A DECISION-AID METHOD TO INCLUDE INDEPENDENT FUZZY MODELLED GENERATION IN DISTRIBUTION PLANNING

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Abstract The classical long range distribution network planning problem consists on deciding network investments to meet future demands at a minimum cost, while attending technical constraints. The decision whether to construct or reinforce substations and branches, leads to a mixed integer programming problem with a great number of decision variables. On account of the time schedule for planning, the problem must be dealt with using a dynamic approach. The task is harder if we consider multiple objectives, when evaluating alternative plans, and uncertainty associated to future injections.

In this contribution, we accommodate load and independent producers (IP) uncertainty using fuzzy models and include the evaluation of the risk, introduced by these non-utility facilities, by adding a new objective function. The final dynamic fuzzy multiobjective problem will be dealt with in a two step strategy.

I. INTRODUCTION

The classical long range distribution network planning problem consists on deciding network investments to meet future demands, at a minimum cost, while attending technical constraints (thermal limits and maximum voltage drop). The decision, whether to construct facilities and branches, leads generally to a mixed integer programming problem with a great number of decision variables. From a pragmatic point of view, the problem consists on presenting to the planner a set of alternative solutions accurately evaluated by several attributes that traduce overall costs and service quality.

The nature of the problem, in what concerns data (loads and independent generation), introduces additional difficulties. In the past, related uncertainties were treated with probability models sometimes without the necessary statistical support due to lack of historical data. In recent years, uncertainty of loads has been modelled by possibility distributions that represent typical situations, as defined by experts' declarations, or as a result of fuzzy clustering studies [1]. On the other hand, an increasing number of independent producers (IP) in the distribution network introduces additional difficulties to the planning problem. The uncertainty related with independent producers' data is also fuzzy modelled, based on the concepts introduced by [2] and developed by [3].

This contribution presents a methodology to deal with the fuzzy dynamic multiobjective problem where the original problem is changed into an operational flexible one that allows the incorporation of all the facts that have impact on the final decision. To accomplish the efficient solutions (investment plans) search several objectives, at Planner's needs, are able to be considered. It is also simple to use exact models to evaluate solutions' attributes without turning the approach much heavier. An AC model could be used, losses could be estimated using quadratic functions and any model for reliability evaluation could be adapted. The final model consists on a the body and the modules (objectives) that fit on the body.

To address the problem a two step strategy is presented. In the first step we present an operational model that uses the robustness concept [4 and 5] to deal with the fuzzy problem as a crisp one. The result of this phase is a list of efficient alternatives. The search for this set of solutions is accomplished maximizing robustness and minimizing traditional costs as investment, operational and non-supplied energy. To include the risk scenario another extra cost is considered. This scenario, which results from the non availability of the supply option from IP, is dealt with as an extra minimization objective in the search process. Each alternative is evaluated measuring risk by the attribute we name as severity. The second step is a decision step in the attributes' space.

To solve the multiobjective combinatorial problem we use a combined heuristic search that generates a representative sample of efficient solutions. The procedure begins by splitting the problem into optimization problems and by using the ε-constraint method. To solve these simpler but yet combinatorial problems, a meta-heuristic, *Simulated Annealing*, is applied.

To deal with the great amount of efficient alternatives from first phase a second decision phase, in the attributes' space, follows [3]. It consists on a decision-aid process for the multiattribute problem that results from the first phase. The results from first phase consist on a list of efficient plans whose analysis can be made by the Planner, imposing successively limits to the attributes or using more formal tools adequate to deal with fuzzy multiattribute problems.

II. PROBLEM FORMULATION

In this section, the model used for the fuzzy multicriteria problem is presented. Possible new branches and substations, and network reinforcements are defined in advance. Plans consist on decisions about building or not new facilities along the periods i (δ_i), till the horizon period (h). Similarly to other approaches, the criteria used to select the best plans are related to money for investment costs, kW for losses and kWh for non-supplied energy (as a measure of reliability and quality of service). Loads and dispersed generation are estimated in advance by possibility distributions $\tilde{\mathbf{d}}_i$ (fuzzy injection in node i), where $\tilde{\mathbf{d}}_i$ is generally a trapezoidal or triangular fuzzy number. Constraints of maximum branch flows $\tilde{x}$ and maximum node's voltage drop $\Delta\tilde{U}_{ij}$ must be met. A radial configuration is also to be followed.

