SAPHO: A prototype expert system to help designing open-air high-voltage substations layout*

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Abstract

We present our experience building a big object-oriented software whose aim is to help designing open-air high-voltage substations layout. We list the motivations and objectives, briefly develop the expertise and then the way we used the object-oriented paradigm as a support for our system. We develop in particular the adopted original control structure.

1 Introduction

The whole layout design of an open-air high-voltage (from 72.5 kV to 765 kV) substation has always been a real challenge to systems designers, so true is it that it requires them to be acquainted with numerous fields such as electrical and mechanical engineering.

Adding the strongly parametrizable and country-dependant type of expert appraisement to the fact that very few people can control the entire design strengthens the difficulty in dealing with it.

In connection with industrial partners, we felt the need to build a software whose aim would be to mix this world-spread expertise together with very up-to-date computation codes, database systems and artificial intelligence techniques.

This ambitious work began in September 1988 with the collaboration of an electric devices manufacturer and a network operating staff, namely Merlin Gérin (France) and EDP (Portugal).

Our objectives are twofold:

- providing a reliable and adaptable expert system to be used in the industrial world, by electric devices manufacturers, by power supply operating staff and by engineering offices
- adding a didactic module, which we plan to be a multimedia system, in order to fulfil educational requirements both for our students and for continuous educational training in engineering offices.

This paper is organized as follows: In next section we briefly develop some of the aspects of the substation design. Section 3 will outline the constraints we have to satisfy if we want to meet our objectives. Section 4 will focuse on the state of development of the preliminary version of our system which we call SAPHO (for Système d'Aide à la conception de Postes Haute-tension Ouverts). It will briefly present some of its aspects and particularly develop the original control structure we are building. It will also briefly introduce the object-oriented concepts we will be using throughout the paper. We finally give our conclusions in section 5.

2 Designing an open-air high-voltage substation layout

We outline in this section the difficulties encountered by system designers when dealing with power systems layout in general and open-air high-voltage substation in particular. We also present the main lines of this design and insist on some of the originalities we did introduce in the expertise.

The complexity of the whole design is of common knowledge and this for the following reasons:

- system designers have to deal with numerous fields going from electrical engineering to mechanics, some of those fields requiring them to become acquainted with very up-to-date research results
- some of the values to consider, such as security distances often differ from one country to another
- experts for the entire design are very seldom
- like any other design, the high-voltage open-air substation design is not a sequential work and you may

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have to re-begin a one week engineering office work when noticing that for example the planned structure won't support the electrodynamic stresses due to short-circuits

The design description consists of the seven following tasks to be fulfilled, each of them taking into account the planification requirements:

1. Single-phase diagram choice among 15 possibilities
2. Electric devices (circuit breaker, surge arrester, current and potential transformer, isolator, wave trap, anchoring insulators and insulator supports) choice
3. Busbar type (rigid or flexible) choice. General busbar and switch-bays (feeder, transformer, coupling) disposition including overall space requirements (clearances, security, span length) computation
4. Busbar sizing (diameter, cross-section and thickness or number of sub-conductors) in order for it to support the rated and short-circuit currents and to lessen the corona effect. This task also includes the sag verification, the frequencies analysis and the aeolian vibrations study
5. Computation of both static and dynamic overloads like wind, ice, short-circuit and combinations of them. Final acceptation of the overall design with devices choice updating if needed and definition of the load to be supported by the anchoring structures
6. Computation of the ground network for step and touch potentials
7. Lightning protection

Let us now give further details about those tasks, intentionally limiting this description to the first five ones, tasks 6 and 7 being not yet implemented.

- *TASK 1:* The single-phase diagram choice (when not imposed) is based upon six questions and two criteria (space and cost). The aim of those questions is to determine what we call the *security and flexibility levels.* The security level is defined as follows: In case of busbar or line fault, you have to be able to keep the largest number of devices busy and so use the least number of breakers. The security level expresses this ability. The flexibility level expresses the easiness to deal with maintenance and changes made to the electrical configuration of the substation. One of those questions is for instance: *Do we accept loosing a switch-bay during the maintenance of one breaker?* If the answer is 'no' we can then eliminate all diagrams with one, two or three busbars, disconnectable or not, having only one single breaker per bay and consider the remaining ones like diagrams with one and a half or two breakers per bay or like "loop" diagrams.

  As an example of this expertise, here are some of the characteristics of two diagrams whose representation is found in figures 1 and 2:

  - *disconnectable single busbar diagram with one breaker* : relative needed space: 85, relative cost: 85, number of nodes: 2, in case of busbar fault all connected switch-bays will be out of service, in case of maintenance on one breaker the switch-bay will be out of service, generally used for voltage up to 245 kV
  - *two busbars diagram with one breaker* : relative needed space: 100, relative cost: 100, number of nodes: 2, in case of busbar fault all connected switch-bays will be kept in service after reconnection, in case of maintenance on one breaker the switch-bay will be lost, generally used for voltage up to 765 kV

