IMPLICATIONS OF USING UNCERTAINTIES IN MULTI-STAGE LONG-TERM DISTRIBUTION PLANNING

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ABSTRACT

This paper presents a new possibilistic (fuzzy) model for the dynamic planning of power distribution networks that finds out solutions corresponding to the simultaneous optimization of the fuzzy economic cost, cost of reliability and optimization of robustness of such networks under uncertainty. In the proposed method the search for the optimal solution is aimed at robust decisions; i.e. the solution is expected not only to be economical and technically desirable, but also to be sufficiently flexible when facing any unpredictable future.

INTRODUCTION

Although numerous optimization methods have been proposed in the past for long term planning of distribution networks [1,2], many of them do not take into consideration uncertainties related to future events. This is a fundamental issue since nowadays, in a competitive business environment, investments are subject to fierce pressures for reducing costs in all aspects of operations, planning and management. Such pressures require appropriate capital expenses in order to achieve sound business results on the long run. To be more precise, the tangible result of improper planning or failure to properly predict future demands inflates expenditures through penalties for poor reliability/quality or forces immediate actions often too expensive (all due to overcapacity or undercapacity of the distribution system). Therefore, tools and methods are sought that may improve expansion and reinforcement of distribution networks taking into account uncertainty as well as financial and technical constraints/requirements.

Instead of usual deterministic least-cost planning method, in this paper a robust method has been proposed for obtaining flexible plans for uncertain futures. The proposed method uses fuzzy sets, also used by other authors [3], among other techniques for confronting planning under uncertainty. The major advantage of using fuzzy sets is that they can be used to model human judgments and inexactly expressed information, thus practical for most utilities lacking historic data necessary to apply probabilistic models.

Evolutionary algorithms are used to determine optimal *multi-stage* distribution network investment plan; i.e. a set of yearly plans (*schedule*) of additions and reinforcements over a mid or long term study period (e.g. 5-15 years in the future). In combination with fuzzy sets, the proposed approach takes care of infinite demand and distributed generation (DG) scenarios so the planner is not compelled to run the optimization procedure for each specific scenario. The paper only shortly refers to the features of the evolutionary algorithms based optimization procedure, using fuzzy sets to model uncertainty in loads, tentative distributed generation, reliability parameters, etc. and also the concept of robustness in planning. The main focus is placed on the repercussions of fuzzy modeling which is demonstrated through a case study of significant size derived from real planning problems of the City of Zagreb distribution system.

METHOD OUTLINE

The method is specifically designed for medium voltage distribution planning in urban areas (with or without distributed generation) using open-loop as preferred layout for the planning horizon (final planning stage). The proposed optimization technique searches for the set of decisions (for every stage) that defines the development of the distribution system. The search is concerned with investment, operational and reliability related costs.

The development of the system is simulated by two interrelated evolutionary algorithms that are used to generate sets of dynamic distribution network solutions. The master (main) evolutionary algorithm is aimed at optimizing the open loop network layout in the last year of the study period (e.g. 5-20 years ahead) and the slave EA is used in each iteration of the master EA to produce an optimized plan for the final year, identifying a schedule (as a set of yearly plans) of additions and reinforcements over the study period. More details could be found in [4].

Incorporating fuzzy sets theory in planning models drastically changes most calculations. Due to the page limitation they are not presented in this paper. More details regarding fuzzy load flow, technical and reliability constraints evaluation and the concept of robustness, ranking fuzzy costs, fuzzy method for determining optimal operational radial configurations for a given spatial meshed layout could be found in [5,6].

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COMPUTATIONAL RESULTS

The model and the algorithm have been intensively validated in large computational experiments and also applied to real distribution networks of significant dimensions (up to 300 nodes representing HV/MV substations, MV/LV substations, switching stations and DGs, then up to 300 existing lines and also up to 30 000 proposed routes of new lines in the distribution network). The largest part of the data on the distribution system have been provided by the Croatian electric utility (HEP).

Due to the lack of space, in this paper only the main data and results of an artificial case study generated mostly from the real data of the distribution system of city of Zagreb have been presented. Figure 1 shows the existing nodes and lines (cables) in the supply area under study. There are two existing HV/MV substations of sizes 2x16 MVA and 2x40 MVA depicted in red colored rectangles. Considering that these supply substations supply wider area, to the supply area under study only a portion of the installed MVAs and feeder bays has been assigned:

1st HV/MV substation: 20 MVA + 10 feeder bays
2nd HV/MV substation: 30 MVA + 12 feeder bays

Dark blue and green rectangles depict 113 existing 10/0.4 kV and 20/0.4(0.42) kV substations respectively. Rose-colored rectangles depict 3 existing DGs. Green colored lines represent 83 existing 20 kV cables and dark blue colored lines represent 38 existing 10 kV cables.

