DISTRIBUTED SUBSTATIONS: AN INNOVATIVE LOW IMPACT SOLUTION

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SUMMARY

While searching for solutions to minimize environmental impact of substations and improve efficiency in services by optimizing costs, AES Eletropaulo promoted an R&D project to implement smaller substations, which are operationally integrated with feeders and amongst each other, in such a way as to optimize power reserve capacity.

ENERQ/USP, ABB and Themag, were invited to take part in this project, thus establishing an attractive partnership in which the Utility describes the problem, criticizes alternatives and evaluates application feasibility; the University researches and shapes solution proposals; the Manufacturer develops proposals and equipment and; finally, the Designer materializes the solution.

This article presents the methodology and the results obtained, and describes solution implementation in a pilot area.

Methodology involves an innovative method in the evaluation of substation alternatives, which contemplates objective issues in direct manner, and intangible issues through structured specialist analysis. Analysis of the grid, which functions as “distributed substation” “interconnection bus”, allowed for optimum location of re-connectors and maneuver switches, maximizing continuity and operational ease.

The pilot project is being implemented in the region of Cotia, São Paulo, where strong environmental restrictions prevent penetration of high voltage lines within load center and 34.5kV power is available at neighboring substations.

OBJECTIVE

The objective of this article is to present the methodology and results obtained, in favor of the implementation of distributed substations in regions with transmission line penetration restrictions, and installation of high transformation capacity conventional substations.

Beyond offering solutions for environmental constraints and occupying less land, Distributed Substations were conceived to offer higher reliability without the need to comply with N-1 criteria, which would result in a high level of transformer idleness because of the substantial capacity reserve required.

PROBLEM DESCRIPTION

The current electrical energy system configuration involves the construction of substations, most of which have a relatively high transformation capacity, enabling load supply even if a transformer burns out. This is the so-called N-1 criteria. This requirement demands that transformers function under high idleness levels, since they must have a capacity reserve to comply with the contingency. A substation with two transformers, for example, should function with 70% nominal capacity, if the 40% overload is tolerated during the contingency of one of the units.

On the other hand, environmental restrictions that prevent high voltage lines from reaching urban centers or environmentally preserved areas, and the increasing scarcity of land available for building conventional substations, has led to a search for other solutions.

Besides, services rendered to residential areas located on the outskirts of big cities, undergoing disorderly and accelerated growth, require simple and low-cost solutions, compatible with the load demanded, which is usually incompatible with conventional substations.

One might add to the already posed difficulties, the high investment required for implementation of a conventional substation.

SOLUTION PROPOSAL

The solution for the described problems is to implement relatively low capacity substations, consisting of one transformer, taking up less land space, and linked by compact lines, which operate in low voltage levels, such as, 34.5kV or 69kV.

Named Distributed Substations, these facilities are linked to the primary grid and operate linked to other substations, in such a way, that the system transforming capacity reserve is distributed between the substations involved.

In this way, the capacity reserve conventionally offered by the N-1 criteria, ceases to be essential for primary system supply reliability, once the group of substations, working together harmoniously, guarantees a high level of service continuity.
Reclosers, sectionalizers or remote and supervision automated systems may be used in grid reconfiguration maneuvers, searching for convenient topographic alterations in order to adapt the grid to contingency situations.

Distributed Substation supply should be done by environmentally sound compact lines, such as 34.5kV grids set on 13.8 kV primary system poles.

Substation arrangement may be in prefabricated modular facilities, such as mobile substations, or even using conventional equipment set in compact form.

The use of reclosers in sidewalk poles, instead of conventional circuit breakers, may be an interesting solution for lack of space.

High voltage lines arriving through gateways, that allow placing circuit breakers towards the back end of the property, and underground exits for feeders, provide solutions for moving transformers, thus eliminating the need for a lateral corridor and reducing the requirements for dimensions of front property line.

**METHODOLOGY**

The methodology used for the development of the study is based on substation development standards, and on analysis and adaptation procedures in the associated primary grid, whose topology and operation are closely integrated with the arrangement and determining operative factors of the substations.

Thus, the methodology comprises the following phases:

**Phase 1: Study of Regional Characteristics and Preliminary Diagnosis**

Initially, a topological study is made of the existing electrical system, and short and medium term load requirements for the region, as well as a study of the electric potential of nearby sources and existing environmental restrictions.

