DISTRIBUTION NETWORK INVESTMENTS TO IMPROVE POWER QUALITY

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ABSTRACT

Distribution system operators are committed to guarantee customers adequate levels of security, reliability and power quality facing financial pressures and noticeable decrease in available capital budgets. In such conditions the distribution planning process becomes business-driven (rather than only engineering driven) with the aim of reducing capital costs of future enhancements and changes in distribution networks. Regulators have to define fair and transparent standards that aims at improving the level of quality provided to customers by selecting the most cost effective actions. In this sense, there is a strict demand for efficient planning tools that enable maximal utilization of existing assets, minimize investments and allow reaching a reasonable level of power quality. In the paper, an efficient tool for optimal network planning is proposed that is able to find the most convenient actions to reduce the number of voltage dips suffered by customers. Capital and operational expenditures are considered as well as technical and economical constraints so that the optimal network plan in given study period represents the optimal compromise between the quality and reliability requirements and budget restrictions. The examples show that it is possible to achieve an adequate average level of power quality by simple network actions and give quantitative information about the investments related to different levels of power quality.

INTRODUCTION

Short interruptions and voltage dips (VD) are disturbances that undermine the quality of supply or, more precisely, the Power Quality (PQ) as perceived by the customers, often causing heavy economic damages to the end-users. The "power quality problem" involves equipment manufacturers, customers, and distributors. It requires adequate standards, and regulatory actions to define penalty liability, contractual clauses, and costs.

In particular, once an average acceptable and fair level of power quality has been established for general customers, the duty of Distribution System Operators (DSOs) is to take all those actions to achieve such level. Definitely, budget restrictions and economic management claim the maximum profitability of investments and planners need specific tools to assess the optimal combination of ameliorative actions. On the other hand, such kind of tools are also useful to Regulators to identify the amount of network investments that correspond to a specific level of PQ in order to find a fair compromise between the opposite needs of customers and DSOs.

In the paper, an optimization algorithm is proposed that is able to find the most convenient set of actions to make it possible that PQ constraints are complied with [1], [2]. The algorithm has been implemented in a tool for the optimal network planning so that the evolution of the network in the medium/long term could be guided not only by costs but also by quality [3]-[5].

Preliminarily the algorithm evaluates the expected VD frequency in each node of the network by means of a stochastic method. Once the level of power quality in a given network has been estimated, whether at least only one node exceeds the prefixed maximum VD number, several specific ameliorative actions are compared. A heuristic optimization algorithm finds the optimal set of corrective countermeasures (e.g. the substitution of overhead lines with cables, the installation of power electronic devices, etc.) by iteratively repeating the procedure until all the customers are expected to suffer for a number of VDs lower than the maximum allowable.

The main feature of the proposed methodology is that the results are not significantly influenced by the cost of VDs that very difficult to be known with an acceptable level of confidence [6]. Indeed, an accurate estimation of the economic damages suffered by the customers as a consequence of network faults involves the exactly knowledge of the network customers characteristics and their sensitivity to the VD. Evidently, at the planning stage most of the input data available to the planner are predicted on the basis of statistical and historical data and, consequently, the cost of VDs is intrinsically uncertain. Furthermore, it should be considered that for economic reasons not all the data necessary to an accurate load modelling are measured so that the assessment of the VD cost is uncertain even in existing and operating networks.

VOLTAGE DIPS

A voltage dip is a sudden reduction of supply voltage lasting from half cycle to several seconds followed by a voltage recovery. VDs are characterized by their magnitude, duration and frequency, which are strictly related to the reliability, the topology and the protection system of the network. Meshed topologies increase the area influenced by faults, overhead lines are less reliable than cables, but faults occurred in cables cause deeper dips, etc.. Moreover, the impact of VDs on the power quality perceived by customers is directly dependent on the sensitivity of loads. Generally speaking, shallow and short dips do not affect less sensitive