Besides existing elements in the network, in Figure 1, 7 new demand nodes (20/0.42 kV substations) and 2 new DGs are depicted as turquoise and orange rectangles respectively. These rectangles are encircled, where numbers denote time stages in which new nodes shall be in operation.

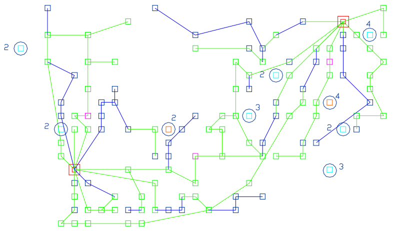

Figure 1 Existing distribution network comprising future proposed demand nodes and DGs

In most of the existing planning methods, prior to the planning procedure, planner is obliged to define available new ROWs (rights of a way, proposed routes of new lines). If using only manually provided reduced set of ROWs planning process usually leads to suboptimal solutions (especially in so called green field supply areas). Therefore, in our approach, connections between all pairs of nodes are viable while building open loop layouts in the horizon period (ROWs define complete graph in which every node has a direct connection with the rest of the nodes). For calculating investment expenditures for connecting two load/supply points GIS (Geographical Information System) tool based on shortest-path algorithm is used. It uses linear elements like road centerlines, cadastral boundaries, ducts, permissible corridors and manually inserted corridors. Costs are calculated based on route length and corrections according to area-specific costs or terrain specifics and also corrections for existing feeders that are to be reinforced [7] (i.e. reuse of obsolete cables ducts).

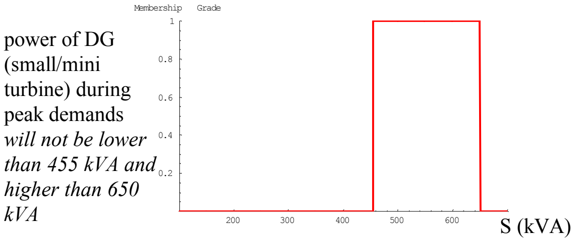

Figure 2 Membership function (fuzzy interval) of DG's power generation during peak demands in the distribution network

Planning period is 5 years henceforward. It has been divided into 5 time stages (duration of each one is 1 year). Forecasted demands of 10(20)/0.4(0.42) substations are represented using triangular fuzzy numbers. Initial load of all demand nodes is 24399 kVA with coincidence factor f_i=0.6. The final stage uncertain load is the following fuzzy number (24747, 26756, 26756, 29817) kVA. The uncertainty in the production of DGs during peak demands in the network is represented by intervals [0.7,1]xS_n, where S_n represents the size of DG in MVA (in Figure 2 membership function of one DG power generation during peak demands is given; DG has a rated power of 650 MVA).

The following planning criteria have been applied in the optimization procedure:

- operational voltage, 10 kV
- max allowed voltage increase/drop, ±5%
- max allowed *SAIFI*, 0.5 yr^{-1}
- max allowed *SAIDI*, 2 hours/yr

In Table 1 intervals (rectangular fuzzy numbers) of reliability analysis input data are given.

Table 1 Fuzzy reliability analysis input data

Fuzzy reliability data		
	a_1=a_2	a_3=a_4
Mean time to switch (hours)	0.25	1
Cables failure rate (yr^{-1})	0.005	0.024
Mean time to repair cable (h)	1.5	30
MV/LV substation failure rates (yr^{-1})	0.015	0.03
Mean time to repair MV/LV substation (h)	10	35
HV/MV substation failure rates (yr^{-1})	0.01	0.02
Mean time to repair HV/MV substation (h)	15	50

Table 2 Input fuzzy data related to the costs evaluation

Fuzzy costs data		
	a_1=a_2	a_3=a_4
Cost of power losses (€/kW)	6	8
Cost of energy losses (€/kWh)	0.04	0.08
Cost of energy not supplied (€/kWh)	0.04	0.08
Cost of new cable construction (€/m)	40	75
Cost of maintenance (percentage of investment cost,%)	5	
Interest rate (%)	10	

The following the criteria have been used to determine candidate lines proposed for the reinforcement in the planning period of 5 years:

- years of age (old lines reaching theirs life span)>30
- cross section<95 mm^2

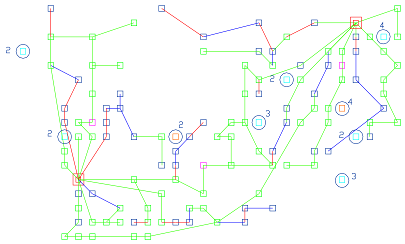

Figure 3 Obsolete 10 kV cables (red-colored) proposed for the reinforcement in the planning period

In Figure 3, 19 red-colored lines are given, out of 38 existing 10 kV cables, that satisfy previously mentioned criteria. All new cables, built in a new ROW or used to replace the existing obsolete ones, are XHE 49-A 3x185 mm^2, 20 kV.

