AN INTEGRATED APPROACH TO ADDRESS THE EXPANSION PLANNING PROBLEM OF DISTRIBUTION NETWORKS UNDER COMPETITION

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Abstract – In this paper we describe a model to evaluate long term marginal prices in distribution networks considering investment decisions and uncertainties related to load evolution. These prices, although harder to compute, display very interesting properties in terms of long term stability and of ensuring revenue reconciliation between costs and remunerations. The model identifies a first set of feasible solutions according to several criteria and allows the user to select the final expansion strategy according to his preferences. The first of these two phases uses Simulated Annealing given its flexibility, easiness of application, ability to deal with discrete decisions and to escape from local optima. At a final section, the approach is illustrated using a case study based on a realistic distribution Portuguese network.

Keywords – distribution networks, expansion planning, long term marginal prices, uncertainties.

1. INTRODUCTION

The implementation of market mechanisms in the electricity sector started in the early 80th in Chile, and it was necessary to wait till the early 90th to witness a major experience in England and Wales. Apart from the typical vertical and horizontal reorganization of the industry, in England and Wales there were very important developments regarding the distribution sector when separating the commercialisation activities from the ones concerned with operation, maintenance and expansion. This move ultimately allowed competition and market mechanisms to expand till end-users. Apart from this strengthening of the market accent, this separation created new challenges to regulatory and tariff setting activities. In fact, distribution wiring companies correspond to a new set of entities that have to be remunerated given that:

- they play a crucial role while physically connecting end consumers, dispersed generation, and the main grid;
- they develop their activities in a monopoly basis given the economic infeasibility of duplicating distribution lines in the same geographical area. This leads to regulation and to the need to transmit signals to adopt more efficient behaviors;
- they have to be remunerated for different types of costs given the time-scale they are related to. These costs can be organized in short term operational costs, and longer term expansion costs;
- they should comply with Quality of Service regulations imposing minimum levels to several indices that, if violated, lead to penalties or to the automatic activation of investment plans;

Given this general framework, the regulatory and tariff problems regarding distribution networks are generally more timely than the ones related to transmission providers. This is also due to the fact that distribution providers are usually less efficient than transmission ones, distribution networks have lower automation levels and the share of distribution costs in the price of the final product is much higher when compared to transmission costs. Typical figures indicate that generation, transmission, distribution and commercialisation activities are responsible for 50%, 5%, 35% and 10% of the final cost of electricity. This means that there is a large potential to improve the performance of distribution wiring companies, and this improvement can be induced by adequately selecting regulatory frameworks and tariffs for use of networks.

Once a regulatory approach is chosen, the tariff method should be selected in order to translate costs into tariffs. This translation can be performed according to several methods that are usually grouped in three classes [1]: embedded, incremental and marginal methods. On their side, marginal methods can be divided in long or short term approaches depending on the considered time horizon. Short term marginal methods lead to nodal Short Term Marginal Prices – STMP – that reflect operational costs as generation, losses and redispatch costs. These nodal prices are reasonably easy to compute, normally as subproducts of generation optimisation problems. Although easy, they display some problems related to the fact that:

- STMP are very volatile [2] since they largely depend on generation costs, on the load profile and its distribution along the network, on outages and on the topology that is actually being operated;
- the Marginal Based Remuneration – MBR – is usually reduced when compared to the amount required by regulated companies. This is known as the Revenue Reconciliation Problem.

A way of coping with these problems corresponds to the use of Long Term Marginal Prices - LTMP. LMTP are computed over a longer time horizon and so the formulation includes both operation and investment costs. This clearly turns the prices more difficult to be computed but they have the potential to solve the referred volatility and revenue reconciliation problems.

In this paper we present an integrated approach to deal with the investment expansion planning problem of distribution networks as well as the related problem of setting tariffs for use of networks that allow distribution wiring companies to recover not only operation but also investment costs. The formulation considers three criteria related to the minimization of investment costs, branch active losses and the energy not supplied. It also has the flexibility to deal with load uncertainties given their importance in longer term approaches. The developed solution algorithm includes two phases. In the first place one identifies a set of efficient or non-dominated solutions using a Simulated Annealing based approach. In the second phase, the decision maker is allowed to select the most adequate solution according to his preferences.

