AN ANAYTICAL DECISION MODEL TO HIGH VOLTAGE NETWORK PLANNING

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ABSTRACT

The replacement of the aged high voltage network equipment, largely contemporaneous in big cities, is a challenging technical intervention. Nevertheless, it represents a window of opportunity to redefine the high voltage network configuration according to the expected growth of energy loads, operational and maintenance costs, and efficiency and quality of service parameters. The network reconfiguration demands a thorough techno-economic analysis, as it is associated with significant technical complexity and high investment costs. The aim of this paper is to present a methodology developed to address this important network planning issue.The key focus of this approach is to find alternatives for the current configuration, to analyse them both technical and economically, to compare the alternatives and choose the best solution according to the investment strategy of the Distribution System Operator (DSO).
The proposed methodology is validated using the high voltage network of a big city in Portugal.

INTRODUCTION

The boost of Portuguese industry economic activity during the 50's and 60's had pushed for the electrification process. It led to the construction of a significant number of electrical installations during a short period of time. Consequently, a lot of assets of the current distribution grid have the same age. [1] In fact, the Portuguese substations are on average 18,5 years old, and if we look at big cities, this can be higher than 30 years old. [2]
This scenario presents two major challenges. First, the present configuration might have a suboptimal efficiency, as it was the result of the need to increase capacity under time and logistic constraints. [3] Second, the aged high voltage network equipment is largely contemporaneous in big cities, thus its replacement represents a challenging technical intervention.
Our aim was to develop a methodology to objectively characterize several alternatives to the present electrical grid configuration when replacing the aged high voltage equipment.

METHODS

The flowchart of the analytical decision model is outlined in Figure 1.

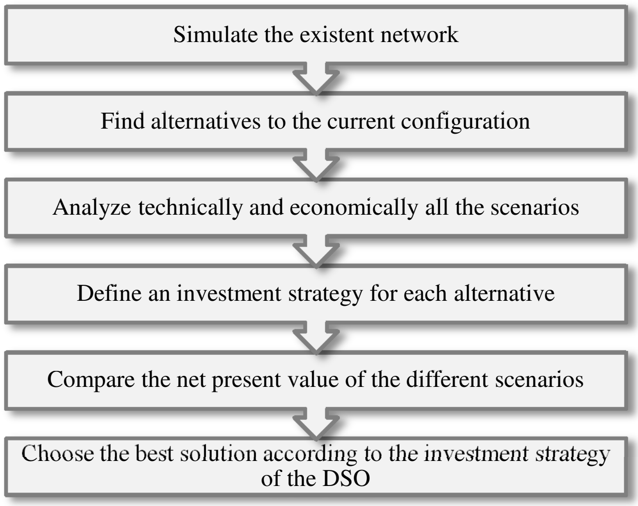

Figure. 1. Flowchart of the analytical decision model. DSO means Distribution System Operator.

MODEL DEVELOPMENT

Step 1: Simulate the existent network

The first step is to simulate the existent network to verify its capacity to feed all the loads in normal and "N-1" operation modes in the time horizon defined for the study. These simulations are done with the aid of a specific software, where the grid is sketched, and using historical records of the loads and the predicted growth for the studied period.

Step 2: Find alternatives to the current configuration

Subsequently, alternatives to the current configuration based on different concepts for high voltage networks are outlined. If contingencies were found on the previous step, these alternatives must eliminate them. Both meshed network and the configuration in which the high voltage busbars are eliminated on the substations (by connecting the cables directly to the power transformers) should be explored.

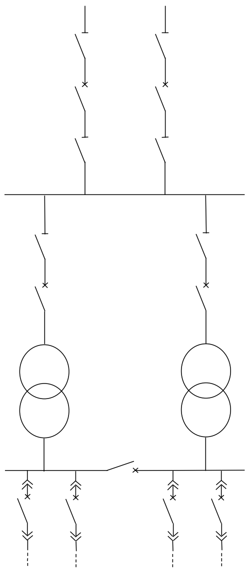

Figure 2. Single line diagram of a HV/MV substation on a meshed network.