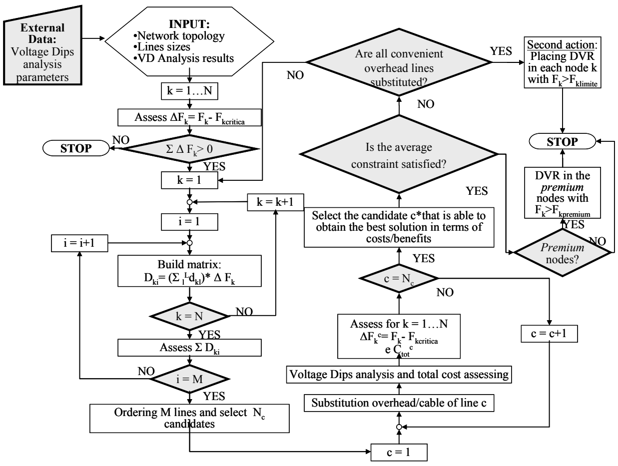

Fig. 1. Flow chart of the algorithm for the Power Quality optimization

load, whereas the deepest dips cause tripping or malfunctions to the majority of the loads (e.g. industrial processes with digital controls). However, since the VD frequency depends on the critical voltage threshold chosen for the calculation, and the maximum critical VD frequency is the parameter to reduce, it is important to select this threshold on the basis of the sensitivity of the customers. Indeed, the greater the remaining voltage selected is, the greater the estimated VD frequency. Different processes or customers, different categories of customers of a complete distribution company have their own withstand to VDs. The impact of VD on loads can be determined on the basis of the withstand declared by the equipment manufactures, by collecting data from measure surveys, or through specific research tests carried out in one's own case to determine the critical voltage magnitude. All these methods are complicated and expensive.

Obviously, also the cost of a single VD strongly depends on the effect that it produces to the customers. Only considering the effects of VDs on the load process, the severity of the economic impact on the customer can be evaluated.

What clearly emerges by these brief considerations is that, before any calculation of the investment necessary to obtain a determined level of quality in distribution systems, it seems indispensable that DSOs have preventively to choice the critical voltage magnitude and to assess the economic value of a single process interruption due to VD. Evidently, without precise information about all their customers this task becomes very difficult and has a tremendous impact on final evaluations.

In this paper a methodology that overcomes these obstacles is presented. The methodology is able to determine, for a specific network, the entity of investments to improve the PQ without any indication of the sensitivity of the customers and the costs that they have to sustain each time a VD occurs.

PQ ORIENTED DISTRIBUTION PLANNING

The main goal of distribution planner is to minimizing the sum of capital expenditures (CAPEX) and operational expenditures (OPEX) in a given study period. CAPEX are necessary to face the natural rise of energy demand, the appearance of new customers and the connection of distributed generation. OPEX comprise the cost of energy losses and maintenance. OPEX are related to efficiency so that the smaller they are the higher is the efficiency of the power delivery. In order to perform an optimal distribution planning input data are essential. In brown field planning some data are known in advance since they derive from the existing network (e.g. the position and capacity of primary substations, the routes and the capacity of feeders, the position and the energy demand of loads, the environmental restrictions, etc.). Some other input data are predicted from statistical and historical analysis and the quality of the prediction has a strong impact in the quality of the solution (e.g. the rise of energy demand, the cost of energy, the penetration of DG, the development of urban or industrial neighbours, etc.). The optimal planning is not only business-driven but it has also to comply with many technical constraints (e.g. voltage profile, thermal feeder capacity, SAIDI, SAIFI, etc.). PQ is now a serious concern for both Regulators and DSOs and for this reason is starting to be considered a technical constraint for optimal development plans. With reference to VDs, the constraint can be expressed as the maximum allowable annual frequency of VD lower than a prefixed threshold. Thus, an optimal planning solution is the one that satisfies all the engineering constraints by minimizing the amount of investments so that budget limitations are not violated.

Celli et al. in [2] have proposed a heuristic algorithm that is able to find the most cost effective actions to reduce the frequency of VDs in distribution networks. Such actions strive to increase the reliability of the network by substituting, if possible and convenient, overhead lines with isolated cables or by modifying the network topologies so that faults cannot propagate in wide areas. The allocation of DG plants in particular nodes to sustain the voltage during faults is another action available to conditioning the voltage during faults (if the DG interface protections do not automatically disconnect generators during faults [7]). Finally, the algorithm evaluates specific VD mitigation actions to achieve the quality level imposed by the planner by installing custom power devices (e.g. dynamic voltage restorer) in some preferential nodes.