In the planning procedure the robustness limit has been set to $rob\_gr=0.2$ and the parameter related to the risk aversion to $\lambda_r=0.5$.

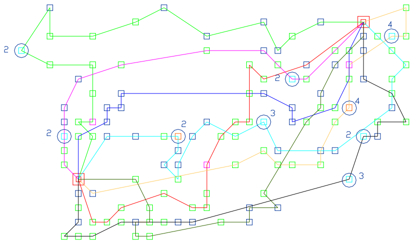

Figure 4 Optimal open loop layout of the distribution system

In Figure 4 the optimal open loop distribution system layout (solution of a master EA) in the horizon year is depicted. The optimal open loop layout comprises 130 cables, 117 demand nodes and five DGs assigned to 8 feeders (loops) connecting two supply substations. According the open loop layout 48 new cables should be laid in new ROWs and 14 (out of 19 proposed) existing cables reinforced in the planning period. In the open loop network 67.77%, or 68 out of 121 disposed, are the existing cables.

As a result of the simultaneous multi-stage planning, in the following figures (Figure 5-9) distribution system nodes and lines present in five successive time stages are depicted. This is the solution of the slave EA for the targeted open loop network given in Figure 4.

Orange-colour is used to depict optimal radial operational topology with respect to the costs of power and energy losses and cost of interruption (*EENS*) subject to the technical (i.e. voltage drop/increase, thermal limit of lines and transformers) and reliability constraints (i.e. *SAIDI* and *SAIFI* indices limits). Dark colour is used to depict cables present in the network that serve as the reserve cables.

In Table 3 supply and demand nodes, DGs and lines (cables) present in the distribution network in different time stages are given. In Table 4 only new lines built in different time stages are given.

Table 3 The distrib. network data in different time stages

time stage	nodes	no of lines	new lines	operating lines	reserve lines
1	113	127	11	113	14
2	118	138	14	118	20
3	120	145	10	120	25
4	122	158	16	122	36
5	122	161	6	122	39

Table 4 New lines built in different time stages

Time stages	1st	2nd	3rd	4th	5th	realized	not realized
lines in new ROWs	6	11	7	13	3	**40**	**8**
reinforcement of existing lines	5	3	3	3	3	**17**	**2**
Σ	11	14	10	16	6	**57**	**10**

