THE SIMPLIFIED SUBSTATION AT GROUND LEVEL: A NEW MV/LV SUBSTATION FOR SPARSELY POPULATED AREAS

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SUMMARY

This article presents the new technical level of prefabricated MV/LV substations designed by EDF with the assistance of several manufacturers, to supply power to underground public distribution systems installed in rural and suburban areas. It begins by establishing the context and motivations of the utility. Then, having explained the procedure adopted for the design, it describes the substation and its components in detail. The advantages provided by this new product, known as PSS for " Poste au Sol Simplifié " (Simplified Substation at Ground Level) are then indicated.

1. THE CONTEXT AND BENEFITS TO BE GAINED

1.1 The concerns of the utility

For several years, an agreement signed between EDF and the French government has committed EDF to placing a significantly greater proportion of MV and LV installations underground, turning away from overhead power systems. This deliberate policy of placing installations underground, in response to ever-increasing pressure in environmental matters, particularly concerns areas with a low population density, which are rural areas and suburban zones on the outskirts of town and cities.
With this in view, a marked reduction in the pole-mounted substations traditionally used for the connection of MV overhead networks is foreseeable, and an increase in prefabricated substations installed at ground level to permit the connection of underground MV and LV cables.
Similarly, the use of substations at ground level is necessary since EDF has decided upon the progressive elimination of old rural substations in tall structures for MV overhead systems, also known as " tower " substations on account of their appearance (they may be as much as 8 m high occupying an area of 4 to 5 m^2 on the ground).
At the same time, to fulfil more stringent environmental requirements, the design of such substations must inevitably take into account the criteria of styling and the blending of the structures into the environment, now more demanding than in the past : the substations must be made both discreet and pleasant in appearance through a careful choice of shapes and colours.

1.2 The gaps left by the present equipment

The different types of substations at ground level available today only partially meet the emerging needs associated with the development of underground systems in rural and suburban areas.
In fact, although the rural substations on the market at present may be suitable from the aspect of their integration into the environment, they have various deficiencies with regard to the objectives recently defined by EDF, essentially concerning safety and the quality of the electricity service.
The existing types of urban substations can be said to fulfil the structural requirements of MV underground systems well. However, considered in terms of the present environmental constraints, they are still relatively bulky, and above all their cost is too high to envisage using them other than occasionally to solve certain isolated and severe problems.

1.3 The benefits to be gained

All the above reasons led EDF to design the new level of MV/LV substation, called PSS for " Poste au Sol Simplifié " (Simplified Substation at Ground Level) on the basis of new components (enclosure, transformer, LV board and possibly MV board) specifically adapted to the different configurations of underground systems encountered in rural and suburban areas. It was important to design a substation taking into account the major orientations laid down by EDF in relation to four major objectives :

- control of distribution costs per kWh,
- improvement in the quality of the supply,
- improvement in the safety of property and persons,
- reduction of the impact on the environment.

2. THE DESCRIPTION OF THE PRODUCT

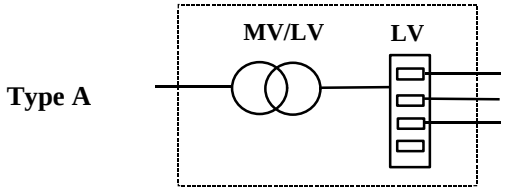
2.1. The design procedure

Initially the design of the PSS was studied by an internal working group at EDF, including the main participants in the project : the specifiers of electrical equipment of course, and also the operators, who cooperated closely right from the design stage of the product. The group thus formed worked in conjunction with an external consultant, a specialist in Value Analysis methodology. An initial general functional specification was therefore prepared.
In a second stage, each of the functions adopted was subjected to value analysis in conjunction with four manufacturers selected following a European call for tenders : ABB, ALSTOM, SCHNEIDER ELECTRIC and TRANSFIX. This procedure naturally led EDF to review certain requirements considered too demanding or excessively expensive. At the same time, a mock-up illustrating the different functions specified in the initial general specification was presented to a significant number of operators. Although their opinion supported the major technical orientations laid down by the working group, it should be noted that some arrangements which looked interesting on paper were eliminated on account of the possibility of incorrect use or misunderstanding by the operators. Bringing in the system operators, the future users of the product, throughout the design phase was therefore an undeniable advantage with a view to rational definition of the product.
As a result of what was learned during these two complementary procedures, a second overall functional specification was drawn up, to serve as a basis for the technical specification of the PSS and its different components, which we shall now present.