Optimization algorithm

Preliminarily, by means of a stochastic method, the procedure evaluates the expected VD frequency in each node of the network. In particular, in the paper the fault position method, that combines the deterministic short circuit theory with the stochastic information given by the fault rate, has been adopted [8]. Only faults in distribution lines have been considered as cause of voltage dips. The

Table I
Typical Italian Fault Rates for 100 km of MV Line

	Permanent 3-phases faults/year	Permanent 2-phases faults/year	Transient 3-phases faults/year	Transient 2-phases faults/year	Transient 1-phase faults/year
Overhead	6	3.6	8	24	45
Cable	1.5	0.9	----	----	----

assumption is justified by the inherent strength of transmission and sub-transmission systems and their rather low fault rate. Thus, the expected frequency of VDs is evaluated on the basis of the line fault rate recorded by Italian distribution companies and reported in Tab. I. It is worth to noticing that the short interruptions caused by line breakers openings followed by high-speed reclosures that clear transient faults are considered PQ disturbances and summed to the true VD (i.e. remaining voltage greater than 10% of nominal one).

Once the level of power quality in a given network has been estimated, whether at least only one node exceeds the prefixed maximum VD number, the optimization algorithm starts.

The individuation of the most effective actions, the comparison of the different planning alternatives and the application of the one that gives the planner the best compromise between costs and benefits are performed by a heuristic optimization algorithm developed by the authors [2]. The flow chart of the algorithm is shown in fig. 1. The first step is the identification of those nodes that suffer for a VD frequency beyond the maximum allowable level. Secondly, the overhead lines candidates to be substituted with cables are ordered in a merit list, on the basis of a specific index (further details in [2]). Finally, the cost/benefit ratio of each candidate is assessed so that the most convenient can be chosen. Thus, the algorithm finds the optimal set of corrective countermeasures by iteratively repeating the procedure until the constraint on the maximum allowable number of VDs deeper than a prefixed threshold is complied with. Whether with such simple network actions, the achieved average level of PQ is not acceptable or high sensitive customers exist, voltage conditioners can be placed in suitable nodes of the networks.

CASE STUDY

The proposed algorithm has been applied to a small portion of an Italian distribution network in order to show the impact of PQ in distribution planning. The network is supplied by 3 primary substations, which feed 113 MV/LV nodes, 37 trunk nodes and 76 lateral ones, as depicted in Fig. 2. The planning period is 20 years long (a so long planning has been chosen only to highlight the effect of PQ in a small application). The active power delivered to MV nodes at the beginning of the study period is 9.2 MW; the load demand rises with a 3% per year constant rate. During the study period, new lines have to be built to supply nodes not connected yet or to face the increased load demand with more delivery capacity. The nodes are mostly rural or

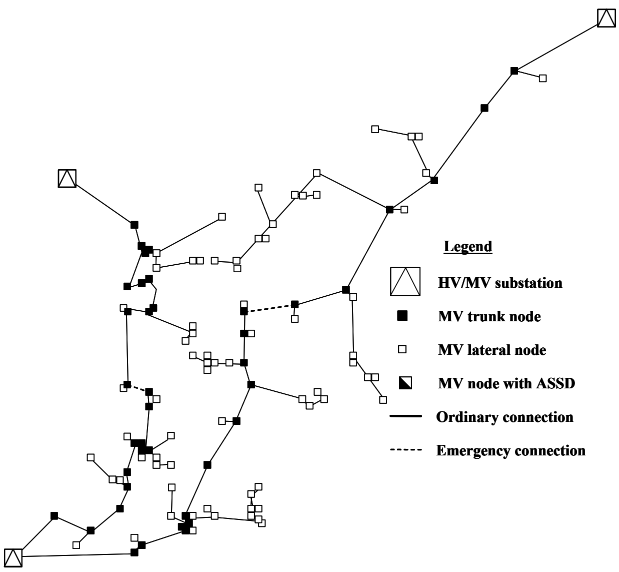

Fig. 2. MV test network

suburban and thus the network has a majority of overhead lines although some buried cables are used to feed some particular nodes. VD in the network can be caused by three and two phase permanent faults (before the fault is cleared all the customers connected at the same busbar experience a a voltage drop caused by the short circuit current; customers upstream the faulted branch are the most affected). All the transient faults (single, two and three phases) determine momentary interruptions to some nodes that are summed to true VDs (the number of affected customers is related to protection and automation system). Tab. I reports the fault rates used in the calculations. In order to consider that faults are widespread along the lines each branch is subdivided into not more than four parts 0.6 km length (i.e. three internal fault points for each branch).