The paper is structured in 5 main sections. Apart from this introductory one, Section 2 gives an overview about regulatory and cost allocation approaches given their impact in the more or less efficient behavior of distribution wiring companies. Section 3 details the mathematical formulation of the problem and describes the two phased solution approach. Section 4 presents a Case Study based on a real MV Portuguese distribution network and Section 5 draws some conclusions from the research that was developed.

2. REGULATORY AND COST ALLOCATION APPROACHES

2.1. Regulatory aspects

Regulation can be seen as an activity aiming at enforcing efficient behaviors in economic sectors that, for some reason, are operated in a monopolistic way. This is the case of transmission and distribution wiring activities on which it is usually unfeasible to invest in the duplication of the networks in the same geographical area. Therefore, in each area there is an unique network that provides that service to several agents. In this sense, regulation tries to substitute the market in inducing efficient behaviors of network companies in terms of approving their costs, of setting limits on prices or on revenues or by comparing companies. This leads to two major regulatory schemes known as Cost of Service/Rate of Return – CoS/RoR, and Incentives. Incentives regulation can be divided in Price Caps, Revenue Caps and in Comparison or Benchmarking.

The regulatory approaches adopted to transmission and to distribution wiring companies are frequently different reflecting the different efficiency levels achieved by these companies, the share of their costs in the price of the final product and the required level of investments in expansion or automation equipments. For several reasons, distribution companies were for many years the poor partners of the industry frequently leading to a situation where the quality of service levels are degraded and economic efficiency is more reduced than in transmission. This generally leads to the adoption of Incentives Schemes in the distribution wiring sector as for instance:

- price caps in England & Wales;
- revenue caps in Spain, Portugal, Norway;
- benchmarking in Chile.

In any case, the situation of the distribution wiring company will have to be fully analysed and characterized in terms of the type of networks, density and number of consumers and the required level of investments. The adopted regulatory approach must be adapted to the regulated company and should be able to transmit signals inducing the adoption of more efficient behaviors. It should be complemented by Quality of Service regulations interpreted as a way to defend consumers and balance pure market driven procedures and to indirectly induce expansion investments if quality of service minimum requirements are violated.

2.2. Cost allocation methods

Tariffs for use of networks must be set so that the regulated companies are remunerated both for their short term operation costs and for their long term investments. This turns it critical to identify these costs and to set the tariffs so that different time frames are adequately considered. Tariff allocation methods correspond to some sort of interface between the network provider and the users in the sense it translates the costs of the provider in amounts to be paid by users, hopefully in a fair, technically sounded, economically efficient, transparent, stable and easy way. These requirements are, in some cases, contradictory since technical robustness and economic efficiency generally vary in the inverse way with easiness of computation.

Tariff allocation methods are usually grouped in three large classes:

- <u>Embedded Methods</u> - these approaches are also known as average cost procedure since they aim at measuring the degree of use of the network by each user, allocating costs in a proportional way to that use [1, 3]. Within this class it is possible to consider Rolled in Methods or Power Flow based approaches. Postage Stamp and Contract Path are examples or Rolled In while MW.mile, Modulus or Use and Zero Counter Flow are examples of power flow based. These methods are generally easy to apply once their assumptions and simplifications are accepted, but their technical robustness is reduced and several of them correspond to a transaction based market implementation not tailored to pool anonymous mechanisms. Nevertheless, they are widely used by their own – for instance, Postage Stamp is used in Portugal and Spain to set transport and distribution tariffs for use of networks – or together with marginal tariff terms to ensure revenue reconciliation;
- <u>Incremental Approaches</u> - in this case, one aims at comparing the operating conditions of the network in case a specified transaction is present or not. The cost to allocate to that transaction corresponds to the surplus of costs coming from the

comparison between those two situations. These are typically transaction based approaches that work easily if the number of transactions is reduced but that can pose transparency and fairness problems if the number of transactions to evaluate is large. In any case, the concepts of Areas of Influence [4] used in Chile and the Benefit Factors [4] used in Argentina to allocate transmission expansion costs to potential users are examples of approaches of this class;

- Marginal Approaches - marginal prices can be defined as the variation of a cost function regarding to a variation of a load [5]. Due to the presence of the network – namely in terms of congestion and losses – it is not correct to evaluate the previous derivative regarding the global load of the system. In fact, marginal prices display a geographical differentiation from where arises the concept of Nodal Marginal Price. Nodal Marginal Prices can be calculated either within a short term operation problem or regarding a long term expansion planning exercise. In the first case, we compute Short Term Marginal Prices – STMP – as a subproduct of an optimisation problem, in sense these prices are closely related to dual variables when the optimum is achieved [6, 7]. Long Term Marginal Prices – LTMP – are harder to compute since they come from long term planning exercises on which one has to deal with load uncertainties, discreteness of feasible solutions and the potential presence of several and contradictory criteria.

