors				
I_n (A)	265	400	630	780
Pw at I_n	22	45	48	60

fig.14: Power loss at In by conventional switchgear devices.



T_N: nominal operating temperature
T_L: limiting operating temperature

fig. 15: typical derating curves of various releases as a function of temperature.

Let us examine thermal problems in greater detail for circuit-breakers:

- Power loss is proportional to the square of the current flowing through them: $P_W = P_N \left(\frac{I}{I_n}\right)^2$

where P_N represents the power loss at rated current I_n.

- the rated current (I_n) of a circuit-breaker corresponds to a specific ambient temperature, for example 40 °C, set by the manufacturing standard. In fact, for some circuit-breakers, the ambient temperature corresponding to I_n can reach and even exceed 50 °C, which provides a certain safety factor in hot countries for example.
- the operating current (I) can vary as a function of ambient temperature, according to the type of release: simple thermal, compensated thermal, electronic (see **fig. 15**), which may enable a maximum operational current other than I_n to be defined.

The parameters used to determine derating take the following into consideration, besides the temperature of the air around the device (T_i):

- The limiting temperature (T_L) of the circuit-breaker internal components:
  - maximum operating temperature of the bimetal strip for a circuit-breaker with a thermal-magnetic release,
  - temperature of the electronic components for a circuit-breaker with built-in electronic release
  - temperature not to be exceeded for the plastic parts most exposed in a circuit-breaker with remote electronics (external relay for an air circuit-breaker...).

These limiting temperatures are between 100 and 150 °C.

- The ratio of the release I_n and the real tripping current when the latter is placed at the temperature used to define I_n

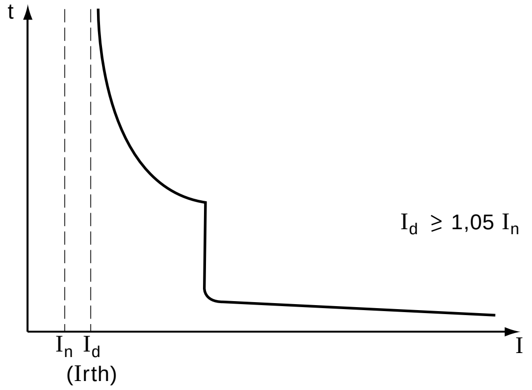


fig. 16: time-current curve of a circuit-breaker.

$K_1 = \frac{I_d}{I_n}$ (see **fig. 16**)

- The cross-sections of the connecting cables or bars which act as a radiator. Their influence is taken into consideration by a coefficient K_2.

NB: the cross-section of the conductors used rarely equals the cross-section used for circuit-breaker certification tests.
The derating allowing for these criteria can be expressed in mathematical terms.

Derating formula:

The circuit-breaker and its connection conductors dissipate heat mainly by convection. This yields the relationship:

$W_1 = h\,S\,(T_L - T_i)$ where

W_1: power loss in W,

h: heat exchange coefficient in W/m^2 °C,

S: heat exchange surface area in m^2,

T_L: temperature of the hot point in °C (e.g. the bimetal strip),

T_i: temperature of the internal air around the device in °C,

$$h = \text{Constant}\,S\left(T_L - T_i\right)^{0.25}$$ (see § 2)

hence $W_1 = \text{Constant}\,S\left(T_L - T_i\right)^{1.25}$

When the device is in open air at 40°C, the resulting relationship is similar.

$$W_2 = \text{Constant}\,S\left(T_L - 40\right)^{1.25}$$

hence $\frac{W_1}{W_2} = \left(\frac{T_L - T_i}{T_L - 40}\right)^{1.25}$

Moreover, we know that

$W_1 = RI^2$ and $W_2 = RI_d^2$

thus $I = I_d\left(\frac{T_L - T_i}{T_L - 40}\right)^{0.62}$

where I is the current flowing through the device and $I_d = K_1 \times I_n$

The final relationship also integrating the effect of the cross-sections (coeff. K_2)

$$I = I_n K_1 K_2 \left(\frac{T_L - T_i}{T_L - 40}\right)^{0.62}$$

- The data for circuit-breaker behaviour used in this formula are contained in files called by the software when temperatures in the cubicle are calculated.