Results and discussion

The test network optimized by the tool for the optimal network planning [3]-[5] without any PQ constraint requires CAPEX equal to 6019.16 k€ to build new lines and to revamp the existing ones so that the energy demand rising can be faced. OPEX are equal to 1852.12k€ (Tab. II) and are essentially due to energy losses in the lines. With

Table II
Optimal Network Arrangements without PQ Constraint

Building cost	6109.16 k€
Cost of energy losses	1852.12 k€
CAPEX and OPEX	**7961.28 k€**
Cost of EENS	379.67 k€
Cost of voltage dips*	209.97 k€
Total cost	**8550.92 k€**
SAIDI	48 min
SAIFI	1.79
Av. VD frequency**	7.59
Max VD frequency**	12.88

*cost of single voltage dip equal to 1000€
**critical voltage threshold equal: 50%of nominal voltage

reference to VD limitation this optimal network can be called the "*do nothing network*" and assumed as reference for further considerations.
Bearing in mind that finding routes for new lines is often a limitation more cogent than budget restrictions the study is performed on the fixed topology depicted in Fig. 2. The optimal network with PQ constraints has been found by varying the critical threshold of voltage (25%, 50%, and 75% of the nominal voltage) and modifying the single VD cost (100€, 1000€, and 5000€). The wide variation of both the threshold and the unitary cost allows overcoming the uncertainties in the knowledge of such parameters and highlighting their impact in planning. The results are depicted in Fig. 3. The graphics show the increase of CAPEX in comparison to the "do nothing" case to achieve a prefixed quality level (the maximum VD frequency on the *x* axis). Each diagram, corresponding to a different choice of the critical voltage, reports three curves, parameterized with the cost of single VD. It is interesting to observe that the curves in each graphic are quite close one to each other. This fact confirms that in the proposed methodology the unitary value of a VD is not a significant parameter. Thus, independently of the VD cost, the curves can be read establishing the PQ constraint that it should be complied with and evaluating the necessary investment, or, alternatively, by setting the maximum budget and reading the maximum frequency achievable for the given network. Furthermore, the graphics show that even the critical voltage does not particularly affect the results. This can be assumed as a general remark. Overhead lines are the main cause of faults and consequently they determine the level of PQ in a given network. The majority of the faults normally cause low short circuit current and the intervention of the line breaker in the faulted line (e.g. single phase to earth fault). Thus, the nodes in the faulted feeder can suffer momentary interruptions whether the fault can be cleared with a fast reclosure, the other nodes perceive a very small voltage drop that in many cases cannot be considered as a voltage dip. Only during three and two faults customers in different feeders can experience a voltage dip but these faults are less probable. As a consequence, the most common disturbance is the momentary interruption that does not depend on the threshold that establishes when there is aVD. It is important to observe that in networks prevalently constituted by cables, permanent faults are more common than transient ones. Thus, the critical voltage can considerably influence the calculation and the results but, on the other side, in cable networks VD are less frequent thanks to the intrinsic higher reliability.
Finally, Fig. 4 shows the marginal costs calculated assuming that a predetermined level of PQ could be more easily reached with a step-by-step process instead of with a single shot from the "*do nothing*" network. As it can be seen marginal costs are very high at high level of PQ. The general remark is that it is not fully justified to achieve with network actions high levels of PQ that probably are too much for a many customers. Top customers can be supplied