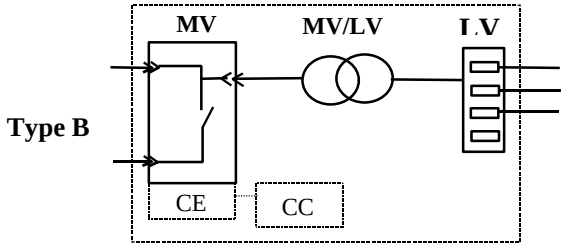
2.2. General presentation

To suit the various configurations of underground power systems in rural and suburban areas, and to permit the diverse operating conditions, two types of substations were created :

The PSS of type A. This is a substation of reduced height, without MV switchgear, supplied by a single branch-line.



The PSS of type B. This is a substation of reduced height, with MV switchgear, supplied by a ring main incorporating a breaking facility.



CE: O*ptional* electrical control of the MV board.
CC: *Optional* monitoring and control of the MV board.

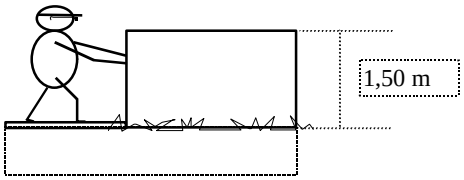
2.3 The main characteristics of simplified substations at ground level common to types A and B

The PSS is a MV/LV substation connected to an underground or overhead/underground public distribution system with a rated voltage lower than or equal to 24 kV. It is a prefabricated substation for outdoor service in compliance with IEC standard 1330 on " Prefabricated High Voltage/Low Voltage Substations ". The rated power delivered is 100 kVA, 160 kVA or 250 kVA, depending on the requirements.
Designed to be fed by an underground MV system via a single feeder, the PSS of type A comprises :

- an enclosure consisting of a buried part called the tank and a part above the ground ;
- an intrinsically safe MV/LV transformer ;
- a LV board known as the TIPI (Power and Communications Interface Board) ;
- a public lighting box ;
- an internal lighting device ;
- space for a low voltage power line carrier interface.

Compared to type A, the PSS of type B, intended to receive power from an underground MV ting main incorporating a breaking facility, includes additional elements which we shall describe in section 2.4.
The PSS are designed as modular assemblies in which the components can be changed as follows : the transformers of different makes are totally interchangeable and the same applies to LV boards from different manufacturers, if necessary, replacing the conductors linking the transformer to the board ; the MV board, if there is one (in a PSS of type B) can be replaced by a board of the same manufacture.

The enclosure. Of a prefabricated type, the PSS is fully assembled and inspected at the factory. This permits great ease of implementation and adaptation on the ground during installation at the site of use ; the PSS can in fact be delivered to site ready for service, that is, fully equipped and ready for connection to the MV and LV systems.
An important parameter considered in the dimensioning of the enclosure is the constraint regarding size. The smallest possible dimensions were selected for the substation taking into account the functions desired. The greatest constraint concerns the height above the ground, set at 1.5 m.
Another technical choice governing the size of the enclosure is that the architecture of the substation is designed to enable a standing operator to carry out all operational procedures from the exterior of the substation.
The intention is to have access to all the internal equipment from one single access side or possibly from two adjacent sides insofar as this contributes to a reduction in the dimensions of the substation. Besides this, an operational footpath, provided along the access side or sides, facilitates the work of the operator.



