DESIGN DECISIONS for PANELS, SWITCHBOARDS, SWITCHGEAR & BUSWAYS

(about costs of technologies, paradigms, use of aluminum, copper, CCA and a patent)

Author name: Affiliation:
Sergio Feitoza Costa COGNITOR – Consultancy, Research and Training Ltd.

Email: sergiofeitoza@cognitor.com.br CV of the author : http://www.cognitor.com.br/en/site/index.php?sec=1

Keywords: IEC, CIGRÈ Simulations, High Power Tests, Switchgear, Switchboards, Bus-bar systems, Testing Laboratory, Internal Arcs, Overpressure, Temperature rise, Electrodynamic forces, stresses, Short time currents, EMC, Magnetic fields, Electric Fields, Substations, Certification, Design, Decisions, Aluminum, Copper, CCA.

1 DESIGN DECISIONS AND TECHNICAL ECONOMICAL ASPECTS (example for temperature rise)

When a manufacturer is developing a new product, or assessing the feasibility of a new design, in general, needs to base the strategy in key technical and economic issues like:

- A temperature rise test in a high voltage (HV) or medium voltage (MV) air insulated switchgear (AIS) cost around 4.000 Euros, take 1,5 days of laboratory use (without considering the costs of prototype preparation and transport to the lab).
- A short time current test (electrodynamic forces) plus an internal arc test (overpressure) in a MV AIS cost around 30.000 Euros, take some 2 lab days.
- The impact of costs and weights associated to the use of copper or aluminum and other materials. Using a lower weight is very important in cases like a floating oil platform but no so much in a land substation.
- The use or not of ventilation. Ventilation is a great resource to reduce materials use but the fan cannot fail.
- The use of two thinner 100x5mm bus bars per phase instead of using only one 100x10 mm per phase.
- The barriers coming from old paradigms which have been superseded by the current knowledge as Cu x Al;
- The fact that technologies superseded in developed countries are produced in developing countries as "news".

In this article, I present an example of development of a new innovative design of a medium voltage air insulated switchgear (AIS). For easier understanding of the concepts, the focus will be mainly in the aspect of the temperature rise requirements. All the design parameters for temperature rise are explained but, for simplification, only the geometry of busbars, their materials and the use or not of ventilation were considered. This example is applicable to switchgear, busways and switchboards (high, medium and low voltages). Although not described we considered also:

- Electrodynamic forces during short-time current and crest current (number of supports and insulators)
- Overpressures of the internal arc tests;

This kind of assessment and decisions are of the same nature of the development of solutions for low cost substations for electrification of rural and remote areas where electricity is non-existent or unreliable (work of Cigre WG B3-43). Implementation of low cost technologies is directly associated with the high costs of testing equipment in testing labs. Another key point is having proper technical standards and power utilities specifications with proper (and not excessive) requirements for these areas. An IEC standard made to assure a good quality of energy in cities of Europe possibly is not the proper one to assure the existence of a minimum electricity service in a poor region of Africa, Asia or South America. The requirements would be excessive as are the 695 pages of the standard IEC 62271-100 (HV circuit breakers). The experts producing IEC standards are more than 90% from developed countries. They participate in these activities to defend the particularities of their own systems and not of other regions which they do not know.

Good news is that the use of software for testing simulations (high power and high voltage) evolved a lot in the last 15 years. They are an important alternative to avoid expensive laboratory tests, especially in the development phase

(read http://www.cognitor.com.br/Article_Competitivity_Eng_04102011.pdf). The simulations of the design alternatives 4 and 5 showed in section 4 are a clear example of this. Imagine the cost of the tests to arrive to those conclusions.
Education & training is also a key item but, unfortunately, placed in the background, in developing countries, with some exceptions and cases of worldwide success.

2 DESIGN PARAMETERS (FOR TEMPERATURE RISE)

The parameters influencing the specifications and tests are well explained in Section 4.2 and Annex A-3 of the IEC 62271-307 - High-Voltage Switchgear & Controlgear – Guidance for the extension of validity of type tests of AC metal and solid-insulation enclosed switchgear and controlgear (<= 52 kV).