6 Method for calculating temperature in envelopes and experimental results (see p. 21)

The modelling method described above acted as a basis for the development of our calculation method which enables us to determine the real operation of the switchboard (maximum current on each feeder...) and thus to optimise use of the assembly and master dependability. As is frequently the case in thermal matters, the numerous relationships between parameters call for an iterative approach resulting in the drawing up of a program, the principle of which is presented below.

6.1 Principle

The program uses two overlapping iteration loops in order to determine the operating level of the envelope in steady state. One concerns resolution of the thermal problem, the other the derating coefficients.
The calculation diagram is illustrated in **figure 17**.

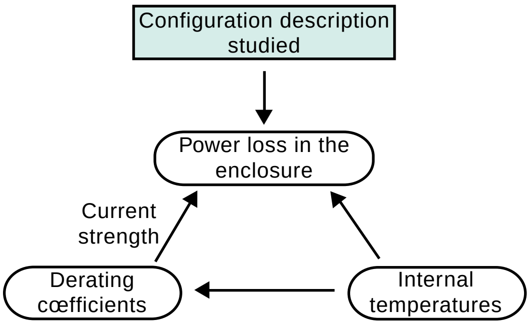


fig. 17*: software operating principle.*

1st stage: description of the configuration, i.e. the type of envelope used, the name and position of the devices. The program calls on the device file to retrive the data described above.

2nd stage: the envelope is broken down into isothermal subvolumes (nodal modelling nodes).

3rd stage: start of iteration loops with calculation of:

- dissipated power (at the first iteration the derating coefficients are taken equal to 1),
- the admittance matrix factors from the balance equations,
- internal temperatures (resolution of the thermal problem),
- the new derating coefficients, followed by a comparison with the above. If the difference is considered too large (iteration stop test), the new current strengths flowing through each device are calculated, followed by recalculation of dissipated power...

4th stage: the results are issued.

6.2 Description of the data to be provided and of the results obtained

Data:

- type of envelope (enclosure, cubicle, switchboard) and material,
- protection index,
- ambient temperature around the envelope,
- number of rows of devices,
- name of devices allowing search in file,
- configuration of the switchboard and position of switchgear.

Results:

- choice of a horizonal and vertical (cross-section) busbar and current strength in these bars,
- total thermal power dissipated in the switchboard,
- derating coefficient for each device, i.e. currents flowing through,
- if applicable, the temperature reached by the bars and its level in the various switchboard areas.

6.3 Modelled configurations

Naturally not all the installation configurations can be considered by this program. Only the most common ones have been selected, i.e. those which let us meet 90% of needs (see **figure 18** which gives an example).

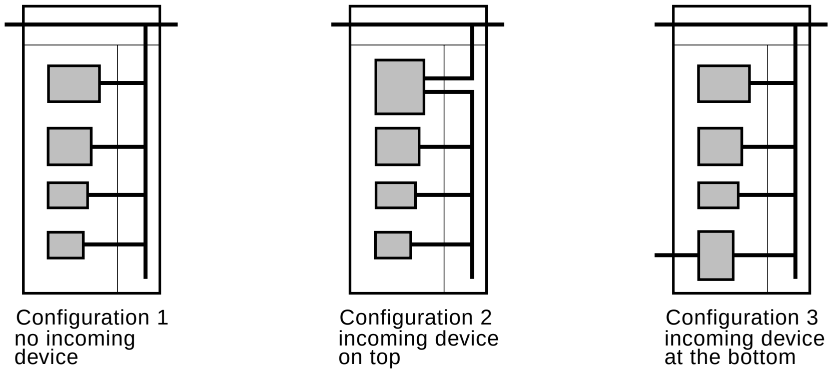


fig. 18: modelled configurations.