A. Model Description

The sensitivity matrix $\mathbf{A_i}$ describes the network in each period i, relating the vector of fuzzy branch flows $\tilde{\mathbf{x}}_\mathbf{i}$ with the fuzzy injections $\tilde{\mathbf{d}}_\mathbf{i}$ (4). Branch limits (5) are considered, as well as maximum voltage drop (6). Constraints (7) and (8) are necessary to ensure consistence of the model. Non-negativity and radial configuration constraints are not represented.

$$\min \mathrm{c}_{\mathrm{inv}} = \sum_{i=1}^{h} \mathbf{c}_\mathbf{i}^\mathbf{t} . \delta_\mathbf{i} \qquad (1)$$

$$\min \tilde{c}_{exp} = \sum_{i=1}^{h} \mathbf{p}_\mathbf{i}^\mathbf{t} . \tilde{\mathbf{x}}_\mathbf{i} \qquad (2)$$

$$\min \tilde{c}_{ens} = \sum_{i=1}^{h} \tilde{\mathbf{e}}_\mathbf{i}^\mathbf{t} . \tilde{\mathbf{x}}_\mathbf{i} \qquad (3)$$

subject to:

$$\tilde{\mathbf{x}}_i = \mathbf{A}_i . \tilde{\mathbf{d}}_i \qquad i=1..h \qquad (4)$$

$$\left|\tilde{x}_{ki}\right| \le \gamma_{ki} . \bar{x}_k \qquad i=1..h,\ k=1..m \qquad (5)$$

$$\left|\Delta\tilde{U}_{ji}\right| \le \Delta U_{max} \qquad i=1..h,\ j=1..n \qquad (6)$$

$$\sum_{i=1}^{h} \delta_{ki} \le 1 \qquad k=1..m \qquad (7)$$

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

m is the number of branches and n the number of nodes.

γ_{ki} are auxiliary variables, indicating that branch k exists in period i.

The feasible solutions defined by these constraints correspond to alternative investment plans. Note that (5) and (6) are fuzzy constraints.

B. Robustness

A key concept to the problem formulation is that of robustness. A given plan is robust regarding a specific constraint if the constraint holds true for every possible value of the uncertain variables and constants. In that case β=1. Otherwise, if some instances of those quantities lead to violation of the constraint, β equals the maximum possibility value for which the constraint is not violated.

A global index β_{PLAN} concentrates this robustness information, allowing the planner to consider plans that face the risk of not being able to accommodate future load demands.

$$\beta_{PLAN} = \min_{c} \beta_c \qquad (9)$$

This concept, when applied to the problem formulation, II, leads to a crisp multiobjective model. On one hand constraints, (5) and (6) are relaxed to the case β=0 and turn crisp; on the other hand, a new objective function is added to the problem:

$$\max \beta_{PLAN} \qquad (10)$$

In consequence, the modified problem has a set of crisp constraints (allowing some violation by the extreme values of the uncertain variables) and an additional objective function that reflects the robustness of each alternative regarding data uncertainty.

C. Severity index

To give additional insight in measuring constraints violations, an index of severity of violation was defined in [3]. The index measures the level of surpassing the maximum technical limit. Equation (11) presents the evaluation of thermal severity. Like robustness it can be evaluated for a plan as a global index (sum of all indices).

$$V_I = \frac{1}{I_{\max}} \int_{I_{max}}^{\infty} u(I)\, dI \qquad (11)$$

From an operational point of view this index allows the planner, that must establish in advance the guidelines for investment, to have an overall network information and proceed, in the second phase, with a supervised search for efficient alternatives.

D. Independent producers

IP are becoming, more and more, one of the most important supply-options available in distribution networks. When planning or during operation study phases, ignore this new presence may lead to uneconomical or technically unsound decisions. On the other hand, there exists an additional risk when considering this extra source of energy. Mainly when dependable on natural resources, there is a great deal of related uncertainty. An improvement, to the model proposed in [6], has been developed to take into account the risk introduced by the failure of these units.

This new environment faces the Planner with two scenarios. One, we name as normal scenario, is equivalent to the operation state considering available all power from IP. Another one results from considering the extreme situation of total non availability from these units. Intermediate scenario could be considered but the extreme cases are generally sufficient to outline the decision process.