It is our belief that the investigation on LTMP has a large potential given their larger stability when compared with STMP [2] and the possibility of inherently solving the revenue reconciliation problem between marginal based remunerations and approved regulated costs [4]. The methodology to be described in Section 3 is included in this line of research as an attempt to tackle with several of these difficulties**.**

3. COMPUTATION OF LONG TERM MARGINAL PRICES

3.1. Expansion model

Electric networks, in particular, at distribution level are characterized by a large number of nodes and possible branches. The nodes are load points, generation from dispersed facilities and substations. Economical efficiency both in operation and planning consists of connecting all the nodes supplying consumers at minimum global cost. This means deciding which configuration and injection points will be used to achieve minimum cost while obeying to technical constraints (namely related to quality of service and congestion). The problem involves many binary variables related to decisions to build or not facilities along a multi stage period.

Concerning the pricing methodology, planning must take into account the network remuneration within a philosophy of economic efficiency. The pricing issue should be based on optimization tools that explicitly include economic interactions between suppliers and loads at various locations while accounting for the power flows that result from these injections. The formulation should also include, in an accurate way, all factors that have an impact in network costs including long term investment costs. Realistic expansion problems have to deal with several objectives to optimize as: investment costs, operating costs, and reliability-related costs. This leads to a multiobjective mixed-integer problem.

According to this reasoning, the mathematical formulation of the problem adopted in our work is described by (1) to (8). It includes three criteria in terms of investments costs, operation costs (measured by losses) and reliability costs (evaluated through the level of energy non-supplied).

$$\min \ c_I = \sum_{i=1}^{p} c_i^t.\delta_i \tag{1}$$

$$\min \ c_O = \sum_{i=1}^{p} p_i^t.x_i \tag{2}$$

$$\min \ c_R = \sum_{i=1}^{p} e_i^t.x_i \tag{3}$$

subject to:

$$x_i = A_i.d_i \qquad i=1..p \tag{4}$$

$$\left|x_{ki}\right| \le \gamma_{ki}.\bar{x}_k \qquad i=1..p,\ k=1..m \tag{5}$$

$$\left|\Delta U_{ji}\right| \le \Delta U_{\max} \qquad i=1..p, j=1..n \tag{6}$$

$$\sum_{i=1}^{p} \delta_{ki} \le 1 \qquad k=1..m \tag{7}$$

$$\gamma_{ki} \ge \sum_{j \le i} \delta_{kj} \qquad k=1..m \tag{8}$$

In this formulation *m* is the number of branches, *n* the number of nodes and *h* is the number of periods considered in the planning horizon. γ_{ki} are auxiliary variables, indicating that branch *k* exists in period *i*. The sensitivity matrix $\mathbf{A_i}$ describes the network in each period *i*, relating the vector of branch flows $\mathbf{x_i}$ with the injections $\mathbf{d_i}$ (4). Branch limits and maximum voltage drops are considered in constraints (5) and (6). Constraints (7) and (8) are used to ensure consistence of the model regarding investment decisions through the planning horizon. Non-negativity and radial configuration constraints are not represented.

In this formulation, the loads in each planning period are assumed fixed. However, this model can be easily extended to consider a fuzzy representation of loads. In this case, constraints (4) to (6) are substituted by fuzzy versions according to the ideas in [8].

The feasible solutions defined by these constraints correspond to alternative investment plans. However, the multiobjective characteristic of the problem together with the number of discrete variables leads to a great number of solutions. To deal with the nature of this problem we propose a two step solving strategy. First, to cope with the multiobjective nature of the problem, we generate a set of efficient solutions that represent the non-dominated frontier [9]. In this step we used a multiobjective metaheuristic to handle with the combinatorial nature of the problem.