The choice of the mode of operation from the exterior and the optimised arrangement of the components inside the enclosure give the PSS a limited footprint at ground level, less than 2 m^2 for the PSS of type A and less than 3.5 m^2 for the PSS of type B.
Generally speaking, we can say that the reduced dimensions stipulated for the size of the PSS make it very discreet and suitable for installation in all types of environment, whilst permitting easy operation of the substation.
Another advantage obtained from such small dimensions, together with the limited weight, is the greater ease of transport of the fully equipped substation to the site, including its transformer.

The LV board. The LV board used in the PSS constitutes a new technical level.
It comprises a circuit breaker for general disconnection at the head of the board, with a rated current of 500 A, and it can be equipped with 1 to 4 public distribution outgoing units depending on the desired configuration; their rated current is 400 A. In addition to these basic arrangements, the main functional features of the board, most of which are new (N) or a substantial improvement (I) of the existing ones, are as follows :

- Protection of the operator against direct contact with live parts by a suitable degree of protection (IP 2X according to IEC 529) (I) ;
- The integration of interfaces permitting a temporary supply of power to all the LV feeders from a source outside the substation, such as an electric generating set for example (N) ;
- The integration of a public lighting outgoing unit with a current of 60 A, supplying power to a public lighting box incorporated in the substation enclosure (I) ;
- The possibility of installing an additional public distribution outgoing unit, temporarily, with a rated current of 400 A, to supply power via temporary service connections to such things as construction sites, fairs, etc. (N) ;
- The possibility for the operator to choose, depending on the desired mode of overcurrent protection for LV feeders, between two types of outgoing unit offering different modes of protection :
    - outgoing unit type 1 including basic single-pole protection by fuses (I) ;
    - *optional* outgoing unit type 2 offering, by means of a selector switch, a choice between single-pole protection by fuses or three-pole protection using either fuses and switches or circuit breakers (N) ;
- The integration of current sensors on each phase in type 2 outgoing units, and devices for independent tripping of the outgoing unit under predefined overcurrent conditions (N) ;
- The incorporation of an *optional* unit to measure and process different electrical variables (voltages, currents, powers) relating to the load of the type 2 outgoing units and the total load on the board (N) ;
- The incorporation of a power outlet socket for connecting mobile electrical appliances (I) ;
- Power supply to the lighting circuits of the substation (I) ;
- Power supply to a possible concentrator installed in the substation for low voltage power line carrier transmission in view of the requirement for communication between the utility and its customers, such as for example remote meter reading (N) ;
- Power supply to a possible interface for remote control of the switch on the MV board (PSS of type B) or a MV fault detector (N).

The board is designed in such a way that all the operational, inspection and maintenance actions can be taken in complete safety, deenergised or live. These operations can be carried out from the front of the board. In particular, the operations of connection and disconnection of the feeder conductors are possible live, off-load, when live working methods are applied.

The transformer. The " intrinsically safe " transformer is a three-phase MV/LV transformer, immersed in mineral oil, sealed, completely filled, and with natural cooling. It allows manual adjustment of the voltage and is available in 100 kVA, 160 kVA and 250 kVA versions.
It should be remembered that, compared to a conventional transformer, this transformer has a device on the primary side performing the protection and disconnection function in the case of an internal fault, and it has a suitable degree of protection against direct contact with live parts at the MV and LV terminals.

2.4 The PSS characteristics inherent in type B

The PSS of type B has an enclosure, a low voltage board and an " intrinsically safe " transformer which provide the functions and performances described for the PSS of type A. In addition to these components it includes the following items specific to this type :

- a MV board ;
- a MV fault detector and its two external indicating lamps ;
- an *optional* interface for remote control of the switch of the MV board (in place of the MV fault detector) permitting remote switching of the switch, the transmission of information on its status and the MV fault detection function ;
- a MV link via cables and insulated terminals between the MV board and the transformer.

The MV board. This is a gas-insulated device of the compact type, in compliance with IEC international recommendations.
It comprises a metal tank (according to IEC 694), sealed, filled with SF6, containing :

- a main MV circuit with a rated current of 400 A, equipped with a MV circuit breaker (according to IEC 265-1) ;
- two earthing switches (upstream and downstream of the switch) ;
- a shunt circuit with a rated current of 250 A, intended for connection of the transformer ;
- an independent manual control for operating the MV switch or *optionally*, an independent electrical control associated with the switch (telecontrol) ;
- plug-in type bushings with rated currents of 400 A and 250 A for connection to MV power systems and the transformer respectively.

