Power Distribution Planning: A Review of Models and Issues

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Abstract--**Power distribution planning is a complex task in which planners must ensure that there is adequate substation capacity (transformer capacity) and feeder capacity (distribution capacity) to meet the load demands. Decisions such as allocation of power flow, installation of feeders and substations, and procurement of transformers are costly ones which must be evaluated carefully. This paper provides a review of research problems as well as models related to the planning of substations and/or distribution feeders. Following a general discussion, we review existing research work under two major groups: planning under normal conditions, and planning for emergency. A discussion on relevant research opportunities is included.**

I. INTRODUCTION

The cost of power distribution constitutes a significant portion of the overall cost (Chapter 1, Gonen, 1986) and a systematic approach to distribution planning can substantially decrease the amount of cost incurred. The purpose of this paper is to provide a comprehensive review of research articles related to the planning of substation and/or distribution feeders, along with a systematic classification of approaches as well as issues. We believe our current effort extends the works of Gonen and Mahmoud (1983) and Gonen and Ramirez-Rosado (1986), and should be of major value to engineers as well as researchers in this important field.

A power distribution network consists of a number of substations connected to each other via feeders, an electric conductor carrying power from a substation to meet load demands along its route. Distribution planners must ensure that there is adequate substation capacity (transformer capacity) and feeder capacity (distribution capacity) to meet the load forecasts within the planning horizon. Alternatives such as procuring transformers, building new feeders and new substations need be evaluated carefully. In general, the decisions in the planning of power distribution system include:

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- Optimal location of substations
- Optimal location of feeders
- Optimal individual feeder design
- Optimal allocation of load
- Optimal allocation of substation capacity
- Optimal mix of transformers by substation

The relevant factors in the decision environment include:

- Kirchhoff's current law
- Kirchhoff's voltage law
- Concave variable cost in feeders
- Radiality of feeders
- Voltage drop on feeders
- Substation normal capacity
- Substation distribution capacity
- Substation emergency capacity
- Feeder emergency capacity

Many earlier models examined planning under normal conditions. Here the issue of contingency planning was ignored where substation and/or feeder failures were not considered or their safety capacity were implicitly factored into the analysis. More recently, there appeared planning models which explicitly formulated contingency issues. In the following sections, we organize the research articles into two major groups:

- **Planning under normal conditions**
- **Planning for emergency**

We will review the articles with respect to the following attributes.

- Nature of the problems being addressed
- Models and the corresponding decisions
- Objective and constraints
- Quality of the decisions

Parenthetically, only published articles will be reviewed (conference presentations will not be included). Further, historical seminal works which laid the foundation for many recent works will also be reviewed for completeness, see also Gonen and Ramirez-Rosado (1986).

II. DISTRIBUTION PLANNING: NORMAL CONDITIONS

Due to the network nature of distribution planning, the models are predominantly mathematical programming formulations: linear programming, 0-1 linear programming, and non-linear programming. Since the dimension of a typical real-life problem is large, it becomes unrealistic to solve these models (except LP) within a reasonable time. As such, there exist quite a of number of heuristic based approaches and more recently AI approaches. In this section, articles are organized according to their approaches towards solutions: optimization models, heuristic and algorithms, and AI/Expert-System approaches.

II.1 Optimization Models

Under optimization models, we have two further classifications: single-period models and multi-period models.

II.1.1 Single-period Models

Single-period models are static models which assume that the load demand would not change during the horizon. They do not look at the load growth factor and there is no need to relate installations of substations and feeders in one year to the next. In general, such optimization models can be categorized into four subgroups: individual feeder models, system-feeders models, two-phase substation-then-feeder model, and substation-feeder models.

• ***Individual Feeders Models.*** This class of problem deals with the design of individual feeders. Ponnavaikko and Rao (1981) optimized the configuration of each individual feeder by deciding on the length, conductor size, and gradation, and by addressing the economic tradeoff between capital and operating costs. Mikic (1986) provided further details of the cost tradeoff.