In the second step a decision-aid procedure helps the planner to select a representative reduced number of solutions to evaluate the average node or geographical region average marginal cost.

3.2. Solution algorithm

To search for non-dominated solutions we could follow one of the three following strategies [10]:

- to build an aggregated function considering all the objectives;
- to conduct the search by interactive methods;
- to generate an efficient representative set of solutions.

The first two strategies are not adequate for this problem as from one hand it is very difficult to build an utility aggregated function with the mathematical representation of the decision maker preference structure. Moreover, this preference structure is not independent of each individual and this would lead to a non systematic and difficult process. On the other hand, interactive methods are not adequate to the size of this problem while also displaying difficulties similar to the previous ones. The third strategy is independent from the decision maker as its outcome is a representative set of efficient solutions. A deeper insight into this set is left for the second phase of the procedure, that can be tailored to specific decision maker concerns and preferences.

To generate the set of efficient solutions we could adopt either the weighting method or the ε-constraint method [10]. The weighting method consists of assigning weights to the different objective functions and combining them into a single-objective function. It can be proved that, provided the weights are all strictly positive, every optimal solution of these partial problems is non-dominated ones for the original multiobjective problem. This method will be completely efficient only if the frontier envelope is convex.

The ε-constraint method consists of specifying bounds on all but one of the objective functions and optimizing the remaining function. Progressive constrained variation of the bounds allows one to obtain different non-dominated solutions. This second approach does not require the non-dominated frontier to be convex. In our solution strategy we adopted this approach because of the discrete nature of the problem and its lack of convexity.

Simulated Annealing

The generation stage problem, although turned into several optimization problems, is still of combinatorial nature. When dealing with real scale problems, exact methods require a computational effort that cannot be accomplished in feasible time. To take this into account we used a meta-heuristic, **Simulated Annealing (SA)**, [11] as the basic optimization tool.

In condensed matter physics, annealing is known as a thermal process to obtain low energy states. The Metropolis method is a simple algorithm to simulate the evolution of a solid in a heat bath till thermal equilibrium is reached. The SA is a mathematical method that bases its performance on an analogy between a physical many-particle systems and a combinatorial optimisation problem. The analogy relies on the following equivalences:

- solutions in the combinatorial problem are equivalent to states of the physical system;
- the cost of a solution is equivalent to the energy of a state;
- a control parameter playing the role of temperature introduces a mechanism of acceptation of new solutions in such a way that allows the process to escape from local *minima*.

$$P_c\left(accept\, j\right) = \begin{cases} 1 & if\ f(j)\le f(i) \\ e^{\frac{\left(f(i)-f(j)\right)}{c}} & if\ f(j)>f(i) \end{cases} \qquad (9)$$

$$c \in \Re^{+}$$

Equation (9) translates the acceptance *criterium* where f(i) and f(j) are the costs of two solutions, c is the control parameter simulating temperature and P_c is the probability of accepting or not worse solutions in an attempt to escape from local *minima*.

Phase 1 – Identification of non-dominated solutions

A SA procedure was combined with the ε-constraint search to solve the multiobjective planning problem. In practice, the initial multiobjective problem was split into several single objective problems successively solved to generate non-dominated solutions.

To apply the ε-constraint method the bounds for each objective function must be evaluated in advance and the SA acceptance function must be modelled to integrate the ε-constraint method. To implement the method we transformed all original objectives but one into constraints to allow partial optimisations. The bounds on these constraints are changed during the process to cover the whole decision space. A particular optimization of this procedure corresponds to a particular set of bounds imposed to all but one original objectives. This is equivalent to reduce the solution space to be optimized from S' to S" (10). The output of this phase is a list of alternative plans that cover the whole decision region.

$$s'' \subseteq s' \qquad (10)$$

Each efficient solution (alternative plan) regarding the defined objectives and taking into account the technical constraints will be characterized by the nodal marginal costs when using the LTMP corresponding to that plan and to each period p. Each plan has an implicit level of tariffs for use of networks for each period p that allow recovering the associated costs.