The MV board forms part of a recent technical innovation well known today (MV switchgear of the RMU type in SF_6), which already takes into account the knowledge obtained from experience with earlier stages, which are :

- protection against internal arcing ;
- reliability of the position indicators ;
- the ability to close with a short-circuit on the earthing switches ;
- good resistance to climatic influences ;
- the use of simple, rugged, maintenance-free mechanical controls ;
- the elimination of insulation in oil.

3. THE ADVANTAGES SECURED BY THE PSS

3.1. Control of distribution costs per kWh

Naturally this is a constant concern of the utility during research for the development of a new product.
In the present case, apart from design cost control by means of value analysis of each of the functions expected from the product, (see section 2.1), the introduction into the PSS of components with new functional features, always synonymous with additional expenditure from the outset, was studied by examining two types of potential savings : the savings on investment costs and on the overall operational costs, calculated over the entire service life of the equipment. The savings identified for each component in the substation are given below.

The enclosure. Savings can be achieved through the optimisation of the MV underground structures in rural areas. As indicated previously, the inadequacies of the present rural substations in functional terms lead to the use of urban type substations, which meet the requirements well, but too lavishly. The development of a new substation, optimised for the connection of rural underground networks, leads to saving on investments.

The transformer. The transformer used in the PSS allows a higher overload factor than a conventional transformer. By permitting an overload of 150 % of the rated power for 3 hours, it contributes to optimisation of the power installed on the system, and thus minimises the utility's investment costs. By subsequently reducing the need to replace the transformer for adaptation to the load, this new function of the transformer at the same time contributes to the reduction of operational costs.
The optimisation of transformer losses is another factor for savings. An investigation has shown that the adoption of a loss distribution (no-load losses and on-load losses), according to the European harmonisation document HD 428, leads to an optimised overall cost for the transformer by taking into account both the purchase price and the price of the losses.

3.2 Improvement of the quality of the supply

Automatic disconnection of the transformer. A device built into the transformer primary fulfils the function of protection and disconnection in the event of the transformer having an internal fault arising from some electrical cause (an overload, for example).
It limits the fault currents flowing in the transformer to a peak value of a few kA, and clears them preventing the deterioration of the equipment located on the MV system upstream.
The device is current-coordinated firstly with the circuit breaker at the HV/MV substation, providing protection for the feeder of the MV system to which the transformer is connected, and also with the protections of the LV system. This arrangement has the advantage of limiting the consequences of the fault inside the transformer solely to the LV system downstream from it, by disconnecting it automatically in a sufficiently short time to prevent the tripping of the protection circuit breaker of the MV feeder concerned. By safeguarding the power supply to the customers supplied by the MV/LV substations connected to the same MV feeder, the transformer and its breaking and protection device participate in improving the quality of the supply.

The temporary provision of a low voltage power supply. The LV board includes interfaces downstream of its master disconnection switch permitting the connection of a temporary power supply facility such as a generating set. This arrangement enables all the LV feeders going out from the substation to be resupplied when the usual power source, which the transformer constitutes, is not available.
Combined with the use of live working methods, this makes it possible to maintain the electricity supply to customers during scheduled works to replace the transformer or action on the MV power system. The duration of interruptions of the supply is also reduced during works in the substation, following incidents affecting the transformer or the MV power system.
The temporary power supply function integrated into the new LV board, considered essential, makes a great contribution to the quality of the supply of electricity as a product. At the same time it enhances the brand image of the utility, avoiding customer dissatisfaction as far as possible, since today the customer takes an increasingly negative view of power cuts initiated by the utility.
Naturally, although incorporating temporary power supply interfaces in the LV board represents an additional investment cost, it will be noted that the cost has been minimised by opting to link the most highly standardised and simplest connection devices in the LV board with more complex and expensive connection devices for tools on the temporary power supply facility.
The effect of this choice is to transfer the bulk of the cost of the function for each board onto the connection devices of the temporary power supply facility, hence the unit cost, in view of its shared use among several substations, is distributed as a function of the number of boards.