• ***System Feeders Models.*** Given a network of substations with demand points and supply points, the objective is to determine the best way to connect the substations such that the demand are met at minimum cost. The models, in general, take on the following mixed 0-1 LP form:

$$[\mathit{Min:}\ c_f x + c_v p,\ \mathit{st.}\ Ap = d,\ p \le Mx,\ x \in (0,1),\ p \ge 0]$$

where x is the decision vector for individual connections and p the quantity of flow; c_f is the fixed charge of the connection and c_v the variable cost per unit power flow; A is the flow matrix, d the demand/supply vector, and M the capacity of the connection.

Adams and Laughton (1974) was one of the earlier works which developed the above formulation. There were two cost components: the fixed cost and the variable cost of power flow for a particular connection. Linearization of the concave variable cost c_v was also shown. Although extensions to multi-period model were suggested, the model largely remained a single-period one. General branch and bound techniques were suggested as plausible solution approaches. The example problems were solved using MPSX software.

Using the transportation model framework, Crawford and Holt (1975) provided a procedure, based on analysis of loads and feeders on a grid basis, to determine the optimal substation service boundary. The procedure might be used empirically to identify desirable substation locations and their sizes.

Wall, Thompson, and Northcote-Green (1979) presented an efficient solution procedure for the distribution flow problem (capacitated transshipment model). The initial configuration of the potential network (based on load demand points), an input to the transshipment model, was also discussed.

• ***Two phase Models.*** Masud (1974) provided a two-phase method for power distribution planning. The first phase (0-1 LP model) determined the substation decisions, with consideration on re-distribution of load. The second phase used a transportation model, with substation capacity from the first phase, to determine the optimal power flow for the feeders. In general, the two phases can be described as follow:

First phase: $[\mathit{Min:}\ c_F y\ ;\ \mathit{s.t.}\ Ry \ge l,\ e\,y = 1,\ y \in (0,1)\ ]$

Second phase: $[\mathit{Min:}\ c_v p\ ;\ \mathit{s.t.}\ Sp = R^*,\ Dp = l,\ p \ge 0\ ]$

where c_F is the substation fixed cost, y is substation decision, R is the capacity choice matrix, l the load vector, e unit row vector, S is the supply flow, D the demand flow, and R^* the resulted capacity vector from phase one.

Fawzi and El-Sobki (1983) adopted a similar model while incorporating non-linear variable power cost and voltage drop. A branch and bound algorithm was used to first decide on the substations (with approximate feeders considerations). This solution then became part of an iterative procedure to determine the optimal feeders configuration.

• ***Substation-Feeder Models.*** This class of problem simultaneously determined the decisions of substation and feeder installation, the feeder flow, and substation load. Added to the system feeder formulation were 0-1 variables (new substation installations) along with the variable cost component based on the sum power flow for the individual substations. The formulation has the following form:

$$[Min:\ c_F y + c_V P + c_f x + c_v p;\quad s.t.\ Ap = d,\ p \leq Mx,\ P = Ep,\ P \leq Ry,\ x,y \in (0,1),\ p \geq 0\ ]$$

where c_V the substation variable cost, P the sum flow to individual substations, and E the flow matrix for substations. As one of the first works which proposed the above fixed charge transshipment formulation, Hindi and Brameller (1977) also provided detailed discussions on the dynamics of the power flow along with some computational experience.

Thompson and Wall (1981) presented a branch-and-bound algorithm for this problem. Two major bounding criteria of the algorithm were: 1) minimum incremental cost bound, and 2) shortest path customer assignment. The former assumed the fixed costs of all potential substations to be zeros and the power flow problem was solved thus giving the lowest incremental cost of power flow. This incremental cost plus the actual fixed cost of the potential substation provided a lower bound cost. For the latter, the flow problem to a specific demand point from a specific potential substation was solved with all existing substations open and all other potential substations closed. This gave the marginal cost of a particular flow. Enumerating all other potential sources resulted in the lower bound cost of serving a particular demand point.