6.4 Results

This «software» approach is particularly advantageous as it lets us carry out the studies below:

Detailed study of a specific configuration

Made to optimise position of a device or choice of busbar, to know the power dissipated by the assembly, to size a suitable air conditioning...

The following example concerns a column of a partitioned industrial power switchboard, form 2, containing:

- a horizontal busbar supplying an incoming device and an adjacent column,
- an 2500 A incoming device
- various moulded case circuit-breakers.

The program provides:

- the derating coefficients K_{decl},
- the currents flowing through each device, I_r.

Remark concerning coefficient K_{div}:

This coefficient enables us to take into account the diversity or bulk factor feeder by feeder, in other words, the operating levels at a specific moment of the various devices:

e.g. at a specific moment, 2 feeders for example will be used to their full and the others at only 0.5 of their possibilities, with the resulting consequences on the thermal conditions of the assembly.

The results are shown on the calculation sheet in **figure 19**.

Derating table for a specific configuration

This software usage possibility, similar to the above usage, lets us group, for a common configuration, the deratings of the various devices allowing for their real position in the switchboard, the conductor cross-sections used, the protective indexes and the external ambient temperature.

An example of such a switchboard concerning devices installed in an industrial power switchboard column is shown in **figure 20**.

```
Masterbloc + MB 2000 IP = 31
Ambient temperature:  35 °C
Switchboard with incoming device on top supplied by the hor. busbar.

Name of device      Position            Kdecl        Kdiv          Ia(A)         Ir(A)
M25 H               1      12           .92          1             2300          2300
C630H/D630          17     21           .92          1             580           542
C630H/D630          22     26           .94          1             592           554
C401N/D401          27     31           .98          1             392           367
C401N/D401          32     36           .99          1             396           370
C250N/D250          37     40           1            1             250           234
C250N/D250          41     44           1            1             250           234

Hor. busbar: current - 2300 A
              cross-section - 3b 100x5

Vert. busbar:
Cross-section: 4b 80x5        Length (m): .24       Current: 2300 A
Cross-section: 4b 80x5        Length (m): .5        Current: 2300 A
Cross-section: 3b 80x5        Length (m): .2        Current: 1758 A
Cross-section: 2b 80x5        Length (m): .2        Current: 1204 A
Cross-section: 1b 80x5        Length (m): .2        Current: 838 A
Cross-section: 1b 80x5        Length (m): .18       Current: 468 A
Cross-section: 1b 80x5        Length (m): .16       Current: 234 A
Cross-section: 1b 80x5        Length (m): .24       Current: 0 A

Hor. busbar temperature:  109 °C

Vert. busbar temperature: 100 °C

Total power loss:  2015 W
devices:  613 W - auxiliaries:  0 W -
Vert. + tap-off busbars:  1282 W - hor. busbars:  120 W:

Ambient temperature:  35 °C
Roof T°:  69 °C - Hor. busbar T°:  74 °C
Device T°:  high - 61 °C / low - 35 °C
Auxiliary T°:  high - 48 °C / low - 35 °C
Vert. + tap-off busbars T°:  high - 67 °C / low - 35 °C
Connection T°:  high - 53 °C / low - 35 °C
```

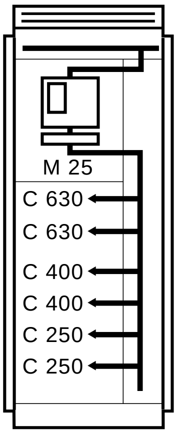


fig. 19: calculation result for a specific configuration.

IP 31

T° amb	35	40	45	50	55
M25	0.9	0.87	0.84	0.81	0.79
M16	0.97	0.94	0.91	0.88	0.86
M08	1	1	1	1	1

IP 42/54

T° amb	35	40	45	50	55
M25	0.79	0.77	0.75	0.73	0.71
M16	0.87	0.85	0.83	0.81	0.79
M08	1	1	1	1	1

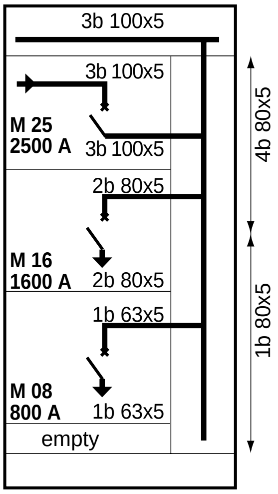


fig. 20: derating of the above circuit-breakers according to ambient temperature.