In this approach we use severity to evaluate the risk that results from the second scenario. We measure the IP unavailability by each configuration degree of severity. The search for efficient plans is made including an extra objective function, minimization of severity when facing the risk scenario. Aside with investment, operation and reliability minimization cost we also minimize the risk.

III. OPERATIONAL MODEL

As a result of the fuzzy nature of the problem the operational model can be formulated using the first three equations of the original model (1 to 3) and adding equation (12) and (13).

$$\max \beta_{PLAN} \tag{12}$$

$$\min Sev_{PLAN\_RISK} \tag{13}$$

The first one evaluates robustness and turns the fuzzy problem into a crisp one. The second one evaluates the risk for the scenario when the production from independent producers is not available.

IV. RESOLUTION STRATEGY

To implement the generation of efficient alternative strategy, the ε-constrained method was used [8]. Bounds were specified on every but one of the objective functions optimizing the remaining function. Progressive constrained variation of the bounds allows us to obtain different non-dominated solutions. This process splits the multiobjective problem into a set of optimization problems that may be solved independently. This approach turns naturally adequate to parallel processing.

Regarding the resolution of the auxiliary optimization problems, the use of mathematical programming tools is restricted to limited size problems, on account of the combinatorial nature of the problems. This approach uses a meta-heuristic, Simulated Annealing, for the resolution of these problems.

In the second-phase, the whole set of efficient alternatives amounts to a great number of different solutions. Thus number of different expansion plans is high enough to be inconceivable to any Planner to make a systematic search to choose the preferred plan. At this phase we suggest the use of more formal methodologies, like the screening methods, to help the Decision Maker (Planner). These methods allow the clustering of better alternatives and guide the Planner to select preferred attributes and proceed with a more detailed search. The conjunctive method [9], where the Planner would be able to impose systematically limits to the attributes, would be adequate. Nevertheless normative methods as ELECTRÉ could be used.

IV.1 Simulated Annealing

Simulated Annealing (SA) is a flexible meta-heuristic adequate to solve combinatorial problems. It relaxes optimality to escape from local minimum. It is based on a similar process to an iterative heuristic improvement together with a control mechanism that allows algorithms to escape from local optima. The flexibility and simplicity of this framework characterize this meta-heuristic's adequacy to model particular and often complex constraints, supplying solutions in acceptable computation time.

To implement the ε-constraint method using SA, a new acceptance function is considered in order to reduce the optimization space according to the constraints. Equation (16) illustrates the new acceptance function constraining the solution space:

we chose an objective, j, to optimize and then for each objective $m \neq j$:

$$P_c(accept\ \mathrm{j}) = \begin{cases} 1 & if\ f_k(j) \le f_k(i) \\ e^{\frac{(f_k(i) - f_k(j))}{c}} & if\ f_k(j) > f_k(i) \\ 0 & if\ f_m(j) < \varepsilon_m \end{cases} \tag{13}$$

$$c \in \Re^+$$

The number of partial optimizations depends on the imposed degree of discrimination, in practice it depends on the chosen ε_m values.

Details about the this method can be seen in [10].

IV.2 Decision-phase

The final list of the non-dominated alternatives will join all the alternatives, after deleting occasional dominated solutions, resulting from the first phase of the multiobjective problem. The Planner is then confronted with a list of plans, characterized by crisp attributes (investment cost, robustness and severity) and fuzzy attributes (the others). The extension of this list depends on the size of the problem as well as on the degree of discrimination of the ε-constraint method. At this point the Planner needs further support namely when the final list is composed by a great number of efficient alternatives.

Although the problem has turned into a non-fuzzy one the final list is evaluated by two fuzzy attributes (related to losses and non-supplied energy). To deal operationally with those fuzzy values we followed the methodology proposed by [11] and used the removal to represent each fuzzy value as presented in table I. At last each alternative (plan of investments during the different stages of the studied period (*h*)) is evaluated by the mentioned attributes:

Robustness

Investment Cost

Operation Cost

Reliability Cost (non supplied energy)

Severity (*risk*)

This last attribute reflects the risk related to each decision represented by an alternative when considering the risk scenario. It measures de degree of possibility of non-delivering purchased energy. This risk index also allows the Planner to evaluate the extent of violations proceeding with a deeper detailed analysis to identify critical points. The detailed study over a limited number of the promising alternatives (selected after the decision-aid phase), may suggest further investments to increase attractive solutions' robustness. This detailed analysis, can be made at any point of the second decision-aid stage together with forward and backward analysis also available. There is no danger of loosing information as all efficient alternatives, generated in first phase, are actually saved.

