RISK MANAGEMENT BASED PROCEDURE FOR MULTI-STAGE EXPANSION PLANNING OF DISTRIBUTION NETWORKS UNDER UNCERTAINTY

Zeljko POPOVIC
Elektrovojvodina – Serbia
zeljko.popovic@su.ev.co.yu

Dragan POPOVIC
DMS Group – Serbia
dragan.popovic@dmsgroup.co.yu

Vojin KERLETA
Technical faculty of Zrenjanin – Serbia
kerleta@tf.zr.ac.yu

Abstract--This paper proposes a new procedure for multi-stage distribution network planning in the presence of uncertainty which addresses several deficiencies of previous contributions. The proposed procedure is based on fuzzy set concept, new pseudo dynamic algorithm, fuzzy mixed integer model and risk management analyses. It enables a large number of quality multi-stage expansion plans to be obtained and evaluated using an appropriate tools for measuring and managing risk. Thus, the suggested procedure provides the decision-maker with a means for determination of the multi-stage expansion plan that responds to all possible futures in the most efficient way.

INTRODUCTION

Distribution expansion planning is a difficult problem of great practical importance with more than four decade history of continued efforts and contributions for improved solutions [1-4]. One of the main difficulties in developing a high quality planning tool, beside large dimension of distribution networks, is time-dynamic nature of the problem. Inclusion of time dynamic in distribution expansion models substantially increases the complexity of the problem. Furthermore, electricity planning is subject to a large degree of uncertainty which additionally increase the hardness of the problem. Among others, uncertainties related to future load growth have the greatest influence on the planning process [5]. In the presence of such uncertainty many possible futures can occur and decision-maker's aim is to obtain a flexible multi-stage expansion plan which may respond in the efficient way whatever plausible future occurs. However, only a few proposed distribution expansion models dealt with such uncertainty, mostly by utilizing scenario approach [5-8]. In this way the uncertainty is modeled as a discrete instead of continues set, enabling generation and evaluation of a very limited set of possible multi-stage planning scenarios.

This paper proposes a procedure for multi-stage distribution expansion planning based on a new pseudo dynamic algorithm, fuzzy mixed integer linear programming model and risk management tools. In the proposed procedure fuzzy sets are used to model uncertainty in future load growth. Such a fuzzy set approach enables a great number of different loading levels, corresponding to certain intervals of future loads, to be considered in the network at each stage. Because one deterministic multi-stage expansion plan could be generated for each possible combination of single-stage loading levels, in the presence of uncertainty a large number of deterministic multi-stage problems are defined. Every multi-stage planning problem is then solved by applying a new pseudo-dynamic algorithm which decomposes a multi-year planning problem into a sequence of single-stage problems. Sequential single-stage planning problems are solved by appropriately formulated (designed) fuzzy mixed integer linear programming model. Considering that all possible loading levels (intervals of future loads) can appear at each stage, overloads (i.e. unsupplied energy due to overloads) may occur in some of obtained multi-stage expansion plans,. These outcomes along with the corresponding possibilities are determined and evaluated (economically quantified) at each stage for every multi-stage expansion plan. Multi-stage expansion plan that minimizes the risk of considerable financial losses (expansion costs), i.e. that ensures optimal balance between capital costs and expected costs of unsupplied energy is selected as the best.

FUNDAMENTAL CONCEPTS

Modeling of Future Load Growth

Uncertainty related to the future load growth is modeled here by introducing fuzzy futures. This concept, illustrated in Fig. 1, reflects the reality that amount of future load growth can be estimated only approximately and that the degree of uncertainty increases with the time horizon the decision-maker considers [5,7]. The proposed concept could be described in the following, linguistic way: “in the next 10 years the load growth is expected to be around 2% per year, no less than 1% per year and no more than 3% per year”. According to this formulation values of future loads are translated into a triangular possibility distribution and described by triangular fuzzy number (TFN) $\tilde{P}$ shown in Fig. 2. This description defines that the load at the given node in each time-stage is expected to be around the mean value P_M, no less than P_L and no more than P_R. Therefore, a number of different values (levels) of demand can occur at each node in each future year and hence different amounts of power that flows over each line in the network may appear.