- ***Discussion***. Willis and Northcote-Green (1985) tested the efficacy of some of the above models based on their 1) overall benefit to planning, 2) capacity to handle large program analysis, 3) sensitivity to load forecasting error, and 4) actual level of improvement. Four sets of simulated tests were used. For overall benefit and error sensitivity, the substation-feeder models were found to be more superior. In an earlier review by Gonen and Ramirez-Rosado (1986), an excellent summary (in table form) of the above models in terms of: issues, solution technique, and computational features was provided, and will not be repeated here. Readers are referred to their fine work for such a summary. Further, they identified the lack of explicit modeling of voltage drop and radiality considerations. Their review also discussed some earlier works in multi-period planning, which is discussed next.

II.1.2 Multi-period Models

Although multi-period problems may be solved as a series of single-period ones thus treating each incremental period as an expansion situation, the resulting solution will not be an overall optimum as current solutions are not influenced by future decisions during the optimization process. Moreover, extending single-period models by the mere time-subscripting of time-dynamic variables and parameters is not adequate. In multi-period problems, explicit modeling of correlated time-dynamic decisions must be formulated. These decisions include: only one installation at a location, conjunctive or mutually exclusive installations, and radiality consideration over time. Using 0-1 variables, these considerations can be modeled as logical constraints. The general formulation can be described as follows:

$$[Min:\ \Sigma_t \{ c_{Ft} y_t + c_{Vt} P_t + c_{ft} x_t + c_{vt} p_t \};\quad s.t.\ A_t p_t = d_t,\ p_t \leq M_t x_t,\ P_t = E_t p_t,\ P_t \leq R_t y_t,\ e_t y_t \leq 1,\ e_t x_t \leq 1,\ G_t x_t + F_t y_t = 0,\ x_t, y_t \in (0,1),\ p_t \geq 0, \forall\ t = 1,\ldots,n\ ]$$

where all cost factors are in terms of present value, n is the planning horizon, constraint sets $e_t\, y_t \leq 1$ & $e_t\, x_t \leq 1$ ensures one installation per site, and $G_t x_t + F_t y_t = 0$ *(G & F are logic matrices)* represent additional correlated time-dynamic installation logic which are usually situation-specific.

The above multi-period model (with some variations) was given in the seminal work of Gonen and Foote (1981) in the form of a comprehensive mixed 0-1 LP which optimally determined: substation locations, substation transformer sizes, additions of incremental capacity, load transfers, and feeder routes and sizes. Detailed procedure on the linearization of the variable concave cost function, using 0-1 and continuous variables, was also included. There were a large number of logical constraints. The example problem was solved using MPSX software.

Sun, et al. (1982) utilized the fixed-charge-transshipment framework of earlier single-period models to develop a procedure to solve the multi-period distribution problem. Their procedure consisted of two phases. The first phase was essentially a static base problem where decisions for substations and flows were first determined. Based on this initial configuration, new inputs (growth and new demand locations) for the next period was incorporated to determine the optimal installation and flow of that period. In turn, the base configuration plus the added configuration then became the basis for the following year's decision and so on until the end of the planning horizon. This procedure would not guarantee an overall optimal solution since current decisions were not related to future ones.

El-Kady (1984) explicitly included time-dependent fixed and variable charges as well as time-dependent cost of losses. Relationships of future installations were modeled using 0-1 variables where fixed installation costs were incurred only once, while variable costs would be accounted for throughout the equipment's life. Additionally, voltage drop in feeders were characterized as a step-wise functions of power flow. The overall problem was partitioned in to smaller problems where the problem size became more manageable.

Gonen and Ramirez-Rosado (1986) pursued the model framework of Gonen and Foote (1981) and provided more explicit considerations. Notable additions were the present value expressions of fixed and variable costs, and the explicit modeling of voltage drop and radiality constraints.