V. CASE STUDY

This contribution presents a multistage real sized case study that illustrates the main issues of the approach. The case study data was synthesized from a real network of a zone belonging to the Centre-West region of Portugal kindly made available from a Portuguese Utility. Extra data regarding reliability parameters was based on typical values presented in literature.

From the original data, some loads were grouped for operational reasons. After this procedure a synthesized network, with 51 nodes and 75 branches was obtained.

Three possible substations, two of them already operating, feed the system: S_1 connected to node 2 (maximum capacity 2400 A), S_2 to node 20 (maximum capacity 1500 A) and the new S_3 to be constructed if necessary (maximum capacity 500 A). From the existent substations S_2 has a reinforcement capacity of 500 A. The case study also includes three independent generation units connected to the network. Three mini-hydro connected to the network are considered. One has 5.25 MW of rated power and the remaining two with 4.65 MW of rated power. Details about the membership functions for the IP can be seen in [3].

Loads are represented by triangular possibility distributions. Three stages are considered and an extrapolation was made in order to consider loads' evolution following a sigmoid curve. Details about data can be asked to the authors.

In order to accomplish the modified ε-constraint method robustness was maximized and upper and down limits for the other criteria were fixed. The extreme limits where calculated optimizing each criteria and relaxing the others. If we were considering the solution space area for three objectives it would be possible to make a physical analogy and consider that the whole criteria's space was divided into elementary cubic spaces which were submitted to successive optimization procedures using the Simulated Annealing (SA).

Several previous decisions had to be made in order to apply the SA procedure: initial "temperature", "temperature" schedule and duration of fixed "temperature". These parameters are derived from previous studies on distribution networks. For the case study, initial temperature was chosen in order to accept in the beginning half of the configurations, temperature schedule was a geometrical one lowering temperature for each interval from 10% and the number of iterations using a fixed temperature was calculated 10 times the average possible neighbours of the initial configuration, for the case in question 600 iterations. The whole set of efficient alternatives, after the generation process, amounts to 90 different solutions.

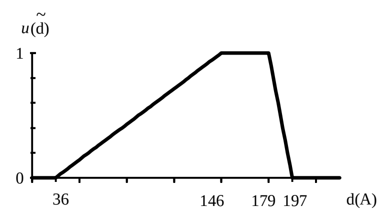

Fig. 3: Mini-hydro connected to node 18

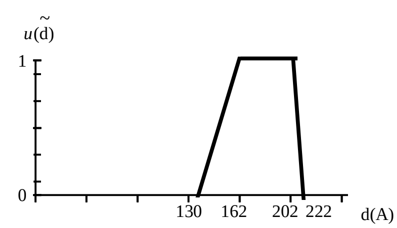

Fig. 4: Mini-hidro connected to node 15

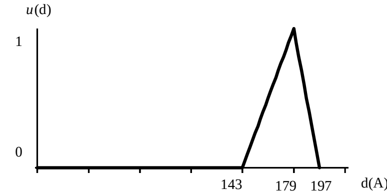

Fig. 5: Mini-hidro connected to node 41

The second step consists on a simulation of a decision-aid procedure. All the decisions to be taken during this phase are subjective and depend on the utility economical policy. At this point the Planner makes a cluster analysis to the list from first phase and to selects one of the clusters for further study. Table I present a group of clustered alternatives selected from the generated list. This set consists on a group of alternatives presenting high degree of membership to robust solutions, when considering the normal scenario. After selecting the main characteristics, the second decision phase should proceed with further clustering or by imposing limits (preferences) by a simulated Planner.

To go on simulating the Planner's attitude, limits are imposed to the alternatives presented in Table I. We will suppose that the Planner selected, for further analysis, robust, in what concerns normal scenario, and cheaper alternatives ($((\beta = 1 \wedge \text{cost} < 310) \vee \text{Cost} < 250)$). He gets table II.