Now, let us consider an existing line A with the (thermal) capacity P_{max} in the future year (stage) t. The amount of power that flows over the line A in the stage *t* is determined as the sum of all future loads in the nodes supplied over the line. Since the future loads are described as TFN, power flow in line A is also described as TFN ($\tilde{P}_A$) while thermal capacity of this line is presented as deterministic (crisp) value (P_{max}), as shown in Fig. 2.

Necessity of satisfying thermal capacity of the line A, in fuzzy notation is expressed as:

$$\tilde{P}_A \,\tilde{\leq}\, P_{max} \tag{1}$$

This fuzzy constraint can be written in the terms of crisp values (de-fuzzified) in the following way:

$$P_{MA} + \delta \cdot r_{\tilde{P}_A} \leq P_{max} \tag{2}$$

$$P_{MA} - \delta \cdot l_{\tilde{P}_A} \leq P_{max} \tag{3}$$

where δ=1–α while $r_{\tilde{P}_A}$ and $l_{\tilde{P}_A}$ denote the right and left spread of fuzzy number $\tilde{P}_A$ ($l_{\tilde{P}_A} = P_{MA}–P_{LA}$, $r_{\tilde{P}_A} = P_{RA}–P_{MA}$). Expression (2) is related to the right-hand side while expression (3) is related to the left-hand side of the triangular fuzzy number $\tilde{P}_A$. Parameter δ defines loading levels that could appear in the network, as discussed in sequel.

By setting δ=1 in (2) is defined that maximal possible level of loads in all the nodes supplied over the line is considered in the stage t, producing the maximal possible loading of line A. In this case an existing capacity of the line A is not sufficient and it should be upgraded from P_{max} to P'_{max} at the stage t, as shown in Fig. 2. In the case when $\delta=\delta^*$ (see Fig.2), the level of loads in all the nodes supplied over the line A is considered to be such that their sum is not higher than P_{max}. Hence, there is no need for upgrading capacity of the line A in the stage t. However, in this case there is a possibility that line A becomes overloaded if load higher than P_{max} occurs. The possibility of appearing flows higher than P_{max} over the line A is calculated as [9]:

$$S_{\tilde{P}} = \frac{p_r}{p_l + p_r} \cdot 100\ [\%], \tag{4}$$

where p_l and p_r are the areas under the membership function, left and right of the thermal constraint P_{max}, respectively (Fig. 3). So, with the possibility S_P line A will be overloaded, i.e. a fuzzy unsupplied energy due to overloads of line A will appear with the possibility S_P.

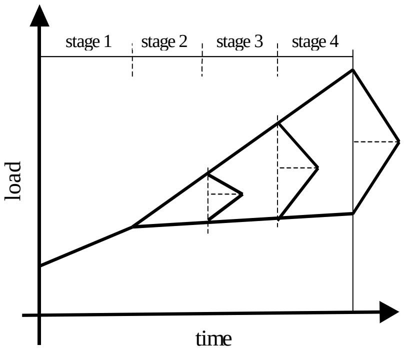

Fig.1. Fuzzy future

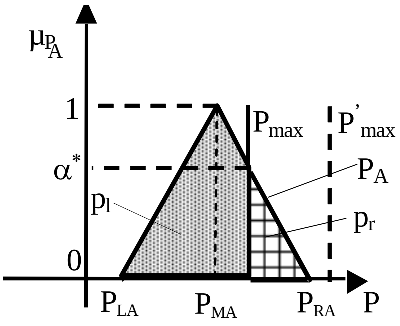

Fig.2. Fuzzy power flow and capacity of the line A

Hence, by changing the value of δ in interval 0 – 1 in (2) and (3) for all the lines in the considered network a great number of different loading levels could be taken into consideration at each stage.

Formulation of Multi-stage Planning Problem in the Presence of Uncertainty

Because each combination of single-stage loading levels defines one multi-stage planning problem, in the presence of uncertainty a number of deterministic multi-stage planning problems exist and should be solved. This number is equal to the number of all possible combinations of loading levels in all considered stages and might be enormously large. Thus, even for small sizes the problem may become computationally intractable. However, granularity of the sizes of elements in distribution networks (lines, transformers) induces that more than one loading level (i.e. the range of loading levels) will correspond to the same expansion plan, i.e. one expansion plan will be optimal for the range of loading levels. According to the proposed concept a single loading level will be considered instead of the range of loading levels. In this way the number of multi-stage planning problems that should be solved is significantly reduced and thus the complexity of the overall problem.