The derating coefficients are therefore drawn up, by excess, placing devices in turn on the top of the cubicle or compartment. See for example **figure 21**.

Curves characterising the thermal behaviour of a type of envelope

Two types of graphs have been drawn up:

- A set of curves used to determine the mean temperature within a specific envelope as a function of the dissipated power and of the external ambient temperature.

See the curves in **figure 22** concerning a non-partitioned distribution cubicle type.

- curves used to determine the watts that these envelopes can dissipate for a specific temperature rise, as a function of their dimensional characteristics.
For example: ext. ambient T° 35 °C, required max. temperature rise

□ cubicle: height 2 m, width 0.9 m, depth 0.4 m
dissipable power: 850 W

□ cubicle: height 2 m, width 0.9 m, depth 0.6 m
dissipable power: 1000 W (see **fig. 23**.)

	IP31					**IP 42/54**				
T°amb	35	40	45	50	55	35	40	45	50	55
C125N/H	0.95	0.91	0.88	0.84	0.80	0.82	0.79	0.76	0.72	0.69
C125L	0.94	0.90	0.86	0.83	0.79	0.80	0.77	0.74	0.71	0.68
C161N/H	0.95	0.92	0.88	0.85	0.82	0.81	0.78	0.76	0.73	0.69
C161L	0.94	0.91	0.87	0.84	0.82	0.79	0.76	0.73	0.70	0.67
C250N/H	0.94	0.90	0.87	0.83	0.80	0.82	0.79	0.76	0.72	0.69
C250L	0.93	0.89	0.86	0.82	0.78	0.79	0.76	0.73	0.70	0.67
C401N/H	0.94	0.91	0.87	0.84	0.81	0.79	0.76	0.74	0.72	0.69

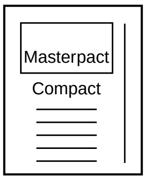


fig. 21: derating of Compact circuit-breakers placed under the incoming circuit-breaker.

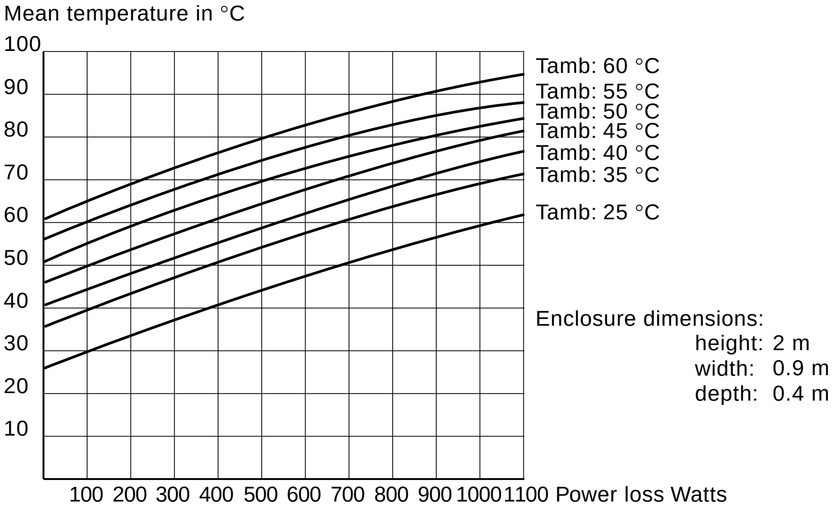


fig. 22: mean temperature of air inside an IP2 form 1 metal distribution cubicle.