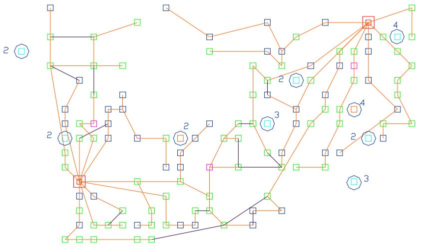

Figure 5 Distribution system in the *first* time stage

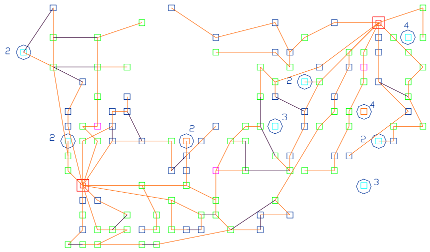

Figure 6 Distribution system in the *second* time stage

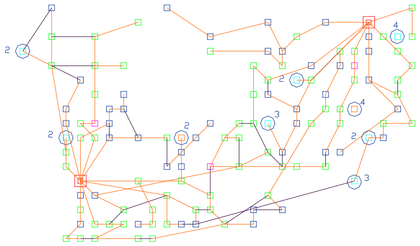

Figure 7 Distribution system in the *third* time stage

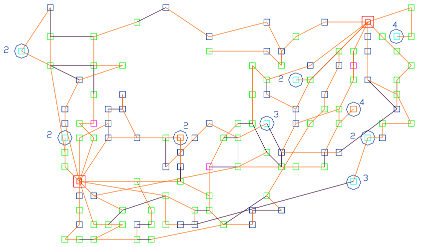

Figure 8 Distribution system in the *fourth* time stage

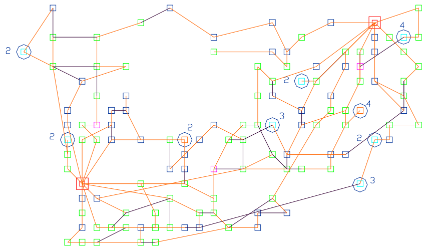

Figure 9 Distribution system in the *fifth* time stage

In Table 5 costs of optimal five-stage development and reinforcement plan are given. Robustness of a plan is equal to 0.61. If distributed generation is not available the robustness of a plan is equal to 0.38. Considering the imposed limit *rob_gr>0.2*, it could be observed that the optimal plan is adequate even if no DG production is available.

Table 5 Costs of the optimal **fuzzy** plan (λ_r=0.5)

(€)	a_1	a_2	a_3	a_4	**crisp value**
investments	79214	79214	148528	148528	113871
maintenece	229900	229900	431117	431117	330508
losses	10582	10582	15718	15718	13150
ENS	783	811	8043	8459	4524
Σ(€)	320479	320507	603406	603822	462053
***SAIDI* (h)**	0.155	0.155	1.25	1.25	0.705
***SAIFI* (yr^{-1})**	0.0313	0.0313	0.094	0.094	0.063

Table 6 Costs of the optimal **deterministic** plan

(€)	a_1	a_2	a_3	a_4	**crisp value**
investments	87391	87391	87391	87391	87391
maintenece	288921	288921	288921	288921	288921
losses	14719	14719	14719	14719	14719
ENS	5023	5023	5023	5023	5023
Σ(€)	396054	396054	396054	396054	396054
***SAIDI* (h)**	0.87	0.87	0.87	0.87	0.87
***SAIFI* (yr^{-1})**	0.082	0.082	0.082	0.082	0.082

Furthermore, the optimization procedure has been carried out for the deterministic demands and prices corresponding to the most possible values a_2=a_3 (α=1). In Table 6 costs of the optimal deterministic development and reinforcement plan are given. It could be observed that the "fuzzy" solution presumes larger investment costs. Investment costs of deterministic solution are 23.25% lower than fuzzy investments, and total costs are 14.3 % lower than the total costs of fuzzy solution. However, the deterministic solution robustness to supply the future adverse power demands equals 0.12<*rob_gr*. In other words, the deterministic solution is inadequate with respect to possibility to satisfy the uncertain future demands. Conclusively, planning with fuzzy loads and prices achieves solutions with higher costs (6 new cables more to build/reinforce) but yet with more robustness. This concept is known as hedging policy in planning.

Table 7 Costs of the optimal **fuzzy** plan (λ_r=0.1)

(€)	a_1	a_2	a_3	a_4	**crisp value**
investments	86981	86981	163091	163091	94592
maintenece	297433	297433	544562	544562	322146
losses	9996.3	9996.3	14848.3	14848.3	10481.5
ENS	656.65	680.765	6720.04	7080.8	1291.88
Σ(€)	395067	395091	729221	729582	428511
***SAIDI* (h)**	0.1395	0.1395	1.1295	1.1295	0.6345
***SAIFI* (yr^{-1})**	0.026	0.026	0.088	0.088	0.057

For $\lambda_r \in [0.35,0.7]$ solutions obtained with different values of risk aversion parameter does not differ considerably. This is not the case for λ_r<0.35 (planer is optimist/risk taker) and λ_r>0.7 (planer is pessimist/non-risk taker). For example, in Table 7 costs of optimal fuzzy plan obtained with the parameter of the risk aversion $\lambda_r=0.1$ are given. This solutions includes 60 new cables to build (17 existing 10 kV cables shall be reinforced and 43 cables laid in new ROWs). In comparison to the solution obtained for $\lambda_r=0.5$ (Table 5) the last solution presumes lower costs. This is due to the fact that these costs are calculated with lower λ_r. But, if costs of the last solution are calculated for $\lambda_r=0.5$, due to the larger investments, costs are higher (562240 €). Conclusively, small changes in risk aversion parameter setting will not significantly influence the solution of the planning procedure.

CONCLUSION

Although numerous optimization methods have been proposed for long term planning of distribution networks, many of them do not take into consideration uncertainties related to future events. Within this paper, a long-term planning method based on evolutionary algorithms devised by the Authors has been presented with special emphasis on fuzzy sets theory used for handling uncertainties. The main emphasis of the paper is on a real case study and the demonstration of the influence of uncertainties on the distribution system planning.

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