Ramirez-Rosado and Gonen (1991) adopted the two-phase approach of Sun, et al. (1982) while incorporating more planning details. Considerations included Kirchhoff's current law constraints and voltage drop. The importance of voltage drop consideration was high-lighted with real-life examples.

II.2 Heuristic and Algorithms

For many real-life distribution planning problems, the mixed 0-1 LP programming formulation can be computationally unmanageable as the number of variables and constraints can be significantly large. In fact, when using branch-and-bound to solve the 0-1 LP (as suggested in the earlier single-period models), the user may stop the solution process if a certain feasible as well as acceptable solution (although suboptimal) has been reached. Another alternative is to simplify the problem by relaxing certain assumptions such that it may be computationally manageable. However, there is no guarantee that the optimal solution to the simplified or relaxed problem will be optimal to the original problem. The two-phase approach of Sun, et al. (1982) and the pseudodynamic planning approach of Ramirez-Rosado and Gonen (1991) are both simplifying approaches to reduce the dynamic problem into a static one, thus allowing the problems to be solved more efficiently at the expense of getting an optimal solution. Dividing the entire problem into several subproblems as shown in El-Kady (1984) was yet another example. In this section, we review several other heuristics and algorithms.

Aoki, et al. (1990) proposed a "branch-exchange" algorithm for an approximate optimal solution for single-period distribution planning. It worked as follows:

- Start with a feasible configuration, add a route to form a loop.
- Then, to gain feasibility, a route (with either high installation cost or constraint violation) is removed. If this exchange resulted in an improvement, retain the exchange; otherwise, abandon the exchange.
- Repeat this procedure iteratively until the objective function cannot be improved any further.

The determination of the most sensitive exchange was selected from the information provided by the simplex tableau.

Nara, et al. (1991) extended the single-period branch-exchange approximation algorithm of Aoki, et al. (1990) to a multi-period approximation algorithm. The algorithm worked as follows:

- ***Forward Path.*** At period t, using the branch-exchange method, the approximate optimal expansion plan for $t=t+1$ was determined. This one-period expansion plan determination was termed the "Forward Path."
- ***Backward Path.*** Unlike the two-phase method which proceeds period-by-period into the future, the proposed algorithm would do a "Backward Path" after each "Forward Path." The "Backward Path" was to return to the preceding period to see if the expansion plan P_0, found up to that period, was indeed the best that could be achieved via branch-exchange. This was done by removing, one preceding period at a time, the period's facility which were not utilized and by performing branch-exchange on the resulting configuration.
- ***Backward/Forward Path.*** If at any period, the plan from "Backward Path" was not an improvement, the backward process would stop and the forward process would resume with the previous "Forward Path" plan (P_0). If the backward process was able to reach the starting period (resulting in a plan P_1), then the algorithm would restart at $t=1$ with the new *period-1* plan as the basis for the next "Forward Path;" the subsequently developed plan P_2 would be compared to the previously determined backward plan P_1, with the better plan to replace P_0 for the next "Forward Path" at $t=t+2$.

Further extending on their previous work, Nara, et al. (1992) provided a "multi-stage" branch-exchange algorithm. Basically, the proposed algorithm attempted to move away from the local optimum found by the single-stage model by forcing further branch-exchanges with more refined branch-selection criteria. Although termed "multi-stage," the algorithm did not address any time-dynamic issues; it was multi-staged in the sense that several series of branch-exchange were pursued.

Quintana, Temraz, and Hipel (1993) divided the planning problem into two stages: clustering and forecasting, and planning. In stage 1, the problem of load growth was solved in two phases. The first phase divided the service area into smaller subareas with the demand points in each subarea summed to form a single demand node; the second phase assessed the demand forecast per demand node. In stage 2, the planning problem was again divided into two phases. The first phase problem was to determine the overall installations required (without knowing when to install) by solving the problem of meeting projected demand at the horizon year. In the second phase, for each intermediate year between the base and the horizon year, determine an optimal intermediate system using only the equipment set from the static optimum problem. This would determine the schedule of the installations and the year-to-year expansion plan. The optimization model of the sub-problem was a constrained non-linear formulation and was solved using a non-linear optimization software.

