DISTRIBUTION EXPANSION PROBLEM REVISITED.

PART 1

CATEGORICAL ANALYSIS AND FUTURE DIRECTIONS

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Abstract

In this paper, previous contributions of the past 40 years in the area of distribution expansion planning are categorically analyzed. The primary focus would be the multistage formulations. Shortcomings form a practical point of view, for the techniques and solutions in each category are identified and discussed. Significant shortcomings are summarized and tabulated to serve as goals for future research.

Key words: Power system planning, Distribution expansion, shortcomings, future directions.

Introduction

While growth of electric energy demand has recently slowed, there will continue to be a need to expand facilities for the foreseeable future. Various plans to timely meet this demand growth, are continually studied for all major components of the electrical systems namely, generation, transmission, and finally distribution. In general, the primary goal in any system expansion is to timely meet the growth of demand in the most economical, reliable, and safe manner possible. Of course, safety and reliability introduce certain operational regulations and constraints that are different in distribution systems than other systems, and therefore must be considered in the expansion plans.

This general description of the expansion problems is somewhat independent of many other issues facing the both the suppliers and the users of electrical energy. For example, consider the deregulation issue, which is an attempt to promote better competition among the suppliers by giving more choices to the users. Although deregulation will impact the supplies' planning strategies, it cannot however, contain or limit the growth in demand or the system expansion in the global sense.

To correctly formulate any problem, a precise problem definition is necessary. In fact, solution set for the problem is greatly reduced and the search algorithm to find it is more intelligently directed once the problem is clearly understood. Design criteria, and assumption statements are equally important element of a good formulation. Once the problem is clearly defined, design criteria has been set, and proper assumptions made, then a choice of an appropriate model, and application to a solution procedure would be in order.

The first paper about distribution planning optimization is attributed to [1] in 1960. Since this paper, there have been numerous publications in this area. References [2-56] are some selected examples of the significant published contributions. We begin with a systematic categorization and identification of common terminology among all previous research. Then, the shortcomings are identified and analyzed which subsequently narrows the focus to a smaller class for consideration. For the sake of completeness, we find it necessary to categorize the previous work along two lines. The first will be based on the optimization methods used, and the second will be based the application for example, the different approaches in problem identification and objectives. Some subdivision in each class will be done as needed to narrow the focus to the particular area of interest.

I - Categorization based on Optimization Methods

In so far as the distribution system expansion is concerned, optimization methods used may be divided in to two distinct categories.

1 – Mathematical programming methods
2 – Heuristic methods, including expert systems and evolutionary algorithms

It is interesting to note that nearly all of the earlier research (1970s and 1980s) utilized mathematical programming algorithms, where as, almost all of the more recent work has been centered around the heuristic techniques, predominantly the Genetic Algorithms (GA) [13-26].

Mathematical Programming Algorithms

Numerical optimization techniques such as linear programming in general, have been proven to converge to the global optimum as opposed to just an acceptable answer as noted form [40, 55]. On the other hand, the mathematical complexities for modeling and decomposition of the real life problems to fit the mathematical models, as well as computational difficulties, makes these techniques very challenging.

Mathematical optimization techniques may be divided into continuous and discrete types. Although the continuous techniques have far less computational complexity, the distribution expansion problem is inherently discrete. For this reason, the overwhelming majority of the past research has utilized the discrete optimization techniques. Nevertheless, there has been some research to model using continuous techniques. [10, 12, 29-30, 37-38]. A few other researchers realizing the inherent speed of the continuous algorithms, proposed hybrid approaches to solve the problem. First using a continuous algorithm, followed by a hybrid technique to discretize the continuous variables [38-39]. Typically, these techniques, render the solution sub optimal as correctly noted by S. Hindi [54]. Since we have opted for a mathematical programming approach for our research, further discussions and analyses on some specific shortcomings of the previous research are differed to subsequent sections.