TABLE I - Original reduced list

Custo ($)	Loss (kW)	NSE (Wh)	β	β_risk	SeV_risk
222.2	582.0	3564.2	0.790	0.790	0.007
247.8	671.4	3552.2	1.000	0.230	0.020
259.0	720.0	3552.2	1.000	0.478	0.009
280.2	480.5	2907.1	0.357	0.325	0.074
281.5	660.6	2796.1	1.000	1.000	0.000
283.0	420.3	2356.9	1.000	0.107	0.095
291.9	493.5	2993.6	1.000	0.529	0.018
298.0	461.1	3110.9	1.000	0.980	0.005
303.2	440.5	2677.1	1.000	1.000	0.000
311.1	395.7	2794.2	1.000	1.000	0.000
312.8	663.3	3552.2	1.000	0.238	0.003
316.5	537.2	2562.4	1.000	0.220	0.000
317.6	582.1	3552.2	1.000	0.454	0.000
320.8	460.0	2737.6	1.000	0.602	0.006
324.6	511.0	3175.7	1.000	1.000	0.000
349.4	551.8	2414.5	1.000	0.326	0.000
357.1	743.6	2655.1	1.000	0.488	0.000
357.4	544.4	2470.1	1.000	0.368	0.000
364.9	479.6	2461.1	1.000	1.000	0.000
364.9	362.0	2520.5	1.000	1.000	0.000

TABLE II - Reduced list

Custo ($)	Loss (kW)	NSE (Wh)	β	β_risk	SeV_risk
222.2	582.0	3564.2	0.790	0.790	0.007
247.8	671.4	3552.2	1.000	0.230	0.020
259.0	720.0	3552.2	1.000	0.478	0.009
281.5	660.6	2796.1	1.000	1.000	0.000
291.9	493.5	2993.6	1.000	0.529	0.018
298.0	461.1	3110.9	1.000	0.980	0.005
303.2	440.5	2677.1	1.000	1.000	0.000

We will now suppose that a careful analysis to table II lead the Planner to exclude all the alternatives which presented robustness, for normal scenario, less than 1 and presenting higher operation costs. He got table III.

Two expansion plans from this final list, 1 and 4, seem particularly interesting on account of their low values for investment costs. Nevertheless, the plan 4 is very exposed to the risk scenario. The Planner might think worthwhile and proceed to a detailed severity analysis on both alternatives.

An analysis of the severity indices of all network components (not described) indicates that the plan 4 presents a 0.02 SeV_risk index for only one branch. This conclusion gives the planner a basis for further economical analysis. He probably will analyze economically both alternatives and ponder the reinforcement for the risk scenario or support on the plans he got and decides for economical commitments with independent producers in order to assure the supply.

TABLE III - Reduced list

Plan	Custo ($)	Loss (kW)	NSE (Wh)	β	β_risk	SeV_risk
1	247.8	671.4	3552.2	1.000	0.230	0.020
2	291.9	493.5	2993.6	1.000	0.529	0.018
3	298.0	461.1	3110.9	1.000	0.980	0.005
4	303.2	440.5	2677.1	1.000	1.000	0.000

VI. CONCLUSIONS

This contribution presents a methodology to deal with risk and shows how to help a Planner to decide about investments on electric distribution planning problems in an uncertain environment. The construction of the fuzzy multiobjective combinatory problem is discussed, along with the strategy used to obtain an approximation to the set of efficient alternatives. A new concept, severity, is introduced to evaluate risk when considering production from non-utility facilities either producing from natural resources or not.

This methodology proves efficient and flexible to include exact models namely when thinking of operating plans. The different criteria can be easily evaluated as they can be completely separated from the body problem. To implement this in practice further developments are already being worked on as: including an AC model for load flow and also include a more accurate model to evaluate reliability as suggested in [12].

Although tested for the electric distribution planning problem, the approach seems adequate to other fuzzy multiobjective combinatorial problems. Besides, as it stands out from the approach description, exact formulations can be used for the different objectives without turning the problem resolution much heavier.

As a final notice, we find interesting to point out the natural adequacy of the proposed methodology for parallel processing. No special computer architecture is needed, as long as each partial problem is completely independent of the others.

VII. ACKNOWLEDGEMENTS

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