II.3 AI/Expert Systems Approaches

Development of expert systems for distribution planning have been reported based on PROLOG, an artificial-intelligent programming language. Wong and Cheung (1987) listed several AI/Expert system for various power-system applications. They presented a set theory based formulation for load allocation in distribution substation. The system was implemented on a PC using PROLOG. The expert system first generates all hypothetical solutions. An evaluator routine then discards the invalid solutions and finally a tester selects the best solution which honors the busbar section as well as overall constraints.

Chen and Hsu (1989) developed a rule-based expert system for the load re-allocation in the case of distribution expansion planning. The authors proposed two algorithms, one to minimize power loss and the other to minimize investment cost. These algorithms formed the basis for the inference engine. The system was implemented on a PC using PROLOG language. The heuristic rules used by the planners were also incorporated in the expert system. The software was also able to calculate the system reliability of a developed plan. The system was used to assist the planners in the expansion of a three station, twenty-eight feeder network west of Taipei.

Hsu and Chen (1990) later designed an expert system for determining substation locations and feeder configuration of a distribution system. The substation locations were determined using an operations research based "location-allocation method." The method was used to minimize the feeder losses and support the inference engine. Real life physical constraints on substation locations, feeders, and right of way were included during the distribution planning.

Brauner and Zobel (1994) divided computer based engineering methods developed over the last three decades in three phases. They characterized the knowledge-based methods as the beginning of the third phase. These methods complement the pure algorithmic methods without being part of the algorithm. The knowledge-based systems provide the flexibility needed for analyzing today's complex distribution networks. The authors also discuss an architecture and components of a knowledge-based programming systems.

III. DISTRIBUTION PLANNING FOR EMERGENCY

In the preceding models, the issue of equipment failure was not addressed. Although not a common phenomenon, transformers and feeders do fail and the cost of power outage can be very significant. However, to account for equipment failure by merely factoring in a safety capacity is not adequate due to the synergistic nature of power distribution. During emergency, sections of a feeder can be switched to feeders of adjacent substations thus allowing the load of the emergency substation (transformer failure) or that of the emergency feeder to be shared. This special feature implies that a substation's capacity is not an absolute value but a relative one depending on such factors as adjacent substation's transfer capacity, feeder capacity, etc. In this section, we divide the emergency models into two sub-categories. The first consists of problems in contingency planning where the environment is generally at the substation level. The second consists of problems in load restoration and load balance both of which are at the feeder level.

III.1 Contingency Models

- ***Single Contingency Capacity***. Many public utilities adopts the *Single Contingency* policy when assessing the maximum load that a substation can take on. This policy stipulates that at any given time the substation capacity of a service area should be able to handle the load even when one transformer in the area fails. The capacity of a substation is the load it can take on when failure occur to either the largest transformer of the substation or one of its adjacent substation's largest transformer. In the former case, it is the sum capacity of the in-service transformers (operating under emergency rates) plus maximum power received from adjacent substations. In the latter, it is the nameplate (normal) capacity of the substation minus the emergency transfer to its adjacent substation. The lesser of the two load situations will be the single-contingency capacity of the substation. This problem of determining a substation's single-contingency capacity, assuming a given substation-load assignment, can be formulated as the following LP model (see also Leung, et al. 1995):

$$[\ Max:\ C_k\ ;\ st.\ C_k \geq L_k,\ C_k \leq E_k + \Sigma_i\, \alpha_{ik} P_{ik}\ ;\quad C_k \leq N_k - P_{ki}\ \forall\ i\ ;\ E_j + \Sigma_j\, \alpha_{ij} P_{ij} \geq L_j\ ,\quad N_j - P_{ji} \geq L_j\ ,\ P_{ij} \leq F_{ij},\ C_k\ \&\ P_{ij} \geq 0\ \forall\ i, j\ ]$$