Heuristic methods:

Evolutionary techniques in general, are stochastic searches modeled similar to some of the well-known natural or evolutionary concepts. In Genetic Algorithms (GA) for example, a solution to a problem evolves from an initial point, similar to the evolution of the DNA strings. Various decisions based on a given design criteria, are usually modeled as a binary string where each position on the string represents a particular decision. Decisions involving more than two choices are represented by several bits in the string [40]. The algorithm begins with a user provided or randomly generated population of candidate solutions. A feasibility evaluation is performed for each individual in the population. From those individuals performing best, the algorithm performs crossover (combining the strings of two parents) and mutation (random changes in the status of one or more bits in the string). The process continues its search and is stopped by a predetermined stopping rule while concluding that; no better solution is likely to be found [40]. It should be realized that, in general, there is no guarantee that GA will find a global optimal solution [40, 57], but experience has shown that the technique often finds reasonable solutions. In this work, we do not fully investigate all the various techniques in this area. A more detailed comparative analysis has been conducted by Willis et. al in [40]. Considering the following table taken from [40], the primary advantage of GAs relative to the mathematical programming was ease of use.

In other examples [24-26], the authors emphasized the superiority of a risk-based analysis over a stochastic analysis when dealing with system uncertainties. In [21] design criteria are developed for an optimized use of protective and switching devices after the routings for the system have been established. The proposed method integrates reliability and the cost minimization objectives into a single criterion. Publication [22] refers to a knowledge based procedure aimed to minimize the engineering costs in long range planning of rural networks where as the distribution expansion problem primarily refers to high growth urban areas. In [23], the discussion is about the general application of the evolutionary technology conceptually. In [50], a two step heuristic method is proposed in which single stage cost optimizations are preformed for each year. Then a fast heuristic dynamic programming routine is used for installation of capacitors and regulators. The results however, indicate that installation of a regulator could differ installation of a substation for five years using the procedure. It is doubtful that under the correct planning assumptions and data, a regulator may differ addition of a substation capacity for that long of a period.

II – Categorization by Approaches to the Expansion Problem

The overall approach of previous research to distribution system expansion may be divided into two distinct categories, single stage (single period or static), and multi-stage (or dynamic). Single stage refers to the case where the full expansion requirements for the area are determined in one period. Multi stage on the other hand refers to determination of the requirements in successive expansion plans over several stages, representing the natural course of progression.

Multi stage approach, due to the inter dependency between stages, is far more challenging to formulate but the solution offers a more useful result. Still, the vast majority of the development (64 out of 81 publications) has addressed the problem by a single stage approach.

The efforts to date also differ relative to desired solution variables. This includes substation location [27-36], feeder routing [41-45], and conductor sizing [37, 46-47]. There are various proposed methods for decomposing the problem into appropriate sub problems [2, 7-8, 48-52]. For example, the geographical planing area may be divided into grids with some load density (usually uniform) [22, 27, 34-36, 49-52]. The optimization problem is formulated to search for the best assignment of each grid block to the various substations (existing substations or future candidate substations). The objective for this class of problems centers around the fact that it is usually more economical to serve any load center form a substation which is geographically closest to that load center. This also tends to reduce the system losses. An example of a properly formulated case in this class is [49]. Note that the proper formulation in this class will only have a practical incentive for solution if the following facts have been considered.

Optimization Method savings(%)	Capacity	Solution Nodes	Ease of Use	Avg. Time(sec)
Numerical (non transshipment)				
Nonlinear	5,000	2,100	4	5-10
Linear	8,000	525	6	9
Numerical (non transshipment)				
Nonlinear	6,000	250	8	6-10
Linear	4,000	50	10	9
Numerical (non transshipment)				
Nonlinear	6,000	300	10	6-11
Linear	10,000	65	10	9

Table 1. Relative performance of distribution optimization methods

1 – The substation locations are chosen form a specific candidate set.
2 – Not all candidate location sites need be developed for the ultimate area growth.