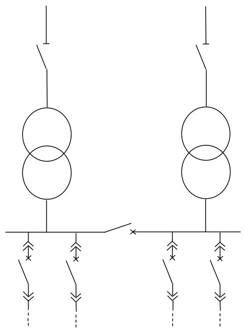

Figure 3. Single line diagram of a HV/MV substation without high voltage busbar.

Step 3: Analyze technically and economically all the scenarios

After delineating the alternatives to the current configuration have been found, technical and economic implications of each option need to be considered. On the technical side, it is important to assess how "N-1" mode is operationalized and what it is the impact on the quality of service and electrical losses. The economic implications associated with the technical characteristics presented before need to be carefully considered. To accomplish that, we estimate the energy not supplied and the losses on the high voltage and medium voltage networks and monetize these quantities.

The investment is then calculated. The asset management strategy of the DSO has to be considered to estimate when each asset of the high voltage network will have to be replaced. The maintenance costs of each alternative also have to be evaluated.

Step 4: Define an investment strategy for each alternative

The next step is to define an investment strategy for each alternative. At this stage, we have to foresee the actions that have to take place in each year to implement each option, considering (a) the age of the equipment, (b) its lifetime, and (c) possible technical constraints for all the loads always have to be feed.

Step 5: Compare the net present value of the different scenarios

A sensitivity analysis is performed, considering two variables: the lifetime of the cables and the lifetime of the high voltage switchgear. This assessment helps us to define the best time to perform each action, on economic terms. The relevance of the equipment's lifetime on the choice between alternatives should also be examined. If the investment ranking of the alternatives remains unchanged when the lifetime is altered the equipment's lifetime is less important and it is not a variable that has to be carefully analyzed and predicted. In contrast, if the ordering of the alternatives based on the investment is altered when the lifetime of the equipment changes, then this variable has to be thoroughly studied to determine the optimal lifetime to be used for each type of equipment.

Step 6: Choose the best solution according to the investment strategy of the DSO

The solution will be chosen considering both economic and technical aspects. On the economical side, the net present value and the initial investment costs of the alternatives will be taken into account. Regarding the technical aspects, the change in operation and maintenance when comparing the alternatives to the present configuration will also be pondered. The selection of the alternative will depend on the weight that the DSO assigns to each of these aspects. During the study time horizon, all interventions on the high voltage network should follow the selected network configuration.

MODEL VALIDATION

We used the high voltage network of a big city in Portugal to validate our methodology.

Step 1: Simulate the existent network

The studied high voltage network used to validate the methodology has eight substations connected to the high voltage transmission network on three different locations: one VHV/HV substation and two switching stations. These locations will be referred herein as **injection points**.

It is an aged network: one third of the 60kV cables were installed before 1980 and are still oil insulated; half of the substations were installed in the 60's and 70's and the youngest ones were built in 1998; only two of the power transformers were already replaced, which means that most of them are contemporaneous to the substation. Therefore, a plan was needed to define the asset management strategy that would assure the renewal of the equipment while maintaining the high quality of service that has been observed in the past years. [4]
For the simulation, the peak power verified in 2012 for each substation was used, as well as the predicted growth of the loads for the time horizon of the analysis, that was assumed to be 10 years and starting in 2016.
Using a simulation software (Dplan®,IOA, Portugal), we verified that all assets have a rated current compliant with the technical specification of the Portuguese DSO for the expected power flow.
Due to the modest predicted growth rates, we don't expect constraints in the capacity of the substations in normal operation: by the end of the analyzed period, the highest percentage in capacity usage is 76% on one substation and the average capacity usage rate is 65%. In addition, the network had "N-1" security for transformers, high voltage network and low voltage network. This means that the service continuity was guaranteed for all the loads if a transformer, a high voltage or medium voltage cable or a switching equipment would be unavailable. Thus, it can be concluded that there is no need to increase the transforming power capacity of the city until 2026, if the real load growth remains close to the forecast.
Although not mandatory for the Portuguese DSO, the unavailability of an injection point was also analyzed. The conclusion was that the feeding of the loads was secured by the high voltage and medium voltage networks for two injection points, and only in one case 6% of the loads were not fed.