where C_k is the substation's single contingency capacity, L_k its load demand, E_k its emergency capacity, $\Sigma_i\ P_{ik}\alpha_{ik}$ the emergency power transfer from its neighbors (each discounted by α_{ik}, the voltage drop factor), N_k its normal capacity, P_{ki} the emergency power out to its *ith* neighbor, E_j the emergency capacity of the *jth* substation (adjacent to *k*), $\Sigma_j \alpha_{ij} P_{ij}$ the sum emergency flow to the *jth* substation, N_j the normal capacity of substation *j*, P_{ji} the emergency power out to *j's* neighbor *i*, and F_{ij} the transfer capacity of the feeders connecting substations *i* and *j*.

- ***Load Reallocation.*** The above model would be repeated for each substation in the service area. When there existed unsatisfied load, Leung, et al. (1995) also provided a load reallocation model (additionally expressing the substation-load assignment as a transportation type demand-supply constraints set) which sought to re-allocate unsatisfied load under the single-contingency environment. It was assessed that there existed considerable synergistic behavior in a power distribution system such as: adding capacity to a substation could provide relief to its multiple neighbors and adding capacity to the shortage substation might not be the most economical.

- ***Multi-period Feeder Expansion***. When load reallocation failed to overcome the unsatisfied load, one capacity enhancement measure was to construct new feeders to facilitate further load reallocation. Under the single-contingency scenario, Sarada et al. (1995) provided a multi-year 0-1 LP formulation which would prescribe the least cost feeder expansion plan. The model determined the installation schedule as well as sites of new feeders, while concurrently determined the optimal load reallocation to meet load demand. However, the issues of adding new substations or upgrading existing substation's transformers were not addressed. The problem, shown as follows, was solved using MPSIII, a PC version of MPSX.

$$[Min: \Sigma_t c_{ft} x_t, \ st. \ A_t l_t + B_t p_t = d_t, \ l_t + p_t \le M x_t, \ G_t x_t = 0, x \in (0,1), \ l_t, p_t \ge 0, \forall t = 1,...n]$$

where x_t is the decision vector for individual connections, c_{ft} the present value fixed charge of the connection, A_t is the load assignment matrix, B_t the single-contingency matrix, l_t the substation-load decision vector, p_t the quantity of emergency flow, d_t the load demand/supply vector, M the capacity of the connection, and $G_t x_t = 0$ represents the constraint set for radiality and correlated feeder installation decisions.

- ***Multi-period Transformer Allocation***. Effectively, the single-contingency required that a substation capacity be planned at the transformer level. Hence, when the addition of feeders would not resolve the demand shortfall, transformer procurement need be considered. Leung, et al. (1996) addressed the multi-period allocation and procurement of transformers under single contingency. The proposed model, shown as follows, was a 0-1 LP model which evaluated such procurement alternatives as additions via purchase, relocations from a transformer storage, and relocation within the service network. The optimal mix of transformer (type and quantity) for substations within a service network was also determined.

$$[Min: \Sigma_t c_{ft} z_t, \ st. \ A_t l_t + B_t p_t = Cz + d_t, \ l_t + p_t \le M, \ Q_t z_t = 0, \ z_t \in (0,1), \ l_t, p_t \ge 0, \forall t = 1,...n]$$

where z_t is the transformer decision vector (purchase, spares, etc.), C the capacity of the transformers candidates and $Q_t z_t = 0$ are logical constraints for correlated transformer procurement decisions. A general model which explicitly examined the optimal procurement and relocation of transformers was formulated in Leung and Khator (1995).