- *TASK 2:* The difficulty of this task is to select the best fit device among a huge number of them. It is one of the longest tasks. To facilitate those choices, we can restrict the set of devices to explore with empirical rules such as: *If available space is restricted, do not consider transverse opening disconnectors (double-rotation disconnectors f.i.)* or *If the minimal temperature at the substation location can be less than -20 degrees centigrade then the family of disconnectors to consider is the pantograph one.*

- *TASK 3:* Expertise about this task is very hard to synthesize, the experts studying each case separately without general structure. First the busbar type (either rigid or flexible) is to be chosen using rules such as: *prefer flexible busbars if building a substation in a seismic area* or *beware of flexible busbars if the short-circuit current is high.* After determination of the number of levels (two or three) and insulating distances, the chosen devices are disposed on switch-bays, starting from the overhead line arrival to the busbars and respecting those security distances. The overall needed space is then computed taking the different types of bays, the connecting lines, etc, into account.

- *TASK 4:* It consists of computing the minimal busbar dimensions (external-diameter, section and thickness if rigid busbar, section, sub-conductors number and bundle geometry if flexible busbar) for it to support both rated and short-circuit currents (adiabatic heating) and corona effect. A busbar

is then selected in the catalogs using those dimensions. For rigid busbars will follow a sag verification, a frequencies analysis and an aeolian vibrations analysis, each of them making use of methods presented by the IEEE [3]. If the busbar is flexible then a sag analysis and a non-resonance verification will be performed using rules such as: *the pendular oscillation frequency must be sufficiently away from half the vertical oscillation frequency of the cable.*

- *TASK 5:* This is the most important task because it may cause us to reconsider everything that preceedes. It mainly consists of a static and dynamic sizing of the structure based upon the presence of wind, ice and short-circuit current. While the static sizing may generally easily be done using simplified methods, the dynamic behaviour requires much more sophisticated techniques such as the ones recommended by the CIGRE ([1],[2]). For those methods, only the most constraining cases will be studied. For instance, in case of short-circuit on a flexible busbar, the following case will be considered: two-phase isolated fault. Many other values will also be computed such as the pitching stresses for bundle configuration, especially the spacer compression.

3 What are the constraints we have to face if willing to computerize the design?

To satisfy the already presented objectives of our system, we have to consider the following constraints:

1. As the target user audience is mainly composed of engineers and students, supposed not to be acquainted with computer science, the first constraint is obviously a **convivial man-machine interface.**

2. If the sequence of tasks to be performed is commonly accepted, the way to achieve those tasks objectives often differ from one country or society to another. Furthermore, the expert appraisement is quite parametrizable, thus providing the following constraint: **providing an easy way to access and modify both expertise and parameters.**

3. The last constraint is to provide the user **explanations** about what is going on.

Our main will is to come to a system where **everything** will be available to the user in a very simple and convivial way. This means that all **formulas, rules, parameters** and **pieces of expertise** should be **accessed** and possibly **modified** by the user (entitled to it) willing to **fashion** the system his way. As will be presented later, this constraint motivates the adoption of an original control structure.

4 Building the preliminary version

We will in this section present the preliminary version of the system. For reasons explained later we chose to build our system using an object-oriented architecture and of course an object-oriented language. You will for this reason first find a very brief approach of what is the object-oriented paradigm and what are its advantages.

4.1 The object-oriented paradigm

Object-oriented programming is a programming style based on the **encapsulation** of both data (the information to handle) and procedure (the way to handle this information) concepts. It is in opposition with the "classical" programming style which maintains a clear gap between data and procedures. The task of program writing thus consists of the definition of a world of independant **objects**, communicating with one another through **messages**, each object being made of a certain quantity of information and procedures to process that information. For instance if we want to compute the permissible current rating of a given busbar:

- in "classical" programming, we will write a procedure computing this value for any busbar, procedure that will receive the given busbar characteristics as arguments

- in object-oriented programming, we will create a busbar object with the characteristics of the given one and ask that object to compute its permissible current rating and to return the result

Objects are the unique type of entities that can be handled by an **object-oriented system**. It means that **everything**, an integer as well as a modeled disconnector, has to be represented as an object. An object is made up of three parts:

- it has a **private memory** consisting of a collection of **attributes** whose value defines its **state**. The value of an attribute is in turn an object. We can distinguish between two types of objects: **complex objects** whose attributes are means of referencing other objects and **primitive objects** that do not have attributes but only a value which is the object itself (an integer for instance)

- it has a collection of **methods** that capture its behaviour. The methods of an object are the only procedures able to manipulate the object private memory and to return its state

- objects communicate with one another by sending messages requiring the receiver object to execute one of its own methods. An object can thus be considered as an independant entity, except for a collection of messages, coming from other objects or itself, it is supposed able to interprete. This collection of messages is called the **communication interface**. Notice that the structure of a message is the following:

```
[receiver  method  arguments]
```

Each object is defined as being part of a **class**. A class describes the structure of a collection of objects having the same attributes and methods, those objects, called **instances**, only differing by the value associated with their attributes. When a message is sent to an instance, the method implementing the response to it is found in the class definition.

Each created class is considered to be **subclass** of an already existing one called its **superclass** and **inherits** the methods and attributes of its superclasses. There is a special class, superclass of all others, serving as root for this hierarchical structure. A new class can bring new attributes and methods adding them to the inherited ones.