With the knowledge of these elements, the balance between supply and demand of energy in the region is analyzed throughout the study period, quantifying the need and location of demand to be made available.

The location of sources vis a vis existing and projected loads, guides the formulation of alternatives for the placement of Distributed Substations, offering the first elements needed to find the appropriate lot.

Parallel to the distribution network study, the environmental restrictions that prevent the use of a conventional solution to increase energy supply, and which restrict, in any way, the implementation of new lines, are identified. It is important to emphasize that there has been an increasing rejection in neighboring communities, regarding the acceptance of substations, especially medium and large substations, due to sound and visual inconveniences, in addition to assumed harmful effects for the human body of the electric magnetic field.

A map of environmental restrictions is made, identifying environmentally preserved areas, high density urban settlements, difficult to overcome geographic landscape patterns, urban peculiarities, highways, rivers, railways and other influential elements in the layout of new transmission lines needed to service the new substations.

The convergence of technical and environmental determining factors offers a complete picture for the analysis of possible locations for substations and the passage of transmission lines, considering, above all, the implementation of compact lines and small dimension property.

**Phase 2: Basic technical characteristics of Distributed Substations**

The number of Distributed Substations is established according to the required power within the study period and the capacity required by each substation, taking into consideration possible land availability restrictions. On the other hand, the voltage available in the energy power sources of the region indicates the best high voltage level choice. The BT voltage must necessarily be the same as that of the existing grid.

Following are proposals of alternatives for single transformer substation arrangements. Among the alternatives to be analyzed, it is important to emphasize the following possibilities:

- Conventional Substation versus Compact Substation; whereby compact means a substation with three prefabricated and pre-assembled modular structures: entrance, transformation, and exit bays.

- Conventional arrangement versus arrangement with circuit breaker only on the high-voltage side or only on the low-voltage side.

- Bus interconnection by express line between high voltage buses in new substations versus interconnection of medium voltage buses by Express feeder, or even, absence of both express lines, interconnecting only by the feeder network that serves the region.

The selection methodology may be through direct method, which is composed of a detailed technical economic analysis or, by an expeditious method, derived from the Delphi Method, used for non-structured problem solving. In both selection methods, cost and technical performance must be analyzed.

While in the direct method for selecting alternatives, the cost of attributes of a technically acceptable alternative is quantified, in the method based on the Delphi Method principles, the problem description is presented to a panel of specialists, whereby factors that may influence selections, alongside means for quantifying them are exposed.
From such presentation, elements are drawn to build a questionnaire, sent to all specialists of the panel, who express their impressions and opinions by answering the proposed questions.

Compilation of resulting data, according to criteria pre-established by the panel, leads to the alternative of their preference.

Considering that the technical performance is defined according to the attributes listed below, advantages are observed in the application of the method derived from the Delphi Method, as compared to the direct method. This is perceived, on one hand because of the difficulty of assigning costs to factors of an intangible nature, as required by the direct method, and on the other hand, due to the speed in obtaining results by the expeditious Delphi Method. The attributes that determine performance are:

a) Construction  
b) Maintenance  
c) Operation  
d) Reliability  
e) Safety  
f) Expansion flexibility

**Phase 3: Integration of Substations to grid**

Once the arrangement, the basic technical characteristics, and substation location are defined, the operative reinforcements and measures to be performed on the feeder grid for adequate integration must be determined.

A power flow analysis indicates regions in need of reinforcement under normal and contingency conditions.

Next, the alternatives for reinforcement, and grid configuration by the definition of switches that usually operate open, or that usually operate closed, are studied.

The analysis of alternatives is made up of studies and simulations, including:

- Grid behavior analysis regarding loading, voltage, and losses, for different possibilities of areas of influence for both existing, and new substations;
- Definition of possible contingencies, which affect the primary grid and distributed substations, including high voltage lines, transformers, and feeder stretch contingencies;
- Load sensitivity, identifying special loads that require distinguished reliability levels, such as hospitals, police stations, industries with sensitive processes, etc;
- Analysis of operative measures to solve pre-established contingencies, considering manual or automatic grid disconnector maneuvers.

The cost of the reinforcement for each of the proposed grid and switch alternatives is evaluated by analyzing the grid under normal and emergency conditions, both in terms of voltage and load.