Low voltage live working. Thanks to an appropriate degree of protection against direct contact with live parts and the possibility of gaining access only to one single potential at a time, the design of the LV board is of a type facilitating live working.
As we have seen above, by the way they complement the temporary power supply function, these arrangements make it possible to carry out certain tasks, replacement of the transformer and interventions on the MV system, by live working without disconnecting the customer.
It is also possible to connect and disconnect the conductors linked to the LV outgoing units of the LV board whilst they are live. This permits the addition of extra outgoing units after the commissioning of the substation, if the LV systems are extended.
Similarly, it is possible to envisage changing the board whilst providing a temporary supply to all the LV feeders at one or more points of the LV systems.

3.3 Improvement of the safety of property and persons

The protection of persons. This concerns any person located closed to the substation and the operator when he carries out the various operational procedures.

Protection against direct contacts
The design of the substation and its different components must first prevent the risk of any direct contact with the live parts of the substation. In practice this is achieved by selecting a suitable degree of protection according to IEC 529 for each component :
- the degree IP 2XD specified for the enclosure in a normal operating situation (doors closed) provides protection against access to the dangerous parts with a wire ;
- the degree IP 2X specified for the different devices inside the enclosure and the links between these devices, when the doors of the enclosure are open, provides protection against access to the dangerous parts with the fingers.

Protection against electrical faults
To ensure the safety of persons, the consequences of a possible electrical fault inside one of the substation components must be mastered. Such a fault can in fact arise inside a component, following imperfections, under exceptional service conditions or on an incorrect switching operation. The design of the PSS and its various components make it very improbable that this should occur, but it cannot be totally ignored. Experience shows that such faults inside an enclosure occur more often in some places than in others. These more susceptible places are as follows :
- the separable MV connectors of the transformer and the MV board (PSS of type B) : the fault may be caused by incorrect construction, failure of the solid insulation or an incorrect plugging-in operation ;
- the MV board : the fault can be caused by failure of the solid or gaseous insulation leading to internal overpressure and the escape of gases ;
- the LV board : the fault can be caused by failure of the solid insulation.

The design of the PSS therefore takes into account these different possible faults by indicating, in the specification of each component, the structural provisions and tests which make it possible to guarantee the safety of persons in the event of an internal fault on that component.
For the PSS of type A, an internal fault test on the separable MV connectors of the intrinsically safe transformer is carried out according to IEC 298 with accessibility of class A (protection of the operator), with the doors of the substation enclosure open.
For the PSS of type B, three tests are specified :
- a test identical to that indicated above ;
- an internal fault test on the MV board according to IEC 298 with accessibility of class A (protection of the operator), with the doors of the substation enclosure open; the test is initiated by a failure to break on the MV switch, simulating failure of the latter ;
- an internal fault test on the MV board according to IEC 298 with accessibility of class B (protection of the public), the doors of the substation enclosure being closed and correctly locked; the test is initiated by an internal arc in the board filled with air at atmospheric pressure, simulating leakage of the dielectric gas.

In addition, for the " intrinsically safe " transformer, the integration of the protection and breaking device mentioned above which acts when an internal fault of any electrical origin occurs, prevents any external manifestation : there is no fire, nor projection of materials, nor leakage of dielectric fluid or gas, nor propagation of an electric arc from inside the transformer tank towards the exterior of the substation. In fact any manifestations of an internal fault are confined to the interior of the tank, although the tank may be deformed.
These provisions, which give a guarantee of maximum safety for persons, are verified by a sufficient number of tests reproducing various possible causes of faults : internal overpressure in the tank, short-circuits between LV turns, leakage of oil, LV single-phase overload, three-phase impedant short-circuit on the LV power system, three-phase short-circuit at the inputs of the MV windings.
The LV board also contributes to the reduction of risks of internal faults. Its high dielectric withstand and its degree of protection IP 2X according to IEC 529, applied individually to each part accessible during operation, guarantee correct dimensioning of the solid insulation and make the appearance of any short-circuit most unlikely.