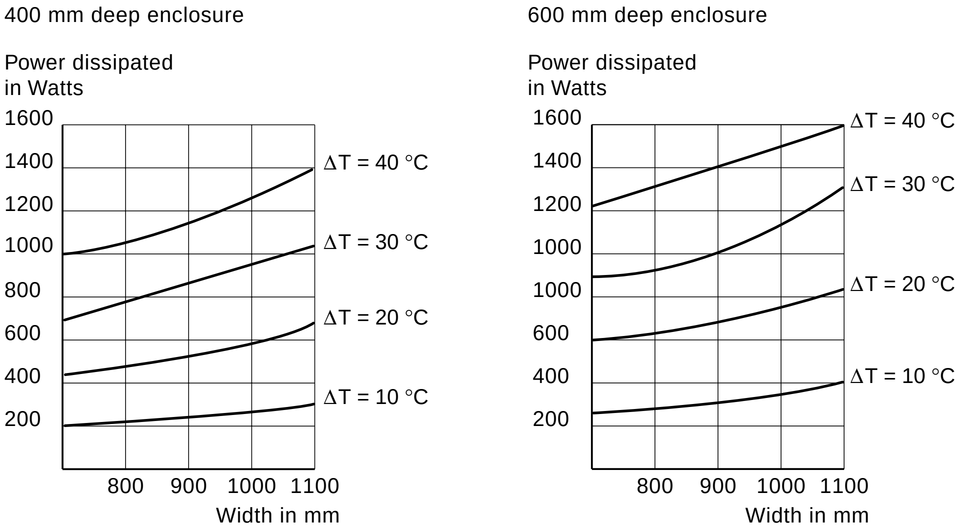


***fig. 23**: power that can be dissipated by an enclosure for a specific temperature rise according to its width. Curves refer to a metal cubicle, form 1, 2 m high.*

6.5 Experimental results

Temperature rise tests have been conducted in the ASEFA Ampère laboratory on various envelope types: metal and plastic enclosures, Prisma cubicle, Masterbloc distribution switchboards.

During these tests the following measurements were taken:

- Temperatures:
  - of air in the various envelope areas,
  - of conductors: busbars and branch-offs,
  - hot points in devices (bimetal strip, electronic ambient).
- Current strength.
- Parameters used for modelling, particularly air/wall heat exchange coefficients.

These measurements have enabled both verification of conformity with IEC 439.1 standard of certain values (see temperature rise limits mentioned in paragraph 1.2 on standards) and validation of this model.

With respect to air temperatures, the difference between the values measured and the values calculated depends on the type of envelope modelled, since modelling approaches differ according to whether or not the envelopes are partitioned.

Out of all the tests carried out on switchboards of various forms (partitioned or not), the maximum differences observed were always less than 6 °C.

The temperatures calculated for the busbars also show satisfactory agreement with the measurements and enabled us to validate the software.

As regards current strengths, differences are on average less than 5%. Consequently, for a recent official approval of a Masterbloc switchboard configuration in temperature rise, the software allowed us to determine the operating level of the switchboard.

8 Method proposed by the IEC 890 report

Not so long ago a large number of electric cubicles were chosen and equipped/filled in the light of experience. This concerns the filling ratio and evaluation of temperature in the cubicle in operation. For example, the maximum external temperature of 30 °C and maximum internal temperature of 60 °C (switchgear manufacturers give derating up to 60 °C).

This practice resulted in unoptimised use of the equipment, untimely tripping of the protective devices or the need for operators to operate with open doors.

The method proposed by the IEC report, even if this is rather a guide than a standard, thus merits attention. It is described in detail in the report of the IEC 890 or in the appendix of the NF C 63-410.

We shall review the basic aspects, show its limits and compare it with the method presented in the «Cahier Technique».

In theory this method applies to envelopes for which the following assumptions can be made:
- even distribution of dissipated power,
- switchgear arranged so as not to obstruct air circulation,
- no more than 3 horizontal separations.

Necessary data:

- dimensions of the envelope,
- power dissipated in the envelope (switchgear, conductor),
- type of installation (insulated envelope or insulated at one end...), (see **fig. 25**).