To be complete we have to tell that there exists a pseudo-variable often called *self* ou *oself* which allows an object to send messages to itself. This variable may then be used to implement recursive functions.

The advantages of such a way of programming are well identified:

- the message passing mechanism is such that the object can be seen as a black box responding to a finite number of activations. A program can thus be constructed as a collection of **modules** interacting only through the communication interface, without any idea of the "internal implementation" of one another

- object-orientedness insures **integrity**, that is when two different classes each own a different method with the same name, the correct one will always be activated by the correct receiver. It allows the programmer to get rid of the data types management. For example, the classes *integer*, *fraction* or *float* have their own version of the "+" method and the system will determine which of these versions to activate when meeting a form "[a + b]", depending on the type of the receiver a

- the inheritance mechanism allows the sharing of knowledge between related classes of objects without having to recopy it

- an **object identity** mechanism allows to distinguish each object from the others thus permitting numerous objects to refer to the same one via that identity. This increases the modeling power, for it is the most rational way of expressing for instance that two persons have the same child

- the encapsulation of the data structure and methods applying to it allows a quicker program updating whenever it is decided to modify this data structure

To end this quite abstract section, we illustrate that theory with an example. The following piece of code gives the definition of both the root class for all busbars and one of its subclasses, the one for rigid busbars. We use the SPOKE syntax which is self explanatory.

The *busbar* class contains (among a lot of others) three slots (attributes) and one function (method). The slots are for the chosen material (Al, Cu, etc), assuming that a class for all materials already has been defined, for the cross-section and for the external diameter. The *Young-modulus?* function gives the busbar Young's modulus which is in fact the chosen material Young's modulus.

The *rigid-busbar* class is a specialization of busbars and thus is defined as being a subclass of the first one. It inherits all characteristics of busbars and defines new ones which are attributes only suited for rigid busbars such as the wall thickness and functions providing useful values needing a complex computation such as the permissible current rating.

Clearly, a second subclass for flexible busbars is to be defined, differing from the first one by the lack of wall thickness and by the introduction of the *number of sub-conductors* and *sub-conductor ray* attributes and the *ultimate-strength?* method.

```
[busbar isa class superset electric-device
   with
     (slot chosen-material range material)
     (slot cross-section range number)
     (slot external-diameter range number)
     (slot mass-pu-length range number)
           ...
     (function Young-modulus?
       form
           [[oself chosen-material] Young])]

[rigid-busbar isa class superset busbar
   with
     (slot wall-thickness range number)
```

```
(slot max-length-all-in-one-block
        range number)
      ...
(function permissible-current-rating?
        ...)
(function inertia-moment? ...)
(function flexion-modulus? ...)]
```

We can now create an instance of the *rigid-busbar* class by simply typing the following lines, assuming the used units are m, m^2 and kg/m:

```
[a-bus isa rigid-busbar
      chosen-material AlMgSi-f22
      cross-section 0.000955
      external-diameter 0.08
      mass-pu-length 2.58
      wall-thickness 0.004
      max-length-all-in-one-block 19]
```

4.2 SAPHO, a preliminary version for our system

We started working on SAPHO in January 1989. What first appeared after a good part of the expertise had been collected was that there was no matter to build an expert system in the computer science meaning of the word. In fact we were facing a very important algorithm making use of lots of techniques, with a lot of unavoidable tasks to perform, the way to achieve them only being subject to changes. Furthermore, this algorithm was quite sequential although there may occur a backtrack to a previous stage of the design from time to time. SAPHO was nevertheless called "expert system" because it was based on expertise and even if it didn't make use of decision trees or inferences, its aim was still to try behaving like an expert in the field.

We based ourselves on the collected expertise, the identified six main tasks to be performed and the interactions between them. The goals of this work were to show the feasibility of such a system, to solve major problems such as interfacing our system with big Fortran codes and try to satisfy the presented constraints. To those ends, it was decided that the six steps of the design would be partially implemented to form a minimal version of the system taking the major part of the problems into account.

We use SPOKE as software support for developing SAPHO. The reasons for this choice are:

- The object-oriented paradigm is particularly well-suited for an easy modelization of physical world components, like a substation or a potential transformer, because it allows the programmer to model the real complexity of such entities without having to simplify them. Another reason for which the object-orientation was chosen is that the design of a man-machine interface is considerably simplified with its use.
- SPOKE is build upon Sun Common Lisp, thus offering an interface to Fortran provided by this language.

The hardware support for our work is a SUN 3/60 workstation with 12 Mbytes RAM.

SAPHO is composed of four modules which we will next briefly develop.

4.2.1 The knowledge base

This module is to contain knowledge about the physical entities involved in the design procedure. All informations about entities such as busbars or string insulators are there to be found. In fact, this knowledge base consists of numerous SPOKE class definitions, each modelling a real-world component, as presented in the example above. The attributes of the entities involved in the design are filled as the system proceeded.

4.2.2 Man-machine interface

The design of a window-based interface was a very interesting part of our work and grandly simplified both by the object-oriented concepts and by the window toolkit of SPOKE. As this is not the matter of this paper, we will not give details about this design. You will anyway find a screen hardcopy at the end of the paper to give you an idea of the interface.