I was member of the IEC working group which prepared IEC 62271-307. I am sure that when it becomes better known it will have, for MV switchgear, the same positive impact of the IEC 60439 and 61439 series for LV switchgear. To get understanding on the effects of temperature rise read first IEC 60943 - Guidance concerning the permissible temperature rise for parts of electrical equipment, in particular for terminals.
The text to follow is a resume of parts of IEC 62271-307. The extension criteria for temperature rise performance are summarised in the Table 1

Table 1 – Extension criteria for temperature rise performance (read IEC 62271-307)

Item	Design parameter	Acceptance criterion	Condition
1	Centre distance between phases	≥	Only to be validated for rated normal currents above 1 250 A
2	Phase to earth distance	≥	Only to be validated if an influence on the surrounding elements due to currents cannot be excluded, e.g. eddy currents and magnetising currents.
3	Enclosure/compartment dimensions (L, H, W) and volume	≥	The enclosure and compartments are of the same construction.
4	Minimum pressure of insulating gas	≥	Same gas; for gas insulated switchgear
5	Current density of conductors	≤	The conductors have the same physical arrangement
6	Resistance per unit length of conductors	≤	Compare conductor material and cross-section
7	Contact surface area of connections / joints	≥	Same or better contact material
8	Contact force of connections / joints	≥	Same or better contact material
9	Permissible temperature of contact materials of connections / joints	≥	Including metallic coatings having the same or lower resistivity
10	Effective ventilation area of partitions and enclosure	≥	Note 3
11	Power dissipation of components	≤	The main switching devices, fuses and CTs are considered.
12	Area of insulating barriers	≤	Barriers have the same physical arrangement
13	Thickness of insulating coating of conductors	≤	Thermal resistivity and emission coefficient of the coating should be the same.
14	Total coated surface area of enclosure for heat transfer	≥	The emission coefficient of the coating should be the same.
15	Temperature class of insulating material in contact with conductors	≥	

The normal current rating is dependent upon the parts that experience the highest temperature rise during current flow through the main circuits. These parts may comprise contacts of switching devices, bolted connections (or equivalent) of conductors, terminals, and accessible parts such as enclosures.

The temperature rise is influenced by the design parameters described. The principles influencing temperature rise and the acceptance criteria are the following.

2.1) Centre distance between phase conductors

In a 3-phase circuit, the AC magnetic field generated by current in a conductor induce eddy currents in the same and adjacent metallic parts. Proximity effect increase the power loss and produces higher temperatures. Centre distance is therefore relevant. Having conductors arranged in the same manner and larger centre distances between phases *produce lower power losses and lower temperature rise*.

2.2) Phase to earth distance

Eddy currents can be induced in metallic, non-current carrying parts. This effect is normally negligible for enclosures. However, AC magnetic fields create heat losses in ferromagnetic steel enclosures. This lead to additional heating power losses and higher temperature rise. Equipment with greater than or equal phase to earth distance then can be considered to produce equal or lower heat losses.

2.3) Enclosure and compartment volume

Temperature rise is influenced by the ability of the enclosure to dissipate heat to the ambient environment. This effect is dependent upon the surface area of the enclosure (and hence volume) and the type of material used. A larger surface area of the enclosure walls will dissipate more heat and hence have lower internal temperature rise. The use of non-ferromagnetic steel for the enclosure can avoid heat generation by eliminating the induction heating effect. IEC/TR 60890 describe the effects.

2.4) Insulating gas

The pressure (density) of gas in a compartment influences the ability to dissipate heat away from current carrying conductors to the enclosure and further to the ambient environment. An increase in the pressure increases the heat transfer capability of the gas resulting in lower temperature rise of the internal parts.

2.5) Conductors

Current flow produces a power loss (I^2R) which is dependent on the current magnitude, I, and conductor resistance, R. The I^2R power loss is the most significant portion of total power loss within the equipment. An increase in cross sectional area of a conductor will lower the power loss of the conductor and decreases the temperature rise. Heat removal from hot spots leads to a temperature rise lowered.