Selection of the best multi-stage expansion plan, among the set of all obtained expansion plans, is not so obvious. Namely, if multi-stage expansion plan that corresponds to the specific combination of loading levels is chosen as the best than certain amount of money could be “lost” if future load growth greater or lower than expected (specified) occurs. In the first case the unsupplied energy due to overloads will appear and produce additional costs while in the second case the elements become oversized and the money is lost due to wasted (oversized) capacity. This implies that the best multi-stage expansion plan should minimize the risk of considerable financial losses in the considered planning period.

The above discussion leads to the following procedure for solving multi-stage planning problems in the presence of uncertainty:

1. By applying fuzzy mixed integer linear programming model single-stage optimal expansion plans will be

determined for all possible loading levels at each of considered stages. Due to the lack of space this model could not be presented here. On the basis of obtained results the range of loading levels that corresponds to the same expansion plan will be determined.

2. Multi-stage planning problem will be defined and solved for every combination of obtained ranges of loading levels by applying a new pseudo dynamic algorithm, presented in the sequel.

3. For each of obtained multi-stage expansion plans the fuzzy costs of unsupplied energy and corresponding possibilities will be determined at each stage in the way presented in [9].

4. Obtained multi-stage expansion plans along with the corresponding outcomes (expected unsupplied energy) will be evaluated and the best one will be selected according to the maximal expected monetary value (max EMV) criterion for measuring risk [9,10].

A New Pseudo Dynamic Algorithm

A new algorithm defines that each multi-stage planning problem is first solved for the horizon stage T, starting from the base (initial) stage. The costs of all possible (proposed) enhancements (reinforcements and/or new constructions) are adjusted to reflect the costs of being realized in the stage T. After that planning problem is solved for the horizon stage, i.e. set of necessary enhancements are determine for the stage T. In the next step the planning problem will be solved for the stage T-1. Enhancements obtained in the previous step are taken into account through appropriately adjusted costs. The costs are adjusted to be equal to the difference between the present worth costs of realizing the enhancements (obtained in the stage T) in the stage T-1 instead in the stage T. The costs of all other proposed (possible) enhancements are adjusted to reflect the costs of being realized in the stage T-1. Based on these adjustments planning problem for the stage T-1 is solved. In the following step planning problem for the stage T-2 will be solved. Here, the costs of enhancements determined in the previous step are adjusted to be equal to the difference between the present worth costs of realizing the obtained enhancements in the stage T-2 instead in the stage T-1. Also, costs of enhancements obtained in the stage T, which are not part (subset) of the set of enhancements obtained in the stage T-1, are adjusted to be equal to the difference between the present worth costs of realizing those enhancements in the stage T-2 instead in the stage T. The costs of all other proposed (possible) enhancements are adjusted to reflect the costs of being realized in the stage T-2. Based on these adjustments planning problem for the stage T-2 is solved. The above described procedure continues until the initial stage is reached.

It should be noted that the proposed pseudo-dynamic algorithm always produces better or at worst the same result as classical backward pull-out approach [11].

APPLICATION

The proposed procedure has been used to solve multi-stage planning problem for the test system shown in the Fig. 3. The three-stage planning period is considered with the duration of two years between the first two stages and four years between second and third stage. The test system consists of one supply node (supply substation), 44 existing branches (solid lines) and 8 possibly new branches (dashed lines). The four size possibilities for constructing and/or upgrading each line are considered. Table I shows assumed unite cost data for each size as well as for all possible upgrade combinations. The conductor sizes are presented in terms of thermal capacity (MVA). In the Fig. 3 capacity of each existing line in the initial (base) year is shown in MVA (bold numbers) while the lengths of all lines are given in kilometers. It is assumed that there is a switch in each line. With empty circles are depicted 36 existing demand nodes while 3 future demand nodes are shown as full circles. Load in node ***40*** is assumed to appear in the first stage and in nodes ***38*** and ***39*** in the second stage. The load growth is assumed to be about 1% per year and no more than 3% per stage in future 3-stage's period. This uncertainty in load growth is translated into triangular fuzzy number (1.01, 1.01, 1.03). Thus, the future load in each consumer node is determined by multiplying the obtained load in the previous stage by this fuzzy number. In this way is taken into account the fact that the degree of uncertainty increases with time. For the final stage, the area is treated fully developed and therefore load growth is not considered for the years beyond. It is assumed that duration of peak loading conditions is 100 h per year and price of undelivered energy is 1 $/kWh. For all capital expenditures the discount rate of 15 % per year has been used.