4.2.3 Fortran codes interface

As said above, the design requires numerous complex computation methods, especially methods using finite elements. We decided to integrate into our system a software called SAMCEF-CABLE developped at the University of Liège. By integration, we mean that we avoided the user the troubles of using such a complex code by automatically generating the input data files (with automatic predetermination of most critical short-circuit conditions), managing the result files and by allowing visualization of those results. The integration was obviously made easier by a very good knowledge of SAMCEF-CABLE.

SAMCEF-CABLE is used in our system to perform the following computations:

- modal analysis of flexible and rigid structures, taking into account the insulator supports or string insulators
- transient response of electrodynamic stresses computation in case of short-circuit

- computation of the stresses induced by every combination of loads such as wind, ice thickness and short-circuit

A lot of small Fortran functions were also added to the system, their integration being facilitated by the Sun Common Lisp Fortran interface.

4.3 Electric devices database

This module is to permit storage of electric devices catalogs in order for the system to select among them the best fit device, that is the one satisfying a number of criteria.

After having eliminated the commercial database softwares, the relational ones because the objects to store were everything but flat tuples and the object-oriented ones because none of the existing few ones was compatible with either LISP or SPOKE, we decided to proceed the following way. For each device type, a file was created, containing the many instances of the class corresponding to that device. That is we managed files of SPOKE objects. Selections were made by loading the concerned file into the SPOKE environment, selecting the best device and then killing all non-selected objects. Although this is a naive approach it provides good results and seems to be sufficient for our preliminary version whose aim is among others to show the feasibility.

The selection operations proceed the following way: Let us take the disconnector choice as an example. First of all, one or more disconnector families are selected using both the highest voltage as an immutable criterion and another criterion, either the available space or the cost, depending on rules such as *the cost is the default additional criterion* or *if the available space level for the substation is limited then the needed space should be used as the additional criterion*. Rules such as *if the minimum temperature is less than -20C then the family must be semi-pantograph* are also taken into account.

The selection is then performed on the selected families using, in the disconnector case, the highest-voltage, the basic insulation level, the rated current and the short-circuit current as criteria.

4.4 A fully adaptable control structure

The identified constraints egged us to build a fully adaptable control structure which we will introduce in this section.

We are confronted with the problem of implementing huge conception tasks, each of them requiring different techniques and expertises. As said above, the corresponding algorithm will be a task chaining one with possible backtracks to previous stages.

What we first thought was to implement each huge task separately using classes including all methods needed to achieve a task. The sequencing of operations inside a task being scheduled by a *leader* method. This unelegant type of implementation surely would have worked, even if making roar object-oriented programming purists, and was motivated by the following remark: Object-oriented programming authors all tell you to model the behaviour of each real world entity in order to be as close as possible to reality, but what if you have to deal with numerous methods such as *select among breakers the one satisfying some criteria*? Do you attach this method to the *breakers class* knowing that it won't ever model one of its behaviours or do you create a *task object* whose only behaviour will be to perform the selection?

We then adopted an architecture, based on the following ideas:

- why not consider *task objects* corresponding to elementary operations instead of a large number of complex operations? We would then have to consider independant entities which we will call actors, each of them having the responsibility of an elementary task such as initialization, computation, help providing or results displaying

- one such actor will have at least two methods, one for its operation and one to activate the next actor once its operation over. It will also own a direct reference to the next actor it has to activate

- there will be a class for each type of actor, and each particular actor of that type will be one of its instances. For example, we can have a class for all actors whose operation is to let the user enter a value for a system variable [1] and instances of that class for each variable to be given a value

- the control structure will then be made of a static network of actors of which the leftmost one is to be activated to start running the system

- one such approach satisfies one of our constraints which is **explanations generating**. Indeed, as each actor is devoted to a type of operation, it is easy to generate rudimentary but sufficient explanations at the activation of any actor and after the result of its operation is obtained. To manage this we can have a standard *trace* for each type of operation and adapt this trace, basing ourselves on the context of the activated actor. For example, if we have an actor devoted to the initialization of the highest-voltage, the (silly in that case) trace will

[1] not such an easy stuff as it seems, because, this type of actor will have to generate a menu with all possible values, allow the user to ask for help about the variable and allow him to enter his value in a convivial way whenever he is not satisfied with the proposed ones

take into account the variable it has to initialize, that is the highest-voltage

To illustrate this, we can consider the simplest type of those actors, the initialization ones. The following pieces of code briefly describe the very simple way of managing this kind of actors and all actors in general. First of all, we have to define a root class *init_actors* for all those actors:

```
[init_actors isa class superset system_actors
   with
     (slot the_variable_to_init
              range system_variables)
     (function actor_operation ...)
           ...]
```

An actor, instance of this class will have the following main characteristics: it will be assigned a reference to the variable he is to initialize and he owns a method allowing it to perform its operation.