Step 2: Find alternatives to the current configuration

Two alternatives were sketched: one that maintains the concept of a meshed network and another that eliminates the high voltage busbars on all substations.
The first alternative consists on the renewal of the high voltage cables and switchgear when they reach their end of life. It also includes the construction of three new connections between substations to ensure that, in a contingency of one injection point, the high voltage network guarantees the feeding of the loads. This would eliminate the problem presented by the loss of one of the injection points.
The second alternative consists in eliminating the busbars of all the substations and the cables that are connected directly to the power transformers, in what we call a "cable-power transformer block". Therefore, each transformer is connected to a single injection point. In each substation, different transformers are connected to different injection points, to gage that in the failure of one injection point, only one transformer of each substation will be out of service. The remainder loads have to be fed by the medium voltage network. The high voltage cables are replaced when they reach their end of life and 4 new connections between sites are established. This configuration also eliminates the problem present before, in the contingency of one of the injection points.

Step 3: Analyze technically and economically all the scenarios

From the technical viewpoint, the main difference between the two alternatives is in the "N-1" operation mode:
a) In the event of the **failure of one power transformer or of one substation**, both alternatives will have the same behaviour: the feeding of the loads will be assured by the medium voltage network.
b) In Alternative 1, the high voltage network guarantees the feeding of the loads if **one high voltage cable becomes unavailable**. Therefore, there will be continuity in service. On the second alternative ("cable-power transformer block"), the failure of a cable will have the same effect as the failure of a transformer. This will have an impact on the Momentary Average Frequency Index (MAIFI). However, this is a very rare and unlikely event. In fact, there are no records of such an event in the last 5 years in the analysed network.
c) In the case of the **unavailability of one of the three injection points**, the feeding of the loads in Alternative 1 is guaranteed by performing a maximum of 6 manoeuvres in the high voltage network. In the same situation, the feeding of the loads on Alternative 2 will be assured by manoeuvres on the medium voltage network. The number of manoeuvres varies between 25 and 40, depending on which injection point fails. The predicted time to perform them is 30 minutes, meaning that the last loads to be fed will have an interruption time of 30 minutes. Nevertheless, the unavailability of an injection point is a rare event that has only happened once in the last 5 years in this network.
Table I summarizes the situations presented above:

TABLE I
"N-1" OPERATION MODES ANALYZED FOR EACH ALTERNATIVE

Contingency in	N-1 operation assured by the	
	Alternative 1	**Alternative 2**
Transformer	Medium voltage network	Medium voltage network
Cable	High voltage network	Medium voltage network
Injection point	High voltage network	Medium voltage network

Another technical difference between alternatives is that the quality of service in Alternative 1 depends more on the reliability of the substation **remote control**, while in Alternative 2 it depends more on the reliability of the remote control of the secondary substations. Therefore, a comparative analysis was executed on the performance of both remote controls, where we concluded that as the indicators are similar for both remote controls, it shouldn't be taken into consideration when comparing the two alternatives.

TABLE II

ANALYSIS TO THE PERFORMANCE OF THE REMOTE CONTROLS

	Remote control of the secondary substations	Remote control of the substations
Avalability	98,5%	99,8%
Efficacy	93,7%	94,7%

Avalability - % of time that the remote control is avalable to comunicate with the comand center
Efficacy - rate of the comands sent that were effective

From the economic standpoint, we monetized three parameters:

a) The **high voltage losses** are different in both alternatives. In Alternative 1, the high voltage losses are reduced when compared to present configuration, because the distance between the injection points and the substations is shortened. The reduction is estimated to be -3,0% of the present value of the investment. Contrarily, the distance is increased in Alternative 2 and so the predicted increase in high voltage losses is +0,9 % of the current value of the investment.

b) The costs associated with **maintenance** are also different. Compared to the present configuration, the costs in Alternative 1 remain unchanged, while in Alternative 2 they are reduced proportionally to the number of switching equipment eliminated. The decrease in maintenance in Alternative 2 is predicted to be –0,2% of the present value of the investment.

c) The **investment** of each alternative comprises the new cables and switchgear needed to implement each alternative. The costs associated with the renewal of the high voltage equipment were also considered. The investment of Alternative 1 includes these costs, whereas the investment of Alternative 2 only accounts for the replacement of the cables and the switchgear of the injection points, because the substations don't have high voltage switching equipment.