2.6) Conductor joints and connections

They are the main contributors to temperature rise due to the I^2R losses in the joint or connection resistance. The resistance (contact resistance or resistance as seen from the terminals) depends upon the raw material and type of metallic coating, contact pressure (or force) and contact surface area. An increase in contact pressure (contact surface) will lower the resistance resulting in a reduction in temperature rise at that location. The resistivity of the coating material has limited influence on the overall resistance. The permissible maximum temperature of the coating as defined in IEC 62271-1. IEC/TR 60890 is rich in information. Copper is deemed a "better" contact material than aluminium when oxygen is present.

2.7) Ventilation area of partitions and enclosure

To enable effective dissipation of heat by air convection, some designs include ventilation openings in compartments and/or the enclosure. Larger ventilation openings imply a greeter heat dissipation and so, a reduced temperature rise. The position of ventilation openings is also important. The modification of the degree of protection (IP-code x grid cover on ventilation openings) have an impact on the heat dissipation. A higher IP-code could reduce the effective ventilation area reducing the air flow and causing higher temperature rise. Read IEC TR 60890.

2.8) Power dissipation of components

The incorporation of components such as switching devices, fuses and current transformers contribute significantly to the temperature rise. These components will produce I^2R power losses. Lower I^2R power losses will produce lower temperature rise. In general, the critical points for testing are in these components.

2.9) Insulating barriers

Insulating barriers between phase conductors or between conductors and enclosure walls may increase the dielectric withstand, however, impeding air flow may reduce heat transfer to the enclosure. This might increase the temperature rise. Therefore, the addition of such barriers will normally require repeating the temperature rise type test. An increase in the surface area of insulating barriers tend to restrict air flow and vice versa. The effect may have a large impact for horizontal barriers.

2.10) Insulating coating of conductors and enclosures

The use of solid insulation on conductors and/or enclosures will restrict the ability to dissipate heat into the surrounding medium due to its thermal resistance. On the other hand, it might help removing heat by radiation depending on the heat transfer capability of the insulating material and emission coefficient of the external surface. Paint or coatings on the conductors and the enclosure can lower the temperature rise by improving the heat transfer by thermal radiation. The colour of the paint has no significant effect , since the emission coefficient is mainly determined by the polymeric properties of the paint.

2.11) Insulating material in contact with conductors

When changing the insulation material of support insulators, the temperature class of the material should achieve the same or larger value in order not to risk a degradation of the material at normal conditions.

3 TEMPERATURE RISE LIMITS

The maximum temperature rise limits presented in the technical standards consider two groups of values. The first corresponds to parts of components whose temperatures should not exceed a certain value which would cause very rapid or immediate destruction. This is the situation of insulating materials, tinned contacts and springs.

The second group concerns components susceptible to gradual aging but whose temperature for fast damage is high. An example is the temperature rise of bare copper contacts limited to 35K. In Table 1, from Sergio's book the reader can observe some of these limits (free download in http://www.cognitor.com.br/Book_SE_SW_2013_ENG.pdf).

Table 1 – Some temperature rise limits specified in IEC standards

Part	Contact material and medium where it is used	Temperature Rise máx. (K) amb 20°C	Temperature máx. (°C) ambient 40°C	Comments
SPRING CONTACT	Copper and copper alloys uncoated - in air - in SF6 - in oil	35 50 40		
	Tinned , in air, SF6 oru oil	50		
	Silver or niquel plated - in air - in oil	65 50		
	For contactors in oil		105	Oil deterioration
BOLTED CONTACT	Copper , aluminum and alloys uncoated in air uncoated in SF6	50 65		
	Tinned, in air or SF6		105	Tin "creep point"
	Silver or niquel plated air or SF6	75		
	Silver or niquel plated in óleo		100	Oil deterioration
	For contactors in oil		105	Oil deterioration
METALIC PARTS	In contact with insulation class • Y / A / E • B / F / H		90 / 105 / 120 30 / 155 / 180	Isolation ageing
	• Acting as spring • In soldering position		caso a caso 100	Permanent deformation /Break
SURFACES	Can be touched (met / non met.) Acessible but not touched		70 / 80 80 / 90	Do not injure persons

4 A PRACTICAL CASE OF DESIGN DECISIONS for PANELS & SWITCHBOARDS.

A manufacturer already designed and tested successfully a switchgear panel 13,8 kV – 1250 A (rated normal current) and 40 KA -1s (rated short circuit current). It is a conventional AIS panel commonly found, all over the world, in power substations and in the commercial market.