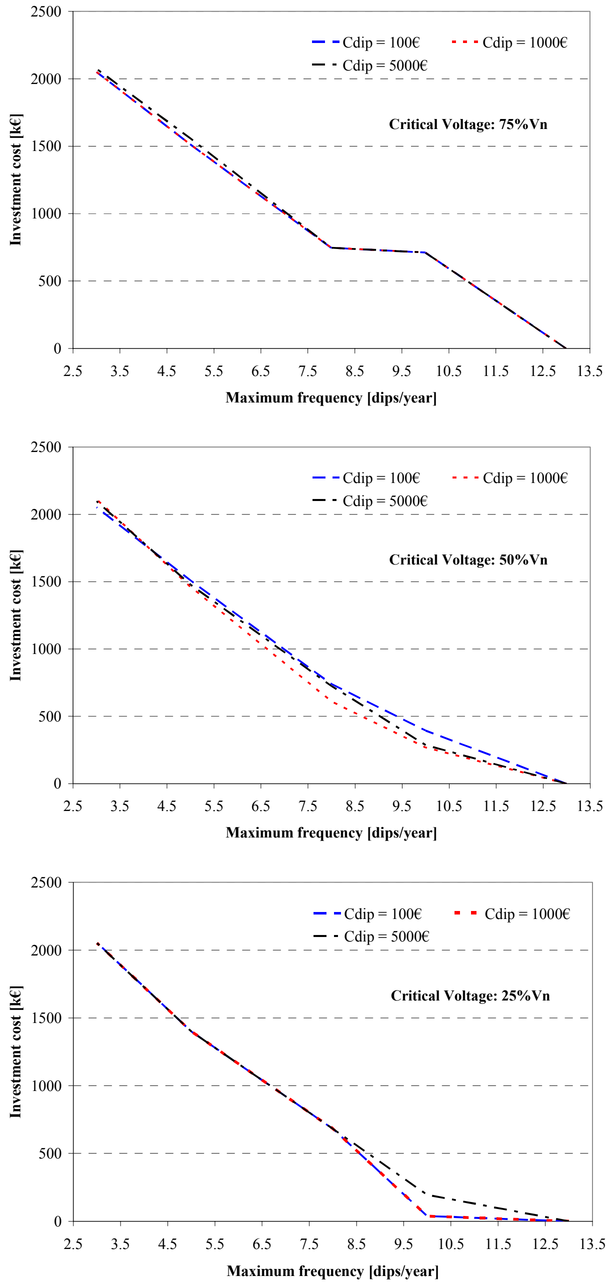

Fig. 3. Building cost varying the maximum VD frequency

with high PQ more easily and cheaply by using power electronics and custom power solutions.

CONCLUSIONS

Distribution system operators are committed to guarantee customers adequate levels of security, reliability and power quality facing financial pressures and noticeable decrease in available capital budgets. Regulators have to define fair and transparent standards that aims at improving the level of quality provided to customers by selecting the most cost effective actions. In this sense, there is a strict demand for efficient planning tools that enable maximal utilization of

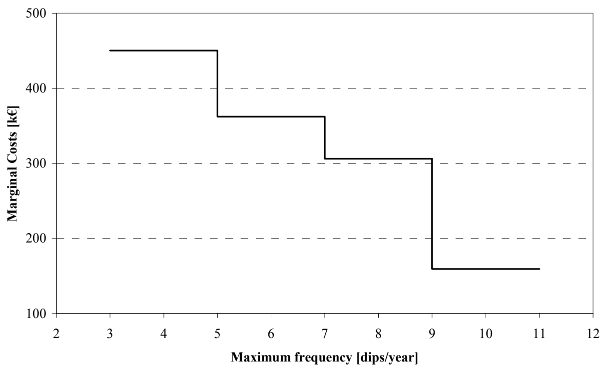

Fig. 4. Marginal cost varying the maximum VD frequency (with the cost of single VD equal to 1000€ and the critical voltage threshold equal: 50%of nominal voltage).

existing assets, minimize investments and allow reaching a reasonable level of power quality.

In the paper, a planning tool is proposed that allows planning the development of a distribution network taking into consideration the Power Quality as an engineering constraint to be complied with. The proposed examples showed that the unitary cost of VD and the definition of the critical voltage does not significantly affect the final result. What clearly emerges from the studies is that, in order to increment the PQ level, high investments are to be sustained by distribution companies. For this reason there is the need of a performance based distribution revenue that considers not only the long interruptions but also the PQ offered to customers.

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