Step 4: Define an investment strategy for each alternative

The investment values associated with both alternatives are obviously high because we are dealing with an aged network, where a high number of assets are needed to be replaced in the following years. In addition, the high voltage equipment is expensive. Moreover, works on the high voltage network have to be carefully planned and performed in a phased manner, because the feeding of the loads has to be accomplished at all times. Therefore, we defined that only one substation would be intervened per year, and that the order of the interventions would follow the age of the installations. We admitted that cables and air insulated switches are replaced when they reach 45 years. The gas-insulated switches were considered to need rehabilitation every 15 years and to last for 50 years.

Step 5: Compare the net present value of the different scenarios

The following table presents the economic comparison of the alternatives that reflects the three parameters explained above:

TABLE III

ECONOMIC COMPARISON OF THE ALTERNATIVES

	Δ Alternative 2/ Alternative 1
Total Investment	-52,2%
Present Value of the Investment	-42,5%
Net Present Value	-39,6%

Net Present Value = investment - Δ high voltage losses - Δ maintenance costs

It can be seen that the different between alternatives is smaller when looking at the Net Present Value of the alternatives, compared to the Total Investment. In fact, all the investment of Alternative 2 is made in the first five years, whereas in Alternative 1 only 78,1 % of the investment is made on this period (the remaining 21,9 % are related with renewal of the aged high voltage switchgear as it reaches its end of life), thus the discount rate of the investment of the Alternative 1 will be higher.

The difference among alternatives is further reduced when considering the costs associated with the high voltage losses and maintenance, because in Alternative 1 there is a significant reduction on the high voltage losses, for the reasons presented before.

The presented values were obtained assuming that the lifetime of the cables and air insulated switchgear is 45 years. Two sensitivity analyses were performed: one varying the lifetime of the high voltage switchgear and another one varying the lifetime of the oil insulated cables, both in a range that goes from 45 to 60 years. The results can be seen on the tables below. As expected, the net present value of the Alternative 1 is reduced when the lifetime of both the switchgear and the oil insulated cables is increased, because the investment is delayed. The same happens in Alternative 2 when the lifetime of the oil insulated cables is varied. But when the lifetime of the switchgear is varied, the net present value of this alternative doesn't change because there is no high voltage switchgear in this scenario.

TABLE IV

SENSITIVITY ANALYZES TO THE LIFETIME OF THE HIGH VOLTAGE SWITCHGEAR AND TO THE LIFETIME OF THE OIL INSULATED CABLES

	Δ Net Present Value when lifetime of the switchgear increases from 45 to 60 years	**Δ Net Present Value when lifetime of the oil insulated cables increases from 45 to 60 years**
Alternative 1	-17,4%	-38,4%
Alternative 2	0,0%	-27,3%

On Table V, it can be observed that Alternative 2 has the lowest investment in all scenarios. We concluded that the comparison of the alternatives doesn't depend on the lifetime of the high voltage equipment, and so this is not a variable that has to be taken into account when choosing the alternative to implement.

TABLE V

ECONOMIC COMPARISON OF THE ALTERNATIVES WHEN THE LIFETIME OF THE SWITCHGEAR AND OIL INSULATED CABLES IS 45 YEARS AND 60 YEARS

	Δ Net Present Value Alternative 2/ Alternative 1	
	If lifetime = 45 years	**If lifetime = 60 years**
Switchgear	-42,5%	-27,8%
Oil isulated Cables	-42,5%	-29,6%

Step 6: Choose the best solution according to the investment strategy of the DSO

In conclusion, both alternatives satisfy the primary goal that was to define a strategy to replace the aged high voltage network equipment. Now that all the variables associated with the developed alternatives are presented, the decision-owner will have to decide which alternative to implement: the one that is more conservative but more expensive (Alternative 1), or the one that has the lowest net present value but that represents a change in the way the network is operated (Alternative 2).

CONCLUSIONS

This paper presents a methodology to find and characterize strategies to replace aged high voltage network equipment in big cities and to redefine the network configuration.

The proposed methodology incorporates both technical and economical features and provides an objective comparison of multiple alternatives. This approach will help to better inform and improve network-planning decisions.

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