This panel has the characteristics and dimensions showed in Figure 1a and was approved in IEC tests for temperature rise, internal arc and short time current and crest tests. The temperature rise lab tests results and simulations (1250 A) are presented in Figure 1b and Table 1 (column Condition 1).

To test an equipment like this for the IEC type tests would involve amounts around 150.000 Euros, if the equipment is approved in the first time in all the tests. For a world-wide big manufacturer, this is not a significant value. For a small or medium one the testing costs are the main barrier for developments, unless they make use of testing simulations.

Table 1 - Temperature rise values (K) - Switchgear as Figure 1a with circuit breaker resistance 54 µΩ per phase - Bare bus bar - Without ventilation openings - Condition 1 (1250 A) and Condition 2 (1600 A)

Measuring point	Condition 1 Laboratory test **1250 A**. Temperature rise (K)	Condition1 Simulation **1250 A**. Temperature rise (K)	Condition 2 Simulation **1600 A.** Temperature rise (K)
A - Terminals for the connection to external conductors	39	38	58
B – C – D – connection between busbars and circuit breaker	56 to 72	55 to 72	76 to 109
E – Connection between the horizontal and vertical bars	44	46	69
F – Short circuit point	34	37	54
Door	12	11	16
Internal air	Not measured	18 to 26	28 to 34

In this example of design decision, the objective of the manufacturer is to develop a new panel as similar as possible to the one approved for 1250 A but with a higher normal current of 1600 A.

We see in Table 1 (column Condition 2) that the temperature rises at 1600 A, using the existing project is, at the critical point, 109 K. Usually, the critical points in this type of switchgear are the connections of busbars to circuit breakers or switches or fuses. The maximum permitted temperature rises in this connection, per IEC standard is 75K. So, the existing equipment, approved at 1250 A, would not pass in the temperature rise test with 1600 A.

After some fast simulations and discussions, we decided to assess the five alternatives in Table2. The comparison between them were made from the point of view of construction costs.
The design objective was to pass in the temperature test having, at the critical connection to the circuit breaker, a temperature rise not higher and, as near as possible, to the limit 75K.

We found the value of current (near 1600 A) which would produce a temperature rise of 75K in the connection. This would be difficult and expensive to do with real testing but is easy to do doing simulations. This value of current was used to calculate the net transmitted power of the equipment. Dividing the construction cost by the power we have a parameter to compare the different design alternatives.

For all the design alternatives, we considered that there was a ccircuit breaker with resistance per phase, as seen from the terminals, of 54µΩ plus 50 W of small components heating the air. In the case where ventilation was considered (natural and not forced) the net opening area, considering filters, was 200 cm^2

Figure 1a – Panel 15 kV– 1250 A and 40 KA (as approved in the laboratory tests)