For a particular plan, LTMP are computed using (11). In this expression, ΔC_{inv}, ΔC_{op} and ΔC_{rel} are the impacts on the global cost from changing the load in node k by one unit.

$$LTMP_k = \frac{\Delta C_{inv}}{\Delta Pl_k} + \frac{\Delta C_{op}}{\Delta Pl_k} + \frac{\Delta C_{rel}}{\Delta Pl_k} \qquad (11)$$

The resulting expansion plans, apart from being completely financed by these tariffs, can also be interpreted as Economically Adapted Systems [12] in the sense they can be seen as reference plans along time in order to cope with forecasted loads.

Phase 2 – Decision Process

This first step generates a list of representative efficient solutions evaluated by the several attributes. Each alternative includes a remuneration scheme for the period under study and it is evaluated according to the attributes of the decision problem:

Investment Cost
Operation Cost (losses)
Reliability Cost (non supplied energy)

Apart from these original attributes, a more extended formulation could eventually include Congestion and levels of Quality of Service as indices to evaluate the goodness of solutions. In this sense, one may specify fuzzy bounds to some constraints and build a robustness index to evaluate the degree of satisfaction of those constraints. On a different basis, the values of the **geographically dispersed Marginal Prices** give more insight about the solution plan and can, to some extent, contribute to the decision process.

The Decision Maker – eventually a Regulatory Entity working together with regulated distribution companies – will have a list of efficient plans together with tariff suggestions. The problem was turned into a multi-attribute one characterized by generally large number of alternatives (having an implicit discrete nature). At this point, the Decision Maker will eventually need further support to select a final plan.

From this phase, the selection of the final plan can be accomplished in terms of a direct procedure. As an example, a prescriptive process, as the max-min method, could be used to reduce the number of alternatives. However, this can be criticized since reducing the scope of choice can be seen as a manipulation of the selection of the Decision Maker.

The adopted approach consisted of reducing the solution space by building representative solutions called **Macro Solutions**. They represent in an aggregated and structured way the whole solution set. The number of macro solution should not exceed the Decision Maker discrimination limit. The Decision Maker should choose a Marco Solution, representing a particular area of the non-dominated frontier. After that he would go deeper by investigating in a more detailed way the non-dominated solutions behind it.

4. CASE STUDY

The methodology described in Section 3 will now be illustrated with results obtained for a Case Study based on a realistic Portuguese distribution network. This network has 49 nodes, 68 possible branches and 3 supplying HV/MV substations. The expansion planning exercise considered three periods. In this exercise we assumed different percentage increases for different nodes. Globally, the load is increased by 40% from the initial to the second and by 10% from the second to the third. Along the planning horizon, several facilities can be built or decommissioned. The study aimed at:

- identifying technically feasible plans;
- characterizing those plans through the investment costs, reliability costs and power not supplied;
- selecting the efficient ones, that is, building the non-dominated frontier;
- computing nodal long term marginal prices for those plans;
- computing the marginal based remuneration recovered by the distribution wiring company;
- checking whether that remuneration covers the incurred costs or not.

In the first place, and as a result of Phase I detailed in Section 3.1, we present in Table I the values of the criteria obtained for some particular efficient expansion plans. Recall that a plan integrates a set of coordinated investments on expansion facilities that is able to cope with load variation along the planning horizon. A more complete description of the set of efficient plans can be obtained upon request from the authors or in [9].

Solution	Cost (10^5\$)	Losses (kW)	ENS (MWh)
42	247.76	642.44	3.53
75	242.98	543.00	3.50
79	320.76	437.76	2.71
89	209.64	612.00	3.50
190	303.19	424.43	2.67
194	298.01	444.41	3.10

Table I - Attributes for 6 efficient solutions.

Secondly, several of these efficient plans were analysed in a more detailed way. Considering, for instance, plan 42 we computed the corresponding nodal marginal prices in each of the three planning periods, namely to investigate if there was a large geographic discrimination or not. In fact, this is an important issue since geographic discrimination of nodal prices is the source of the Marginal Based Remuneration and so, to some extent, it can be interpreted as a basic resource of wiring companies subjected to marginal tariffs. Figure 1 displays the values of nodal prices for the third period of plan 42. It can be seen that geographic discrimination is a fact and prices do vary from values inferior than 1$/kWh to more than 6$/kWh.