A similar formulation extended the problem to include substation-siting [27]. Due to the independence from requiring candidate locations, this approach is conceptually superior. Unfortunately, from a practical point of view, it is of little, if any interest. In practice as correctly done in [34-36, 49], substation location is determined by a variety of factors among which, load density is just one. For example, consider the following moderate distribution planning area having three sub transmission corridors as shown in Fig. 1

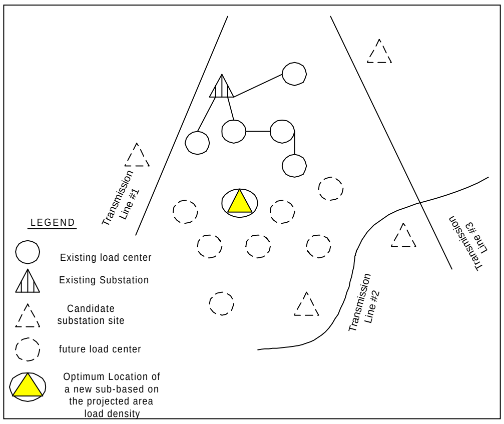

Fig. 1-Example of a developing area.

One existing substation and four possible future candidate sites have been shown. Notice that each of the candidate sites has an easy access to one of the transmission lines. Considering proper planning, the sites may have been purchased long before the load growth and before the eventual escalation of land prices. Depending on the direction and density of the ultimate load growth, two to four of the candidate locations may be developed. Now let us assume that an optimization algorithm has determined the optimum location for one of the substations to be as shown (which would be in the center of the area with highest density). This site due to its distance from the nearest transmission corridor, is already impractical, and most often the single cost of acquiring transmission right of way or easement is enough to make the plan economically unfeasible.

Another possible classification seen in the more recent literature focuses on reliability objectives. The number of the customers, who demand a more reliable service form their suppliers, has been increasing. Consequently, the suppliers must pay more attention to this issue. Several studies addressed the impacts of unreliable service, including attempts to quantify the cost of reliability as seen by the suppliers as well as their customers [2, 21, 44] this is typically represented by the reliability vs. combined cost curve of Fig. 2

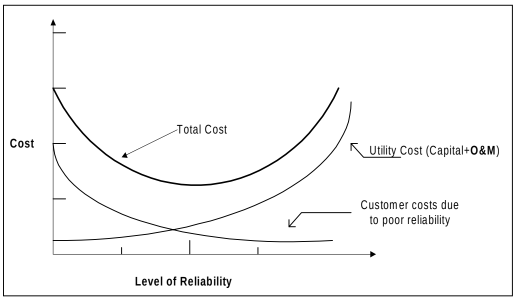

Fig. 2- Combined costs vs. Reliability

Although these efforts have better illuminated the significance of reliability and have quantified some of the penalties incurred, the combined cost vs. reliability curve is still a crude estimate. Furthermore, comparison of this approximate cost against the fairly precise installation and maintenance costs of the switching and the protection apparatus is far from accurate for the following specific reasons.

Firstly, the cost of reliability is not only an estimated cost, but also, it only considers one component of the service reliability, namely the service continuity. Even at that, as noted by some others [56], more accurate determination requires more accurate data form both the supplier and the customer sides, which is presently unavailable.

As a simple example for clarification, consider two similar outages of equal duration in two areas with similar load compositions. Further suppose that the customers (lets say just the residential customers) in one the areas are more sensitive to interruptions. Then, for the outage in this area there may be complaints and lawsuits for food spoilage, or loss of production, which could have a potential high cost to the supplier. The other similar outage in a less sensitive area could have no additional costs to the supplier other than loss of usually metered energy. It is unlikely that such issues have yet been investigated or considered in quantification of the reliability values. It is even more unlikely, that any credible data for an estimate could be found.

Secondly, there is more than one dimension to the service reliability than just the service continuity. At least one other component of reliability can easily be attributed to service quality. For example, an extended low voltage condition could bear much higher costs for both parties in terms of say motor damage, than an outage condition of the same duration. Again the cost assignments for the service quality facet of reliability, similar to the one for service continuity can only be a rough approximation at this time although there may be more ongoing sophisticated analyses such as the one suggested by [53].

Based on the above rational, inclusion of any components of reliability such as service continuity should be formulated as a separate objective for the analysis. Except for [8, 57] who first proposed inclusion of reliability into a multi objective problem, other researches similar to [2, 50] have integrated the costs of reliability along with the fixed and variable costs of the expansion alternatives into a single criterion optimization model.