Calculation:

Temperature is calculated only at 2 points of the envelope:

at mid-height

$$T_{0.5} = T_a + \Delta T_{0.5} \text{ where } \Delta T_{0.5} = d\,k\,P_W^{0.804}$$

- d is a coefficient taking into account the presence of horizontal separations.

☐ if $A_e < 1.25\ m^2$, d = 1 (definition of A_e, see below)

☐ if $A_e > 1.25\ m^2$, d = 1 with and without ventilation apertures for 0 separation
d = 0.5 with and without ventilation apertures for 1 separation
d = 1.10 or 1.15 if ventilation apertures for 2 separations
d = 1.15 or 1.30 if ventilation apertures for 3 separations

- k is a constant characterising the envelope: its value is determined on charts, (see **fig. 24**).

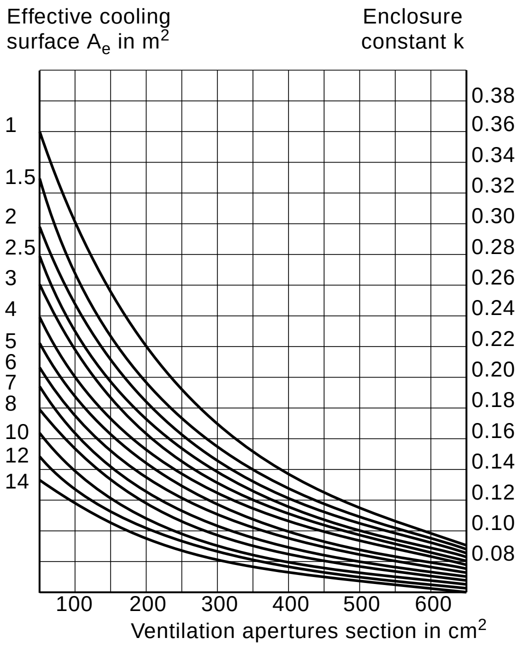
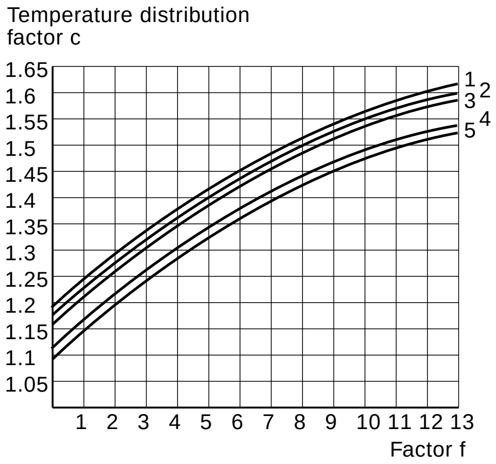


fig. 24: Enclosure constant k for enclosure with ventilation opening and an effective cooling surface area of $A_e > 1.25\ m^2$.



Curve/Installation type

1	Separate enclosure, detached on all sides
3	Separate enclosure for wall-mounting
2	First or last enclosure, detached type
3	Central enclosure, detached type
5	Central enclosure, wall-mounting type
4	Central enclosure for wall-mounting and with covered top surface

fig. 25: temperature distribution factor c for enclosures without ventilation openings and with an effective cooling surface $A_e > 1.25\ m^2$.

k is a function of the heat exchange surface of the envelope A_e (m^2).

$$A_e = \sum A_0 b$$

where A_0 is the geometric surface of the various envelope walls.

b is a constant allowing for the type of wall and type of installation.

Values of b:

☐ exposed upper part	b = 1.4
☐ covered upper part	b = 0.7
☐ exposed side surfaces	b = 0.9
☐ covered side surfaces	b = 0.5
☐ side surfaces of central envelopes	b = 0.5
☐ lower part	b = 0

- Pw power dissipated in watts

at the top of the enclosure:

$T_1 = T_a + \Delta T_1$ where $\Delta T_1 = c\,\Delta T_{0.5}$

where $\Delta T_{0.5}$ represents the above temperature rise

- c is a temperature rise constant determined from charts

Example of a chart, see **figure 25**

c is function of A_e and of one of the two factors, f or g

$f = h1.35/(L\,P)$ if $A_e > 1.25\ m^2$

$g = h1.35/L$ if $A_e < 1.25\ m^2$

Limits:

The main limits of this method are that it:

- applies only to non-partitioned envelopes of the cubicle and enclosure type and not to highly partitioned power switchboards.
- does not take into account the position of the heat sources which in most cases are not distributed evenly.