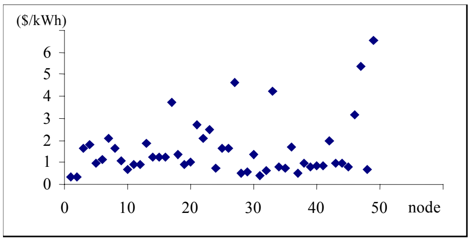

Figure 1 – Nodal Marginal Prices obtained for plan 42 in the third period ($/kWh).

Then, we computed the Marginal Based Remuneration, MBR, for the third period of plan 42. MBR is obtained considering that each load Pl_k pays and each generation Pg_k is paid the nodal price ρ_k at the node k they are connected to. This rule is translated into expression (12)

$$MBR = \sum_{\text{nodes } k} \rho_k.(Pl_k - Pg_k) \text{ \$/h} \qquad (12)$$

Table II includes for period 3 – the period in which loads are higher – the values of the LTMP, the symmetric of the injection values and the contribution of each node for the global network remuneration according to expression (12). The sum of these partial contributions leads to 1078.4$/h in this period. Considering that each period has 8760 h during which the load is assumed constant, the global remuneration along the three periods is given by (13).

Node	LTMP $/kWh	-Pinj kW	MBR $/h	Node	LTMP $/kWh	-Pinj kW	MBR $/h
1	0.34	0.0	0.00	26	1.64	121.30	198.33
2	0.34	28.6	9.73	27	4.63	11.30	52.32
3	1.66	116.8	194.41	28	0.48	27.88	13.38
4	1.80	46.7	83.92	29	0.55	19.59	10.81
5	0.96	34.7	33.41	30	1.35	116.78	157.22
6	1.15	0.0	0.00	31	0.39	4.52	1.79
7	2.08	173.3	359.87	32	0.62	38.42	23.82
8	1.61	30.9	49.85	33	4.25	12.05	51.20
9	1.07	41.4	44.17	34	0.79	56.51	44.88
10	0.70	52.7	37.18	35	0.73	0.00	0.00
11	0.89	34.7	30.76	36	1.67	6.03	10.09
12	0.88	3.8	3.33	37	0.50	82.12	41.15
13	1.88	20.3	38.19	38	0.98	39.18	38.27
14	1.27	61.0	77.23	39	0.79	57.26	45.47
15	1.22	0.0	0.00	40	0.87	54.25	47.00
16	1.27	17.3	21.98	41	0.86	9.04	7.76
17	3.72	74.6	277.17	42	1.95	48.97	95.67
18	1.35	0.0	0.00	43	0.95	17.33	16.48
19	0.89	22.6	20.16	44	0.93	42.19	39.42
20	1.02	0.0	0.00	45	0.76	18.08	13.82
21	2.72	87.4	237.55	46	3.14	3.77	11.84
22	2.08	17.3	35.99	47	5.36	-134.86	-722.9
23	2.51	90.4	226.92	48	0.70	-122.05	-85.53
24	0.73	52.0	37.97	49	6.54	-134.86	-882.0
25	1.64	17.3	28.33				

Table II – Partial remunerations for the third period.

$$MBR = MR_{p=1} + MR_{p=2} + MR_{p=3} =$$
$$=(742.1+1024.1+1078.4)\text{x}8760=249.187\text{x}10^5\$ \qquad (13)$$

In order to evaluate the Revenue Reconciliation Problem, we added investment, operational and reliability costs along the three periods (14). The values in (13) and (14) match remarkably well indicating that this problem was addressed in a successful way.

$$Costs = \sum_{p=1..3} (c_{I,p} + c_{O,p} + c_{R,p}) =$$
$$=247.7\text{x}10^5+29.5\text{x}10^3+162.2\text{x}10^3=249.617\text{x}10^5\$(14)$$

5. CONCLUSIONS

In this paper we described an integrated approach to deal with the expansion planning problem of distribution networks while addressing in a simultaneous way the tariff setting problem ensuring revenue reconciliation. The adopted approach is flexible enough to cope with different and frequently contradictory criteria, to deal with the discrete nature of the problem and to integrate load uncertainties in a multi-stage formulation. This kind of approaches has a large potential both for regulatory entities and for the wiring companies themselves to prepare reference expansion plans together with adequate levels of tariffs. In this sense it can lead to an extremely useful tool to improve the stability and predictability of the industry in a larger and larger uncertain environment.

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