Bearing in mind the above mentioned factors, the cost/benefit ratio for each of the alternatives of switch location is calculated by comparing the gain in Non Distributed Energy, on one hand, with the cost of grid reinforcement and reclosers, on the other.

The cost of Non Distributed Energy is calculated as follows:

- Segmentation of feeders in load blocks, meaning a portion between two switches;
- Setting a load sensitivity rate for each block;
- Evaluation of the load and duration of power breakdown in the case of a fault, for each one of the load blocks.

The results of the study will determine the primary grid reinforcement needs, normal condition’s operating topology, and the maneuvers to be executed for each contingency.

**CASE STUDY**

**Region Under Study**

The region under study encompasses a group of mountainous municipalities, approximately 30 kilometers away from the São Paulo Municipality. The load center for the region is the city of Cotia.

According to its geophysical and weather characteristics, this region presents several restrictions to set up transmission lines, due to its difficult landscape as well as the strict environmental laws protecting the Atlantic Forest Reserve.

On the other hand, in the last few years the region has experienced a strong growth in electrical energy demand, caused by an increase in its economic activity, supplying the demand of this prosperous mountainous area.

The electrical power system serving the region includes three substations, in areas surrounding the load center, which feed a nine-feeder, 13.8kV - primary system.

Substation transformation is at 138/13.8kV, 88/13.8kV, and 138/34.5kV, with significant 30MVA slack in 138/34.5kV transformer capacity.

The 13.8kV feeders serving the region operate in radial configuration, with 336 MCM and 4/0 AWG aluminium cables. That primary system operates close to its loading limit, especially in the event of a contingency in certain stretches, characterizing a need for voltage expansion supply.

The main technical and operative characteristics of the substations and feeders that currently serve the region are:

**SE COTIA:** Two 15/20MVA 88/13.8kV transformers, operating at 85 % nominal capacity and nine overhead three-phase feeders in aluminum 336 MCM gauge cables, three of which are designated to serve the load center.

**SE ITAPECERICA:** Two 15/20MVA 34.5/13.8 kV transformers
transformers, operating at 40% nominal capacity and nine overhead three-phase feeders in aluminum 336 MCM gauge cables, being that one of them is designated to serve the load center.

SE ITAPEVI: Two 15/20MVA 34.5/13.8kV transformers, operating at 75% nominal capacity and nine overhead three-phase feeders in aluminum 336 MCM cables, and some of them are designated to serve the load center.

**Diagnostics**

The region identifies and characterizes the need for 13.8kV energy capacity supply expansion, availability of 34.5kV supply in a nearby substation, and still, the presence of a severe environmental restriction for implementation of high voltage lines, serving as the application for a typical solution proposal.

After loading the circuits, a short and medium term load requirement projection was drafted for the region, resulting in a 10 MVA need for the next 4 years and 20 MVA for 8 years ahead.

Thus, two new distributed substations, named – SE Raposo I and SE Raposo II, are to be set up in the region. The choice of land lots for substations involved several factors, some of which are as follows: availability, topography, cost, dimensions, location with respect to load center and ease of feeder entry and exit.

After a study of the region, two properties were chosen.

**Proposal And Selection of Alternatives**

The arrangement of substations was decided based on the Delphi Method. Alternatives for supplying the region were proposed considering arrangement and interconnection of the new Raposo I and Raposo II substations. The selection of these substations was made based on the opinion of a panel of specialists, considering the following basic technical characteristics:

- Restricted dimensions enabling implementation in a plot of small dimensions, in comparison to one that would accommodate a conventional substation;
- 34.5/13.8kV nominal voltage;
- One 15/20MVA transformer;
- Arrangement for exit of two feeders in the initial configuration, and the possibility of future expansion for a third feeder;
- Feeding through 34.5kV compact line, set, if convenient, on the same existing primary grid structure;
- Integration of new substations on the primary grid, in such a way that, contingency of feeders and of the substation itself is supplied by automatic load transfer system.

Results were obtained through three questionnaires that deal with substation arrangement, pre-fabricated modular structures, and the manner of interconnection of distributed substations.