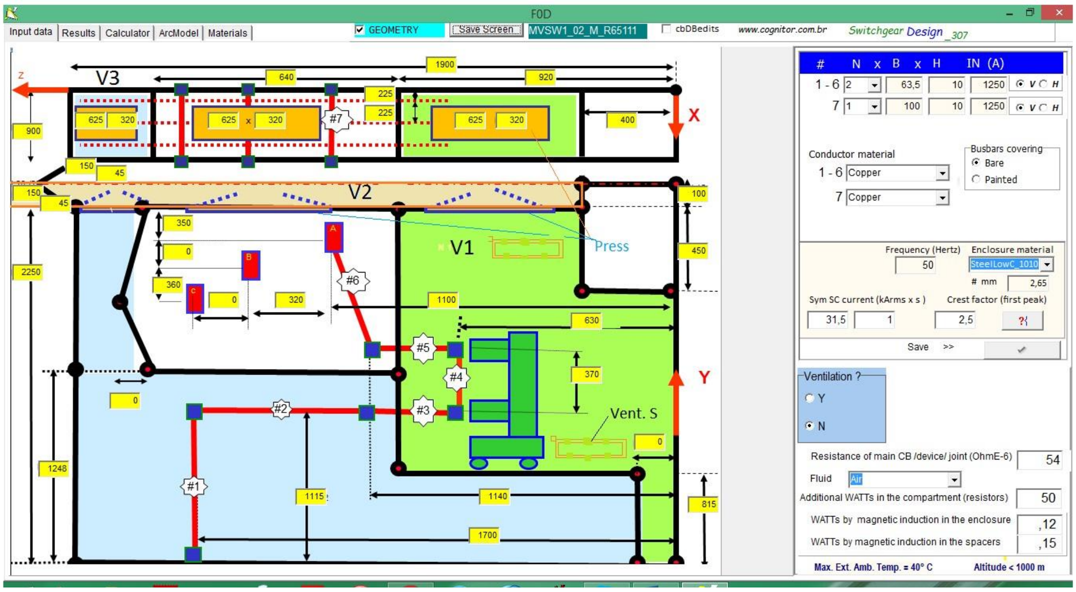
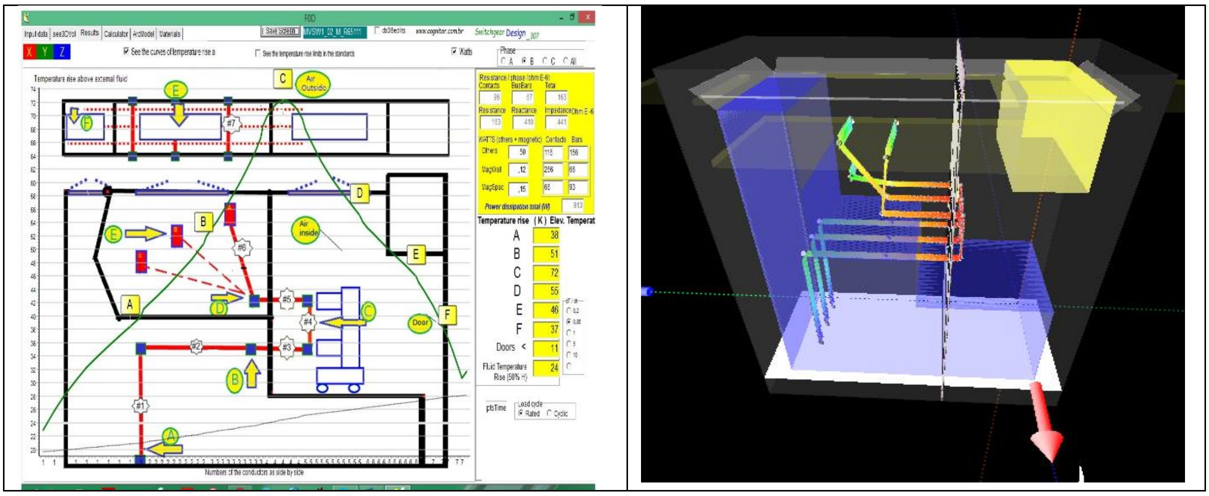


Figure 1b – Results of temperature rise tests with 1250 A



The data used for the calculations of the alternatives (Design 1 to Design 5) is presented in Table 2.

Design 0) is the <u>conventional</u> already tested design <u>without ventilation openings</u> (Figure 1a)

Design 1) <u>Conventional</u> flat copper busbar <u>without ventilation openings</u> (like Design 0)

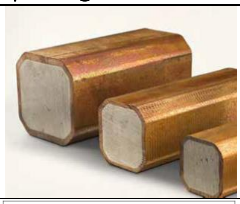
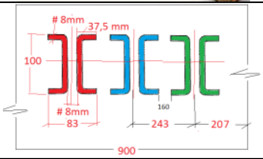
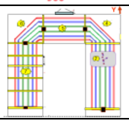
Design 2) <u>Conventional</u> flat copper busbar <u>with ventilation openings</u> (without forced ventilation)

Design 3) <u>CCA (copper clad aluminum) busbar</u> which is a combination of an internal part of aluminum and an external part of copper (where most of the current flows). <u>Without ventilation openings</u>

Design 4) Inverted <u>U aluminum profiles</u>. Interesting solution for small space and high short circuit current levels. <u>Without ventilation openings</u> Read previous article "Finding Optimal Switchgear Design in http://www.cognitor.com.br/DesignOptimization.pdf .