We do actually consider two sub-types of those actors: the first one, the simplest, will be for actors clearly knowing the next actor they have to activate and the second one for actors in which a test will be performed on the value assigned to the variable in order to determine one of two actors to activate next. Here is the code for the first sub-type:

```
[next_known_init_actors isa class
          superset init_actors
   with
     (slot next_actor range system_actors)
     (function display_trace ...)
     (function display_trace_when_over ...)
     (function activate_next_actor ...)
     (function activate ...)]
```

All those characteristics are self explanatory, but let us precise that the *activate* function is the only function through which any actor can be accessed. It is responsible for the sequencing of actions inside that actor.

The second sub-type is defined by:

```
[next_unknown_init_actors isa class
          superset init_actors
  with
     (slot it_is_ok range boolean)
     (slot next_actor_if_ok ...)
     (slot next_actor_if_not_ok ...)
     (slot the_value_to_compare_to ...)
     (slot superior_to range boolean)
           ...
     (function display_trace ...)
     (function display_trace_when_over ...)
     (function activate_next_actor ...)
     (function activate ...)]
```

The attribute *it_is_ok* is to reflect the result of the test to perform, the *the_value_to_compare_to* slot is for the value that will be compared to the entered value for the variable to initialize and the slots *superior_to*, *inferior_to*, etc, are to tell what kind of comparison operator will be applied. One may wonder why the other functions for that class look similar to the ones of the above olass: in fact their names are the same (this is a feature of object-oriented languages) but the content differs (for instance, the trace to generate clearly differs from one case to another).

This structure cannot convivially satisfy the remaining constraint that is **access and modification of expertise** since the user would have to deal with generating new actors and modifying bindings. Thus we decided to consider three abstraction levels:

1. **the basic level**, which is made of the already introduced actors network
2. **the middle level**, which is made of a collection of instructions to generate actors and establish bindings between them, and which generates the *basic level* by simply executing those instructions
3. **the electric strategy level**, which allows the user to read and possibly modify the expertise by adding, suppressing, interchanging or modifying high-level instructions, expressed in a very simple formalism. This level generates the *middle level* by execution of those instructions

As an illustration of this architecture you can consider figure 3 where an example of the mapping between two initialization high level instructions and the actors (small number in that case) network is showed.

Our main will was to allow **everything** in our system to be accessed by the user in both reading and writing accesses. All system entities such as formulas will thus be available and the user will be able to define his own entities in order to fashion the system his way.

How will he do that? Those entities will be stored as named objects and those names will be used to compose the high-level instructions. The user defining his own entities will give them a name. Suppose for instance that we have a high-level instruction to compute the busbar external diameter to support the rated current using a formula entity named *formula_1*. If the user whishes to use another formula, he will only have to enter it in the system, in a way described later, to give it a name and to replace *formula_1* by that name in the instruction.

All entities and expertise (the high level instructions) will be editable in a suited editor, allowing the user to modify them or to compose his own ones by simply selecting on menus everything he needs. If we consider

formulas, those menus will present mathematical operators and all system variables (their name). A menu for all system entities (their name) will always be user available in order for him to access these entities or to select their name for insertion into a high-level instruction. The user willing to compose a new high level instruction will be provided a menu with the simple syntax of those instructions and the menus for all system entities.

The system entities are:

- **formulas**: a formula will be written in a lisp-like formalism for the simplest of them. For complex computations, FORTRAN codes will be used as formulas, assuming the user is familiar to this language
- **parameters**: a collection of parameters will be available for value modification, that is the user will be able to give a value corresponding to his country to parameters such as *the percentage of the span to consider in order to proceed to the busbar sag analysis*. He will also be allowed to add new parameters which he will insert in his formulas
- **system variables**: in order to be used by high-level instructions and formulas, the system variables such as the highest voltage will be available by menu. Each variable is assigned a collection or interval of possible values and the user will be abilited to modify them
- **selection criteria**: the attributes of all classes of the knowledge base will always be available to compose the selection high-level instructions
- **rules**: a collection of rules will also be user available and definable
- **checkings**: a checking is a collection of tests to validate the value assigned to a system variable with regard to already initialized ones. They are to ensure a consistency of the system. For instance, a checking based on the highest voltage can be done when initializing the rated current

It is now time to introduce the high level instructions. There will only be three types of them because our experience with the expertise told us it would be sufficient [2]. Each of those instructions will correspond to at least one actor, selection operations for instance requiring many of them. We will only give one example of the most complex instructions for each type:

1. **initializations** : For initialization of the planified highest voltage and basic insulation level, we use the following instruction:

```
[init_and_test highest_voltage using (< 300)
  (if_ok [init lightning_impulse])
  (if_not_ok [init switching_impulse])]
```

That particular instruction means that once a value has been given to the highest voltage, a test on this value is made in order to determine the next instruction to execute. That is, if the highest voltage is less than 300 kV then proceed to the lightning impulse initialization, else give a value to the switching impulse. As can be seen on figure 3, this will generate a three actors sub-network. Notice that many instructions can be inserted in the if_ok and if_not_ok branches.

2. **computations** :

```
[test_then_compute external_diameter
  using (= busbar_type rigid)
    (if_ok with formula_1)
    (if_not_ok with formula_2)]
```

In this case, the formula to be applied in order to compute the busbar external diameter depends on the busbar type.