Each alternative was evaluated according to cost and performance, by contemplating the weight of several necessary factors, according to the panel specialists. According to the results of the panel’s evaluation, the following conclusions were attained:

a) Use of conventionally set equipment was preferred over pre-fabricated modular structures, on account of price;
b) Interconnection of substations via feeders that supply the region was preferred, instead of 34.5kV express lines or even 13.8kV express feeders;
c) Substation BT circuit breaker was spared by using only a recloser at each feeder, justified by project price, space occupied, and simplification of substation arrangement;
d) One of the distributed substations has a reconstructor on site, and the other one, has one installed on a sidewalk pole.

Considering the questionnaire results, AES Eletropaulo invited ABB to join the effort, and proposed, alongside THEMAG, arrangements that comply with technical requirements, evaluating the application of several resources for simplification, compression, and savings, which are commonly not considered in conventional substations. Among them are:

- Control center;
- Protection and control systems sheltered in closets exposed to weather;
- Reduced battery system;
- Reduced distances by using fire guard walls;
- Reconstructor remote automation.

The selected arrangement can be seen in the attached figure, which on site, occupies over 100m².

Integration of substations within the local grid was executed through reinforcement of some feeder stretches, and implementation of automatic reclosers in strategic points, so as to sustain contingencies of transformers and high voltage lines associated to the new distributed substations.

**Number and Location of Reclosers**

The number and location of the reclosers were determined based on the analysis of the cost/benefit ratio, resulting from setting up each reconstructor.

Since the emphasis is on improving the continued service of some of the blocks supplying the main loads, the following procedure was implemented:

- Suggestion of several alternatives to locate the reconstructor, based on the installation of the equipment on the feeder, at the beginning of each block.
- Analysis of the benefits for each of the suggested alternatives, considering the cost of installing the reconstructor and the savings in non-distributed energy, as a result of a fault in each of the blocks.
- Choice of the best alternative for the location of a reconnector;
- Repeat the process for ‘n’ reclosers;
- Calculate the annual incremental benefit, in terms of non-distributed energy savings, as a result of installing 1, 2...n reclosers at the optimal location
- Calculate the ROI period for each increase in the number of reclosers.

The following graph in Figure 1 show the results obtained for the different fault rates, since the choice of an alternative should take into consideration future fault rates, thus representing a sound benefit ratio.

The example shows the choice of an alternative with 2 NC reclosers, as in Table 1.

![Figure 1 – Annual non-accumulated gain (incremental) for the alternatives](image)

Table 1 – Period of Incremental ROI for the alternatives

<table>
<thead>
<tr>
<th>Fault Rate</th>
<th>Number of Reclosers</th>
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<tbody>
<tr>
<td>1.0</td>
<td>0→1, 1→2</td>
</tr>
<tr>
<td>1.4</td>
<td>1→2, 2→3</td>
</tr>
<tr>
<td>1.8</td>
<td>2→3, 3→4</td>
</tr>
<tr>
<td>2.2</td>
<td>3→4</td>
</tr>
<tr>
<td>2.6</td>
<td>0.8, 1.0</td>
</tr>
<tr>
<td>3.0</td>
<td>1.2, 1.4</td>
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<tr>
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<td>2.0, 3.4, 4.1</td>
</tr>
<tr>
<td>3.8</td>
<td>0.6, 2.5, 7.1</td>
</tr>
</tbody>
</table>

CONCLUSION

The methodology and results presented for the implementation of distributed substations are adequate as the solution for increasing energy supply in regions with transmission network penetration restrictions, and for the installation of conventional substations with high transformer capacity, which need relatively large lots.

Besides offering solutions for environmental determining factors and occupying land of small dimensions, Distributed Substations demonstrate high reliability levels, substituting with economical advantages, the N-1 criteria, which results in high level of transformer idleness due to the large reserve of required capacity.

The application of the methodology in the region of Cotia, which comprises several environmental restrictions proves its efficiency. This solution was conceived with 34.5kV lines, supplying two compact 15/20MVA 34.5/13.8kV substations, integrated by the primary distribution network, which through convenient automated maneuvers, allows the achievement of reliability levels similar to the conventional N-1 criteria.

The compact distributed substations solution may be applied to higher voltage feeders - 69 and 138kV, and allow for implementation within service land strips under transmission lines.

REFERENCES

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[13] Instrução Técnica 37/01 do Corpo de Bombeiros – Medidas de segurança contra incêndio em Subestações Elétricas, atendendo ao prescrito no Decreto Estadual 46076/01.