Design 5) Advanced design using a mix of copper and aluminum parts. Details cannot be disclosed because it is in the process of generating a patent. It is focused in cubicles and busways for normal currents higher than 1250 A and short circuit levels above 31,5 kA. For this case, the confirmation of results of the simulations presented here are waiting for a validation test to be done in a laboratory. Sergio is looking for manufacturer partners to develop the idea.

Table 2 – Design alternatives and order of magnitude of the cost of construction of one unit 15 kV - 1600 A – 40 kA

Item	Order of magnitude in U$D	Typical figure
Design 0- Copper (per phase) Vertical bar: 2 x (63,5 x 10) Horizontal bar: 1 x (100 x 10) No ventilation openings	U$D / KG (material) 7,26	
Design 1- Copper (per phase) Vertical bar: **3** x (100 x 5) Horizontal bar: 2 x (100 x 10) No ventilation openings	U$D / KG (material) 7,26	Same as above
Design 2 - Copper (per phase) Vertical bar: **2** x (100 x 5) Horizontal bar: 2 x (100 x 10) With ventilation openings - free air passage area **200 cm^2**	U$D / KG (material) 7,26	Same as above but with ventilation openings but without fan or exhauster – free air passage area 100cm^{2}.
Design 3 - CCA (copper clad aluminum) Copper 30% vol, Aluminum70% vol, Vertical bar: 4 x (100 x 6) Horizontal bar: 2 x (80x6) No ventilation openings	U$D / KG (material) 9,16	
Design 4 – Aluminum 2 U profiles 100x37,5x8 mm (~2 x 175 x8) No ventilation openings	U$D / KG (material) 2,1	
Design 5 – Mixed "SFC" profiles special arrangement (copper+ Aluminum) With or without ventilation openings	U$D / KG (material) 7,26 to 2,1	

Insulators Epoxy type 15 kv	U$D / piece 3,0	
Enclosure Steel plate 1,9 mm mounted	U$D / kg 3,0	
Mounting (costs of hours of work with general mounting)	U$D / panel 250	
Costs of development and tests	Not included	Suppose approved in tests
Cost of switchgear components (1 circuit breaker + 3TCs+ 3 TPs)	U$D / panel 8000	

Note: For "Design 3" (using CCA - copper clad aluminum), as it is a recent material in the market, the values used are only an estimated order of magnitude. The relative values were used for the physical properties of the materials

Material	Density	Electrical resistivity	Thermal conductivity	Specific heat
Copper	8,89	1,78 E-8	387	394
CCA 30%Cu 70% Al	4,56	2,27 E-8	238	711
Aluminum	2,70	2,82 E-8	203	890

5 COMPARISON OF ALTERNATIVES AND COMMENTS

The simulation method is presented in the articles and links in the end of this text. To check each design alternative, we simulated a temperature rise test finding the value of the current which would produce a temperature rise of 75K in the hot spot point (connection of the circuit breaker to the bus bar). These are the maximum values obtained in points like B-C-D in Table1. The values of these currents are presented in Table 3.

We considered the optimum design as the one with lowest cost per net transmitted power (USD/MVA). The net transmitted power was defined as TP = 1,732* rated voltage phase to phase (13,8kV) * current in Table 3 (kA) minus the power losses $Z*I^2$. In these cases power losses are a small number if compared with the transmitted power but in some other kind of projects is a way of identifying the quality of the solution (lower inductances and resistances).