- ***A Systematic Planning Scheme.*** In contingency planning, the activities of capacity determination, load reallocation, feeder installation, and transformer upgrade are all inter-related. Khator and Leung (1995) provided a systematic planning scheme which integratively used the models discussed earlier in this section.

III.2 Load Restoration and Balance

Other then models which address the single-contingency situation, there are research works which explore planning situation with fault considerations. When a fault or failure occurs, the process of switching emergency load to feeders with excess capacity is not a simple task. Essentially, this amounts to the reconfiguration of the whole network, which is a large scale combinatorial problem.

Aoki and others provided much of the earlier effort in this area. An approximate algorithm for loss minimum load allocation was developed in Aoki, et al. (1987a), and for emergency service restoration in Aoki, et al. (1987b) which was extended in Aoki, et al. (1987c) to include operating constraints. Aoki, et al. (1988), further refining their work, proposed the following algorithm which quickly restored the emergency loads in a distribution system.

- Connect emergency loads to an adjacent feeder (main feeders)
- Transfer excess loads of the main feeders to other feeders (first stage support feeders) in descending quantity of $h_j/\alpha_j \ (H_j+\beta)$, where h_j is the effective length of violation withdrawal, H_j the effective length of remaining violations, α_j the priority of support, and β a constant. Proceed if unsuccessful.
- Determine $max: [h_j/\alpha_j \ (a_j+\beta)]$ for each switch, where a_j is the magnitude of candidate section load that can be transferred via cut switch j. Transfer load to first-stage feeders. Return to preceding step for first-stage support.
- If necessary, perform load curtailment and restoration of curtailed loads.

Aoki, et al. (1989) proposed a procedure of deciding the open positions of switches in order to achieve load balancing of transformers and feeders while subject to their capacity limits. The procedure identified rules to systematically balance two transformers at a time until approximate balance was achieved to all transformers.

Civanlar, et al. (1988) presented a scheme, with a simple formula, for determining the open/closed states of the tie and sectionalizing switches to reduce power losses in distribution feeders via feeder reconfiguration.

Extending the work of Civanlar, et al. (1988), Baran and Wu (1989) developed two different methods to assess power flow after a load transfer was made. The two methods were based on a set of recursive equations which described power flow. Both loss reduction and load balance were estimated.

The issue of protective device co-ordination was incorporated in a feeder reconfiguration algorithm by Hsu and Jwo-Hwu (1993). The algorithm first identified a set of switchable regions in which switch operations were allowed. The protective devices were designed such that proper co-ordination could be attained during load balancing and load reduction where switches were assessed on/off states.

Nara, et al. (1994) provided a multi-year expansion 0-1 LP model which considered faults. The model, similar to such multi-period models as Nara, et al. (1991), was solved by an algorithm which first decomposed the planning problem into subproblems according to the pre-determined fault cases; the subproblems were then solved using branch-exchange. Further improvements were made via iterative use of the branch-exchange method.

IV. FUTURE RESEARCH DIRECTIONS

IV. 1 Planning under Normal Conditions

- ***Solution via Genetic algorithms.*** Distribution planning models under normal condition are largely quite complete in that most of the important issues have already been incorporated. The major research need appears to be in developing more efficient solution techniques since a multi-period formulation typically consists of a large number of 0-1 variables as well as constraints. In fact, many of the later articles were either algorithms or AI/Expert-system approaches to determine approximate optimal solutions. With the recent development in genetic algorithms, their application in distribution planning could prove to be fruitful.
- ***Sensitivity to load forecast.*** One planning concern which largely remains unexplored is sensitivity of the expansion plan with respect to changes in demand forecast. The accuracy of the demand forecast is dependent on many factors and whose level of precision is usually not guaranteed. With a more efficient solution procedure, it becomes easier to perform sensitivity analysis to handle variations in forecast as well as exploration of many what-if analyses.
- ***Fuzzy formulations.*** Along a similar vein, many coefficients and constraints are modeled as "crisp" values, i.e., not subject to variations or cannot be violated. Such "crisp" conditions can result in an optimal solution which is not realistic --in practice, certain level of deviations or violations may be tolerated to avoid large capital expenditures. Hence, a fuzzy programming approach to formulate distribution planning should prove to be promising.