3. **selections** :

```
[select_single disconnector
  using criteria
  ((= disc_type chosen_disc_type 1)
  (= manufacturer (siemens merlin_gerin) 1)
  (>= disc_highest_voltage highest_voltage
          1 25%)
  (>= disc_bil bil 1)
  (>= disc_rated_current rated_current 0.5)
  (>= disc_sh_circuit_current
                sh_circuit_current 0.5))]
```

Selection operations are certainly the most complex ones and they correspond to lots of actors. This example asks the system to select a single device for each of the mentioned manufacturers, device that will be of the chosen type and that will satisfy all specified criteria. It is clear that a solution will always have to be provided, so, if a criterion cannot be satisfied by the stored devices, the system will have to proceed to an approximation on that criterion, that is, if there are devices satisfying all criteria but the one involving bil, the selection will return among those devices, the one whose disc_bil attribute is the closest to the system bil. In that rare case, the system will go on working with that approximation if told to, telling you anyway to contact a manufacturer to build a special device for

[2] for all tasks but the *disposition* one that will need the integration of a CAD tool in the system and for which other instructions will be introduced

your needs. If you prefer waiting for the dimensions of that special device, the session will be stopped until you enter the new device in the system.

The numbers at the end of each criterion express a relative importance among those criteria. This will be useful to determine a single device. In effect, suppose we have a collection of possible devices, if we wish to select the most adequate one, we have to sort those devices on the criteria, in order to get an ordering of devices. If we consider the example, it can easily be seen that the device satisfying all equality criteria and whose attributes involved in inequality criteria are the smallest ones to be found in the ordering, will be selected. What if we are to decide between two devices having the following characteristics:

- A1: supported highest voltage 245, supported bil 1050, supported rated current 1600 and supported short-circuit current 40
- A2: supported highest voltage 300, supported bil 1175, supported rated current 1200 and supported short-circuit current 31

It must be possible to tell the system to begin sorting for instance on the highest voltage, then on the bil and so on. An hierarchy for criteria is thus to be established for the final sorting.

Some criteria are to be considered carefully. If we consider for example the highest voltage, it is not acceptable to select devices supporting 765kV if the planified highest voltage is 420kV even if obliged to go that up because of other criteria to satisfy. That is the purpose of the percentage found at the end of those criteria. In our example it tells the system not to go beyond 25% of the planified highest voltage.

We hope that the syntax of those instructions will not be too discouraging so that the control structure will effectly be adaptable. The instructions are of so high level of abstraction that we believe the entire expertise can be expressed using few of them thus insuring an easy reading and understanding of it.

5 Conclusions

We are currently developing a fully adaptable expert system called SAPHO. For this system to be good, we are confronted with a substation design combining high levels of both security and reliability at the lowest price. These requirements necessitate a good level of expertise and some complex computation methods in order to be as close as possible to reality thus insuring reliability and money saving (no oversizing).

Those complex methods are of difficult use and often discourage the user because of teduous manipulation. SAPHO fully integrates those methods and the expertise needed for their manipulation. It also provides a very convivial man-machine interface and a high level of expertise easily adaptable by a user who is not the system conceiver.

We hope SAPHO will satisfy both students, in a didactic point of view and the industrial world, by the time saving it brings and the facts that it synthesizes the procedure to be followed and that it helps not to forget any detail.

6 Acknowledgements

We would like to thank Mr. J-C Leroy from Merlin Gérin and Mr. F. Mira from EDP for the very valuable help in the expertise collection and synthesis. We would also like to emphasize the initiating procedure of this project made by Mr. M. China from Merlin-Gérin and the help of his A.I. team.

7 Trademarks

8 Bibliography

[1] CIGRE Brochure SC 23 (Substations), *The mechanical effects of short-circuit currents in open air substations*, 1987

[2] Lehmann W., Lilien J.L., Orkisz J., *The mechanical effects of short-circuit currents in substations with flexible conductors - Numerical methods - Computer approach*, CIGRE report 23-08, 1982

[3] IEEE Substation committee, WG 69.1, *Guide for design of substation rigid bus structures*, March 1979