Comparision with our approach

We observe that both approaches yield similar results for non-partitioned cubicles with distributed heat sources (see curves in **figure 26**).

As regards highly partitioned envelopes, the location of the heat sources and the exchanges between the various areas considerably affect temperature rise!

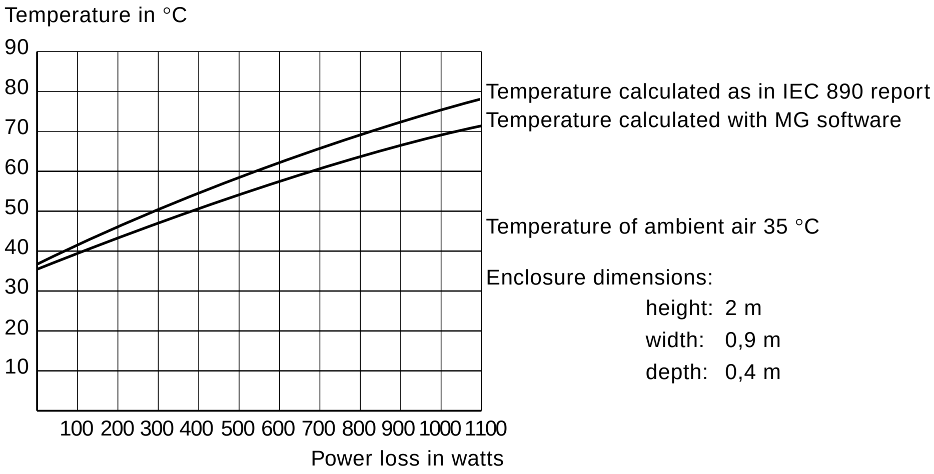


***fig. 26**: Air temperature at mid-height of an IP2, form 1 metal distribution cubicle.*

8 Conclusion

The importance of electric switchboards in distribution is an established fact.
At a time when availability of electrical power and operating dependability are absolutely vital, thermal mastery of electric switchboards is a fundamental goal.
Standards concerning envelopes and products specify the thermal limits not to be exceeded.
All that was left was for professionals to become "thermal architects" in design of envelopes and electric switchboards. This has now been achieved, even for partitioned switchboards.

Reminder: definition of the various temperature scales:

■ degree Celsius (formerly centigrade) °C: relative temperature
Reference points :
□ 0 °C: temperature of melting ice
□ 100 °C: temperature of boiling water at normal atmospheric pressure.

■ degree Fahrenheit °F: unit used in English speaking countries:
Reference points:
□ 32 °F: temperature of melting ice
□ 242 °F: temperature of boiling water at normal atmospheric pressure

Equivalence $1^\circ\mathrm{F} = \frac{5\,^\circ\mathrm{C}}{9} = 0.55\,^\circ\mathrm{C}$

Conversion $T\,^\circ\mathrm{F} = \frac{T\,^\circ\mathrm{C}}{0.55} + 32$

■ degrees Kelvin K: international system unit. Absolute temperature scale, since its definition relies on exact phsyical bases.
Same graduation as the Celsius scale, but the origin is offset: the temperature of melting ice corresponds to 273 K
Conversion: $T\,\mathrm{K} = T\,^\circ\mathrm{C} + 273$

Schneider

Direction Scientifique et Technique,
Service Communication Technique
F-38050 Grenoble cedex 9
Fax. (33) 04 76 57 98 60

Real : Sodipe (26).
Printing : CLERC Fontaine - 1500
- 100 FF-