This is one of the significant issues noted in the previous contributions, which needs modification. We propose to include service continuity concerns as a separate objective function in an overall multi objective decision making process after a truly multi stage single objective optimization formulation is developed.

III Multi stage expansion planning:

Aligned with the direction of our research, we narrow our focus to the relatively few multi stage approaches to the expansion problem that used mathematical programming algorithms [2-13].

Adams and Laughton [11] first proposed a decomposition method to extend their static formulation for a multistage. The formulation however, was not fully implemented. Gönen and Foot [3] published the first fully implemented multi stage formulation of the distribution expansion as a single objective optimization problem. The solution relies on Mixed Integer Linear Programming (MILP) technique. Due to the inclusion of numerous decision variables including for example number of feeder bays and number of feeders per transformer, the approach is limited to small size problems. These variables are unnecessary due to standardization within the industry. For example, a standard 12 KV substation usually contains 3 – 90 MVA Transformers and 12 feeders (four feeder bay per transformer). Or a 2 – 45 MVA transformer, six feeder bay design is the accepted 21 KV configuration. The formulation addresses neither the voltage drop nor the reliability issues.

The methodology presented by D. I. Sun [4], and later by Remirez/Gönen [6], is what can be best described as a pseudo dynamic algorithm. In this type of algorithm, the ultimate expansion stage (or horizon stage) is considered first. A single stage (Static) optimization is formulated and the optimum expansion profile generated. This procedure identifies the set of expansion elements (substations and feeders) to be used for the entire planing period. Then a series of concatenated single stage optimization algorithms are employed for the intermediate stages as required by the load growth. The optimization algorithm for the intermediate stages are so formulated to only select elements form the solution set provided by the first horizon stage algorithm.

The procedure discussed in [4] is very similar to the static models of [54], and [33], which utilize the fixed charge Transportation model for the MILP solution search. It does not consider the voltage constraints nor does it address the reliability concerns.

A more general MILP formulation of [4] was later developed by the authors to include voltage drop constraints, but not reliability [5]. Formulation of the voltage drop constraints is somewhat complicated and cumbersome to implement. Six different types of constraints must be considered, some of which require additional slack variables. As explained above neither formulation can be considered a true multi stage solution. Perhaps most importantly, the procedure as to the dynamic nature of the multi stage objective function had been implemented within the linear programming algorithm, was not presented in [3, 8, or 5].

Similarly in [2, 7, and 8], the algorithms proposed are comprised of a set of static algorithms used by different parent algorithms to achieve the multi stage objectives.

El-Kady, presented a sparsity based MILP formulation in [9]. Explicit voltage drop constraints were implemented, but require lineariztion and use of a Step-Wise feeder Flow-Impedance characteristic for the feeder links. This procedure requires a significant number of additional integer variables, and does not consider reliability.

Nara et. al [7] proposed a coordinated decomposition algorithm based on Branch Exchange. This technique, in which the different options for the feeder links are exchanged in search of better solutions, requires and relies on explicit inclusion the radiality constraint which may be effectively managed implicitly as noted by [54, and 10]. Although it is clear from the publication that the radiality constraint works well for the horizon stage, it was unclear for the intermediate stages. The proposed formulation also uses a complex forward/backward algorithm. The authors attribute the need for this complex procedure to the fact that there may be possibilities for better expansion profiles if the procedure is calculated form a different initial condition. The formulation does not consider feeder losses or reliability.

Kagen and Adams [8] proposed Benders decomposition technique in a master integer program (IP) which derives a series of continuous sub problems solved by linear programming (LP). The first LP sub problem is solved using a primal simplex algorithm and the successive ones are determined by sensitivity analysis in the interest of efficiency. The authors have correctly addressed the reliability issue in a multi objective formulation, and have considered system losses using a piece wise linear model in their formulation.

In [2] a multi stage decomposition algorithm is introduced that subdivides the problem into several single stage optimization sub problems. The sub problem solutions are coordinate through an interlacing strategy. The non-linear, single criterion objective function, which includes the combined costs for reliability, but is iteratively linearized by a variable coefficient, labeled as dynamic cost coefficient. As noted by R. Billinton in [2] the procedure may render a sub optimal solution. A more significant problem with the approach as mentioned earlier, is comparison of the crudely estimated outage costs against the fairly accurate installation costs of switching devices in a single objective optimization formulation.