By applying the proposed procedure 36 multi-stage expansion plans are obtained in the considered period. The results for two characteristic cases are shown in Table II. The first case (Case 1 (C1)) is characteristic because the

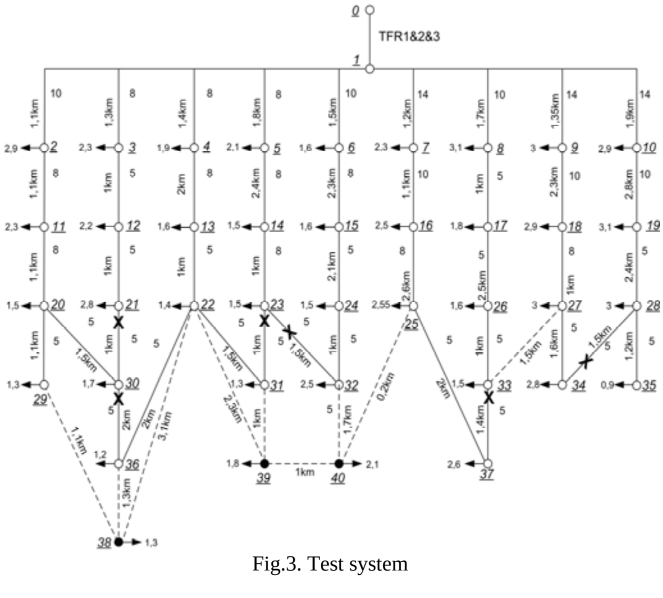

Fig.3. Test system

undelivered energy could not occur whatever future loads appear in demand nodes, i.e. reinforcements and constructions in the network are such that overloads are not possible. The second case (Case2 (C2)) describes the best multi-stage expansion plan obtained according to the Max EMV criterion. In this plan capital cost becomes lower due to accepted overloads but unsupplied energy (due to overloads) produces additional cost. The sum of capital cost and expected cost of energy not served in this plan is minimal among all obtained plans. Hence, if this plan is chosen the decision maker will "loose" minimal amount of many whatever future load growth occurs, i.e. the optimal balance between present worth capital costs and costs of energy not served is established within the plan

CONCLUSIONS

A new optimization procedure for multi stage expansion planning of distribution networks in the presence of uncertainty has been presented. The goal of this procedure is to determine multi-stage expansion plan which minimizes risk of significant expansion costs, i.e. which responds in the most efficient way whatever plausible future occurs. It requires a great number of high quality multi-stage expansion plans to be generated and appropriately evaluated.This is achieved through the application of fuzzy set concept, new pseudo dynamic algorithm, fuzzy mixed integer linear programming model and appropriate possibilistic tools for measuring risk and selecting the best multi-stage expansion plan. The proposed procedure overcomes deficiencies of previous approaches and thus improves planning process in competitive and uncertain environment.

TABLE I. – CONSTRUCTION & UPGRADE COSTS

	Cost [$ x 10^3/km]			
To / From	5	8	10	14
0 [MVA]	**60**	**80**	**100**	**140**
5 [MVA]	-	**72**	**91**	**120**
8 [MVA]	-	-	**85**	**105**
10 [MVA]	-	-	-	**90**

TABLE II. – CHARACTERISTIC SOLUTIONS & BUDGET REQIREMENTS

		Upgrades & Constructions		Present worth costs [$]			
		Case 1	Case 2	Capital		Expected energy not served	
	Link	Size [MVA]	Size [MVA]	C 1	C 2	C 1	C 2
Stage 1	***3*** - ***12***	**8**	**8**	**204045**	**74745**	-	**15123**
	7 - ***16***	**14**	-				
	8 - ***17***	**8**	-				
	25 - ***40***	**5**	-				
Stage 2	***1*** - ***2***	**14**	**14**	**239279**	**335419**	-	**5930,3**
	1 - ***5***	-	**10**				
	7 - ***16***	-	**14**				
	8 - ***17***	-	**8**				
	2 - ***11***	**14**	-				
	22 - ***39***	**5**	-				
	29 - ***38***	**5**	-				
	31 - ***39***	-	**5**				
	36 - ***38***	-	**5**				
Stage 3	***2*** - ***11***	-	**14**	-	**1744,4**	-	**13,45**

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