Table 3 – Design alternatives X costs for a maximum 75K temperature rise in the hot spot. Circuit breaker resistance of 54µΩ plus a 50 W resistor. Ventilation area = none or 200 cm^2

Design	Current (A) for a temperature rise of 75 K in the region of points B-C-D (hot spot)	Cost of net transmitted power INCLUDING CB + TCs + VTs (as in a panel) **(USD / MVA)**	Cost of Net transmitted power NOT INCLUDING CB + TCs + VTs (as in a busway) **(USD / MVA)**
Design 0 - Copper *** Vertical bar:2 x (63,5 x 10) mm *** Horizontal bar:1 x (100 x 10) ***No ventilation openings	1280 A	44	305
Design 1 - Copper *** Vertical bar:**3** x (100 x 5) mm *** Horizontal bar:2 x (100 x 10) ***No ventilation openings	1690 A	37	235
Design 2 - Copper *** Vertical bar:**2** x (100 x 5) mm *** Horizontal bar:2 x (100 x 10) *** With ventilation openings - free air passage area 200cm^2	1695 A	28	**226**
Design 3- CCA (copper clad aluminum) Copper 30% /Aluminum70% vol, Vertical bar: 4 x (100 x 6) *** Horizontal bar: 2 x (80x6) *** No ventilation openings	1700 A	38	235
Design 4 Aluminum *** 2 U profiles 100x37,5x8 mm (~2 x 175 x8) ***	1730 A	**14**	**208**
Design 5 without ventilation openings Aluminum+ Copper "SFC" profiles special arrangement Without ventilation openings	1570 A	**24**	237
Design 5 with ventilation openings Aluminum+ Copper "SFC" profiles special arrangement *** - free air passage area 200cm2 – bars painted	1750 A	**22**	**214**

If the reader wants to do a complete technical economical assessment follow this link and download the free software Decidix designed by Serio Feitoza http://www.cognitor.com.br/c_Feasibily_Analysis.htm . It is a powerful free tool developed to assess generation and T&D energy projects. In this link, there are instructions on how to use and a class about the concepts http://www.cognitor.com.br/ENG_Part2_Methodology.pdf

Some conclusions may be taken from the numbers presented in Table 3. We will mention only some of them but the reader eyes may identify many others.

Looking to that numbers, Design Alternatives 4 and 5 seems to be very attractive although they are not "conventional design" found in the commercial market.

Most of the designs found in the commercial market, are derived from successful AIS designs developed in the decades of 70 and 80 in developed countries. In these countries, AIS systems are losing space for GIS alternatives. However, in developing countries they are still very much used and produced by the same international companies.

It was not presented here but Design Alternatives 4 and 5, if used as GIS would permit much more compact designs with much lower costs of transmitted power (more attractive design)

The author of this article is in the process of patenting a type of construction like Design Alternative 5 and looking for manufacturers interested in developing the idea. For contacts write to sergiofeitoza@cognitor.com.br

-- END OF THE ARTICLE --

The author of this article is Mr. Sergio Feitoza Costa. Sergio is an electrical engineer, M.Sc in Power Systems and director of COGNITOR. Sergio has 25 years of experience in design, operation and management of high power, high voltage and other testing laboratories. After activities in testing labs Sergio acquired 16 years of experience in the use of testing simulations in support to manufacturers and certification companies. Sergio is the author of the simulations software SwitchgearDesign. Sergio is currently involved in the implantation of a new set of big laboratories which are under construction in South America (High Power lab 2500 MVA, High Voltage testing up to class 550 kV and temperature rise up to 25.000A)

The simulations to predict the results of the tests were done using the software SwitchgearDesign developed by Sergio Feitoza. The reader may find Information in free training movies in the following link in You Tube
(Item 1, Item 3 Item 7 in English https://www.youtube.com/channel/UCyQtdE7dQTvsZPHBw3ostMg/videos?view=0&sort=dd&shelf_id=0

In these links there are some videos and reference material, inclusive for validation of testing simulations:
Cognitor site and CV http://cognitor.com.br/en/site/index.php?sec=1

YouTube movies (free) about concepts and simulations in (some in English, in Spanish & Portuguese)
https://www.youtube.com/channel/UCyQtdE7dQTvsZPHBw3ostMg/videos?view=0&sort=dd&shelf_id=0