Protection against step voltage
During an operational incident or according to the operational diagram, an increase in potential can be observed around the substation. Of course, the resulting step voltage must not present any danger to the operator or any person close to the substation.
The step voltage is reduced by making an equipotential ring in the ground around the substation enclosure. It is constructed by burying a bare copper conductor with a minimum cross section of 30 mm^2 at a depth of at least 0.40 m located around the substation enclosure at a distance of 0.50 m.

The protection of property. This is achieved by taking into account mechanical and climatic stresses which can apply to the PSS.

Mechanical stresses
In relation to mechanical impacts, the enclosure and its various components withstand 20 J and 2 J respectively ; these values correspond to the degrees of protection IK 10 and IK 07 to EN 50102 respectively, and are generally allocated to equipment for outdoor (20 J) and indoor (2 J) installation. These levels ensure that the equipment has good mechanical withstand both during transport and during its operational service life.
More generally, the enclosure and the associated operational footpath are designed to obtain sufficient mechanical strength in relation to the various loads and stresses encountered : loads on the roof and floor of the enclosure, the weight of the transformer, loads on the trapdoors for access to the tank of the enclosure and on the operational footpath (taking into account the areas which may or may not be accessible to road vehicles) ; wind pressure on the enclosure and internal overpressure in the event of an internal fault.

Climatic stresses
The degree of protection IP 25D according to IEC 529 specified for the enclosure, with the access points closed, provides protection against rainwater : this level guarantees protection against jets of water from a hose from all directions.
In addition, various structural measures are envisaged to ensure the roof of the enclosure remains perfectly watertight over a period of time, to evacuate water at the lowest level of the tank thus avoiding any accumulation of water on the floor inside, and to avoid any infiltration of water through the vertical walls of the enclosure.

3.4 Reduction of the environmental impact

Integration into the environment. One of the main objectives of the study was to create a small and compact substation to be as discreet as possible. For this reason the external volume of the PSS, its shape, dimensions and aesthetic appearance were devised in conjunction with architects, with a view to ensuring that the substation blends well into its environment and does not attract illicit posters.
Furthermore, from the outset, the study took into account the recycling of the materials used at the end of their useful life. We would also indicate that other functional features reduce the impact on the environment, for example the reduction of the transformer noise level.

Recovery of the dielectric liquid. To meet the increasingly strict requirements regarding protection of the environment against liquid dielectrics, the PSS is equipped with an impermeable oil pit, to recover the whole of the dielectric liquid if there is any leakage from the transformer tank. This arrangement is intended to prevent the consequences of leakage occurring during the service life of the equipment (not following an internal fault in the transformer, for which no leakage is allowed, as indicated in section 3.3).

Reduction of the risk of fire. This is the result of the " intrinsically safe " transformer concept, in which the protection and disconnection device fulfils the requirement to avoid any external manifestation in the event of an internal fault.

4. CONCLUSION

This article has presented the new technical level of prefabricated MV/LV substations known as PSS for " Poste au Sol Simplifié " (Simplified Substations at Ground Level), developed by EDF with the cooperation of several manufacturers It is intended to serve underground power systems in rural and suburban areas, which occupy an increasingly important place in the present context of the distribution of electricity in France.
The design of this new substation has taken into account in particular the need for better control of distribution costs, the ever-increasing societal demand for greater respect for

the environment, the customers' demand for a high quality electricity supply and the endeavour for maximum safety for people and property.

This level has now almost been achieved : the product specifications are finalised and the equipment development phases are completed. Interest has been shown in this product during the experimentation now in progress, and we have noted that it is well-received by operators, utilities and the representatives of local authorities.

The PSS, adapted to rural and suburban areas which generally have a low population density and hence a low current density, complements the range of substations used in the urban environment.

Its industrial production is expected to begin in the year 2000.