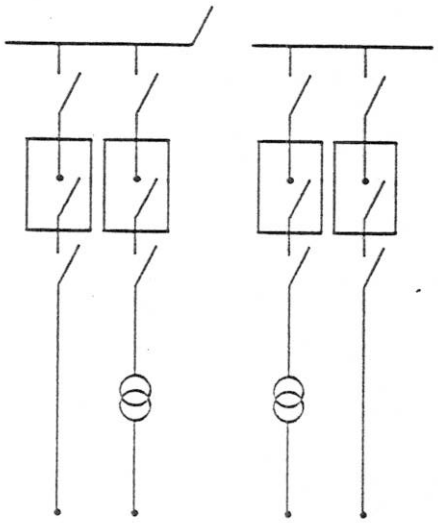


Figure 1: single busbar diagram

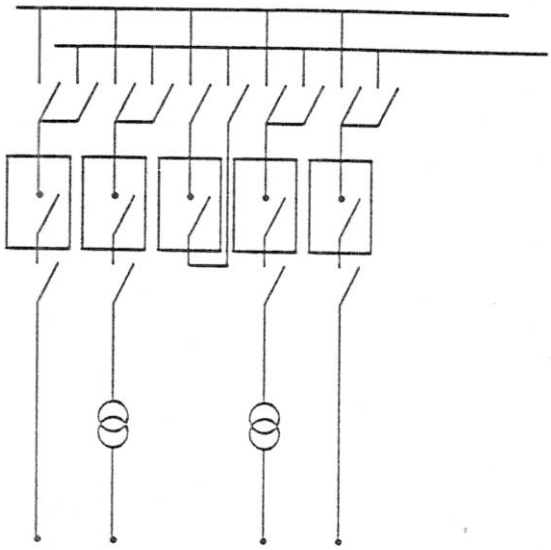


Figure 2: two busbars diagram

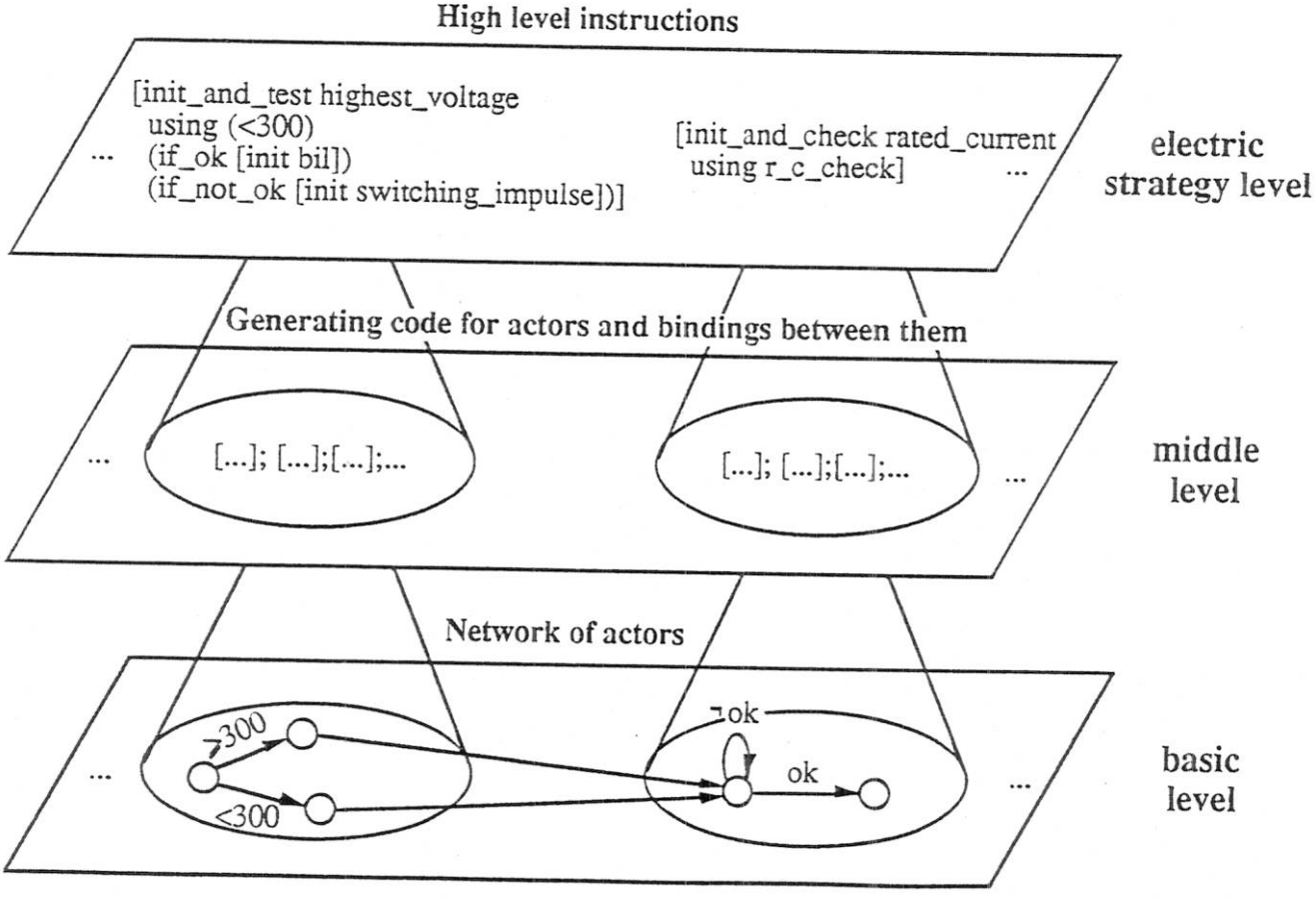
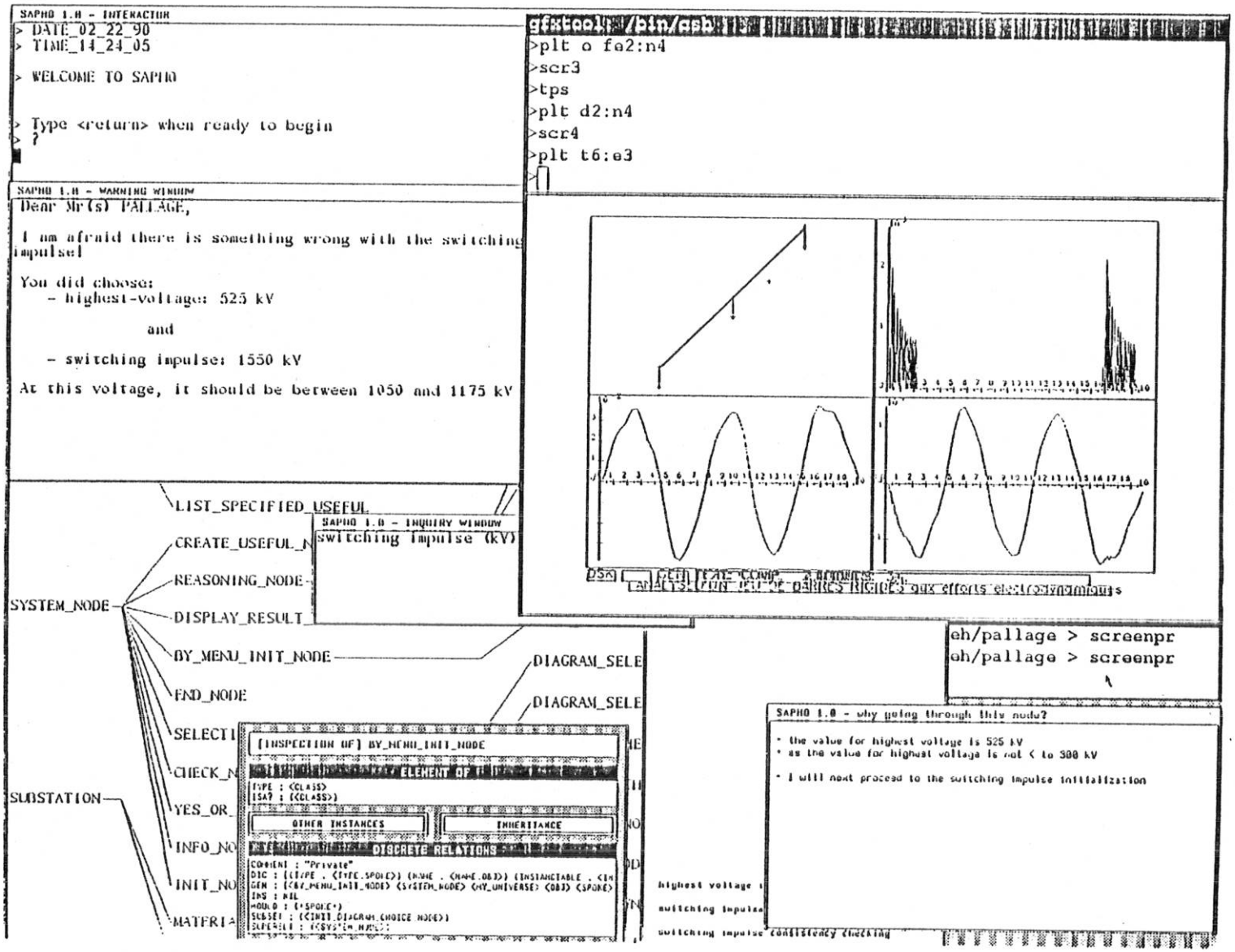