IV. 2 Planning For Emergency

- ***Incorporating Variable Costs.*** In the modeling of contingency, there remains considerable issues which have yet to be addressed. So far, existing works have not adequately incorporated the impact of variable costs, either that of the feeders or the transformers.
- ***Transformer-feeder Model.*** Load reallocation, feeder configuration, and transformer planning should be concurrent decisions and not incremental decisions. The existing works thus far belong to the latter case.
- ***Locating new substations.*** Similarly, the issue of substation expansion under single contingency has not been explicitly addressed.

One approach to formulate a comprehensive multi-period contingency model which incorporates the aforementioned issues is to build the single-contingency conditions into the existing normal-condition model, which could take the following form:

$$
\begin{aligned}
[\mathit{Min:}\ & \Sigma_t \{ c_{Ft} y_t + c_{Vt} P_t + c_{f't} z_t + c_{ft} x_t + c_{vt} p_t \} \\
\text{s.t.}\quad & A_t l_t + B_t p_t = Cz + d_t \\
& l_t + p_t \le M_t x_t\ ,\ P_t = E_t p_t \\
& e_t y_t \le 1\ ,\ e_t x_t \le 1\ ,\ e_t z_t \le 1 \\
& G_t x_t + F_t y_t + Q_t z_t = 0 \\
& x_t\ , y_t\ , z_t \in (0,1)\ ;\ l_t\ , p_t \ge 0\ , \forall\ t = 1,\ldots,n\ ]
\end{aligned}
$$

- ***Fault-Maintenace Model.*** Maintenance of transformer and feeders means that these facilities will be out-of-service temporarily. This is similar to anlayzing faults or contingency. A maintenance-planning model within the context of fault or contingency framework would be of utility.

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VI. BIOGRAPHIES

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Discussion

R. BILLINTON, S. ABORESHAID AND M. FOTUHI-FIRUZABAD (Power Systems Research Group, University of Saskatchewan) The authors have done a commendable job in presenting an interesting paper which reviews the research problems as well as models related to the planning of substations and distribution systems.

In light of the paper's value to power system engineers, designers and planners, it is regrettable that references to the application of probabilistic methods to power system distribution planning, whose material is completely within the scope of this paper, were omitted. Engineering libraries are rich with books in the area of power system reliability and planning (for example [1-4]) which have devoted one or more than one chapter to the area of distribution and substation planning using probabilistic concepts. In addition, IEEE transactions [5-10], IEE proceedings [5-10], as well as the proceedings of specialized conferences such as Cigre, Inter-Ram and PMAPS contain many outstanding contributions in this area.

Once again We congratulate the authors for their timely and useful contribution.

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Suresh K. Khator (University of South Florida, Tampa, FL) and **Lawrence C. Leung** (Chinese University of Hong Kong). We would like to thank Professors Billinton, Aboreshaid and Fotuhi-Firuzabad for their kind complements towards our paper.

In 1983, Gonen and Mahmoud provided a bibliography on power distribution planning, in which articles on power system reliability were included. Such, however, was not the case with a subsequent paper (Gonen and Ramirez-Rosado 1986) where articles concerning power system reliability were not included.

In our view, we have two major categories: planning under normal conditions and planning for emergency. The former implicitly assumes the normal functioning of equipment. The latter addresses emergency situations, i.e., the situations *when* failure occurs (contingencies and load restoration).

Reliability of power systems essentially addresses the likelihood of failures (the question of *if* failure occurs), which could indeed be another category. Although a relevant aspect of power distribution, we view it a major topic by itself (as reflected by the voluminous literature).

We do wish to thank for drawing our attention (and the readers' as well) to the reliability aspect of power distribution (along with the representative literature).

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