Blanchard et al. in [13] proposed a multistage model solved by a heuristic method in five phases. The mathematical model is a quadratic mixed integer programming, and uses a solution strategy based on the pseudo dynamic algorithms used by Sun in [4], and Gönen in [6]. The algorithm does not consider any existing facilities and the authors did not see a need for implementation of voltage drop or reliability constraints.
The authors advocated acceptability of a compromise solution between the quality (near optimality) and the CPU calculation time, which is similar to the arguments found in the evolutionary technique approaches. The studied example problem considered four substations but relatively few, only eight some in excess of 58 MVA, bulk load centers, which is not considered a typical distribution system.
A fundamental question may be whether or not these multistage approaches can find the global optimum. The answer for the heuristic techniques is uncertain as discussed earlier. As for the decomposition techniques, the question can only be answered with certainty if an approach that guarantees global optimality is developed and the solutions compared. This is rarely practical.

			Past							Future					
		NOP	SSSB	MS	VOL	LOSS	REL	MO	MSUGO	MSGGO	BUDG	SEI	MRMS	UPOSS	MSMO
Single Stage	Math Prog.	4			X										
		6			X	X									
		4					X								
		1		X	X										
		8	X												
		1			X		X	X							
		1		X	X	X									
	Heuristic	1			X		X	X							
		2					X								
		1			X										
		1	X												
		1			X	X									
Multi Stage	Math Prog.	3							X						
		1	X						X						
		2					X		X						
		1			X	X			X						
		1			X		X	X	X						
	Heuristic	1							X						
		1			X	X			X						
		1					X		X						
	This work	Phase 1		X	X	X				X	X		X		
		Phase 2		X	X	X				X	X		X	X	
		Phase 3		X	X	X	X	X		X	X	X	X	X	X

KEY:

NOP:	Number of Publications	BUDG:	Budget Considerations
UPOSS:	Upgrade Possibility	MS:	Multiple conductor Size
MRMS:	Multiple Routs Multiple Size per Rout	VOL:	Voltage Drop Constraints
MSUGO:	Multi Stage, Uncertain Global Optimality	REL:	Reliability Considerations
MSGGO:	Multi Stage, Guarantied Global Optimality	SEI:	Social /Evironmental Impacts
MO:	Multi Objective	SSSB:	Substation Siting, Service Boundary
LOSS:	Distribution System Losses	MSMO:	Multi Stage Multi Objective

Table 2 summarizes the results of this categorical analysis with respect to the necessary issues (in addition to the commonly considered supply/demand issue) that must be considered in distribution planning.

Summary of the significant shortcomings

The following significant problems were noted in the extant literature of the previous research.

1 – The literature reveals some confusion and lack of understanding about the distribution expansion problem objectives from a practical point of view.
2 - Voltage constraints are completely ignored in some cases and inappropriately applied in some others.
3 - Reliability issue is either completely ignored (in the overwhelming majority of the previous work), or incorrectly quantified monetarily and integrated with other costs in a single objective formulation.
4 - Budgetary constraints, which are faced by all utilities, is missing from all formulations.
5 - Variable routing and conductor size options between nodes have not been properly addressed.
6 - A true multi stage approach that guarantees global optimality has not yet been developed.
7 - Upgrade possibilities, which must be considered in distribution expansion planning, have been completely ignored. Inclusion of this issue introduces a considerable challenge in formulation and implementation of a multi stage approach.

Conclusions

A categorical analysis of the past 40 years of research indicates that even though many advances have been made towards the solution of distribution expansion problem, there still remain many areas for future research. Implementation of multiple routing and size options, inclusion of upgrade possibilities, and treatment of reliability and other objectives are major areas in need of future development regardless of the techniques. A clear definition of the distribution expansion problem from a practical point of view in a truly multi stage formulation that guarantees global optimality are the primary goals of this research.

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