Figure 3: abstraction levels


SAPHO 1.0 - INTERACTION
> DATE_02_22_90
> TIME_14_24_05
> WELCOME TO SAPHO
> Type <return> when ready to begin
> ?
SAPHO 1.0 - WARNING WINDOW
Dear Mr(s) PALLAGE,
I am afraid there is something wrong with the switching impulse!
You did choose:
- highest-voltage: 525 kV
and
- switching impulse: 1550 kV
At this voltage, it should be between 1050 and 1175 kV
>plt o fe2:n4
>scr3
>tps
>plt d2:n4
>scr4
>plt t6:e3
SAPHO 1.0 - INQUIRY WINDOW
switching impulse (kV)
LIST_SPECIFIED_USEFUL
CREATE_USEFUL_N
REASONING_NODE
DISPLAY_RESULT
SYSTEM_NODE
BY_MENU_INIT_NODE
END_NODE
SELECTI
CHECK_N
YES_OR_
INFO_NO
INIT_NO
MATERIA
SUBSTATION
DIAGRAM_SELE
DIAGRAM_SELE
(INSPECTION OF) BY_MENU_INIT_NODE
ELEMENT OF T
TYPE : (CLASS)
ISA? : (CLASS)
OTHER INSTANCES
INHERITANCE
DISCRETE RELATIONS
COMMENT : "Private"
eh/pallage > screenpr
eh/pallage > screenpr
SAPHO 1.0 - why going through this node?
• the value for highest voltage is 525 kV
• as the value for highest voltage is not < to 300 kV
• I will next proceed to the switching impulse initialization
highest voltage
switching impulse
switching impulse consistency checking