Articles and book by Sergio (free download) : http://www.cognitor.com.br/en/site/index.php?sec=5

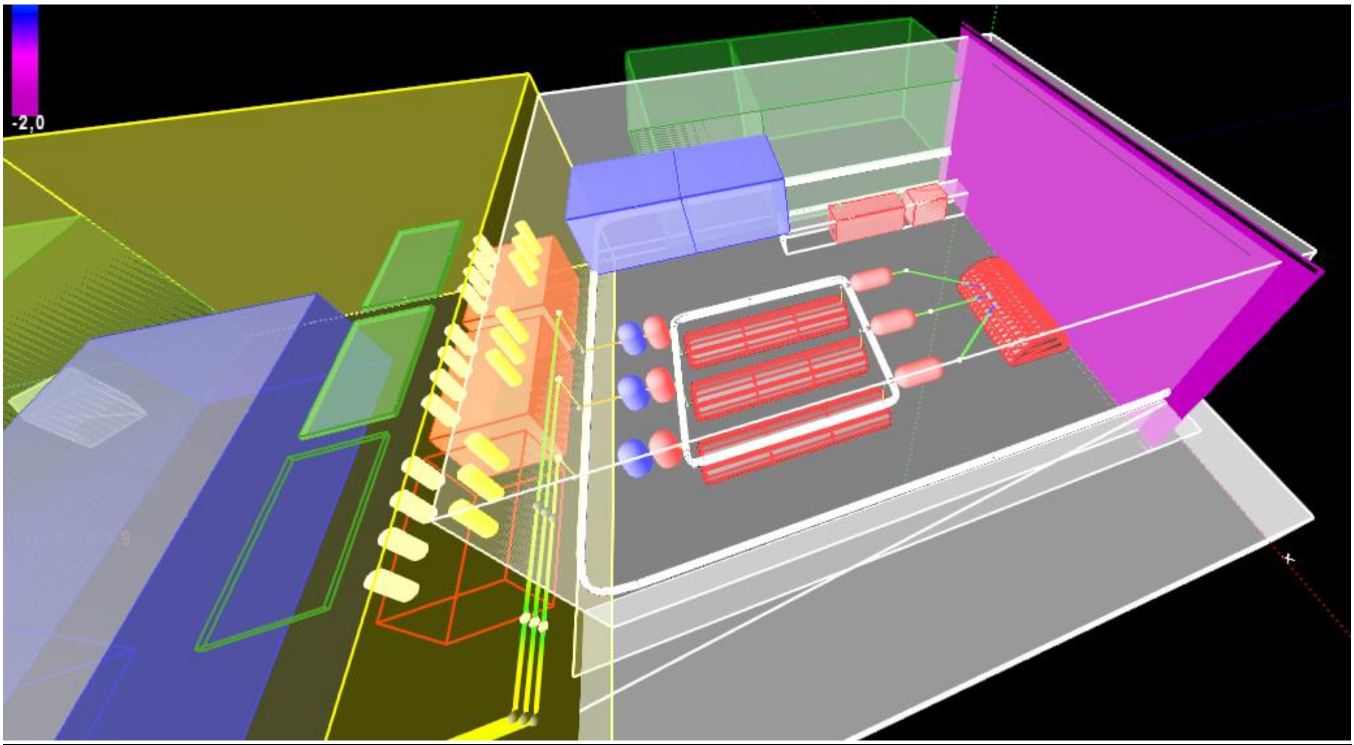
Information on trainings http://www.cognitor.com.br/en/site/index.php?sec=3

More information on trainings, forum, etc..: http://www.cognitor.com.br/en/site/index.php?sec=6

LinkedIn posts : https://www.linkedin.com/today/author/0_0Qwvfip2RwUUnZw30ieO2m?trk=mp-reader-h

Sergio Feitoza, in the vacant time, is musician (guitar), composer and singer. Here is part of a recent show https://www.youtube.com/watch?v=TYPnmY7_LYE

Example of use of Design Alternative 4 (High Power testing laboratory)



Costs for Design Alternative 5