OPTIMAL DISTRIBUTION PLANNING — INCREASING CAPACITY AND IMPROVING EFFICIENCY AND RELIABILITY WITH MINIMAL-COST ROBUST INVESTMENT


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SUMMARY

This paper is on optimal distribution planning. What does distribution planning mean here? What is the meaning of optimal in the context of distribution planning?

In this paper, a distribution system is viewed as a network composed of many nodes (hundreds, sometimes thousands) and an even larger number of branches. The network operates radially. The redundancy of branches is typically of 5% to 15% — 5% for large, widely spread networks with a strong rural component, 15% for smaller, urban networks. Redundancy serves reserve and reliability purposes, for it allows for network reconfiguration. Most of the nodes of a distribution system correspond to delivery points or load points. Some nodes are injection points — distribution substations; some other nodes are switching stations; some others are simple connection points. Most of the branches correspond to electric cables. Other branches correspond to switching devices.

Distribution planning is to choose a new distribution system from a set of possible distribution systems so as to meet the expected load profile in a better way, more reliably, and with fewer losses. The new distribution system is a plan, a plan to be carried out by project services if the plan comprises acquisition or installation of new equipment or a plan to be carried out by dispatch services if the plan involves only changes in the network configuration (i.e. switching operations).

If one can define criteria to measure the goodness of a plan, then there will be one plan that ranks above the others — that plan will be the optimal distribution plan. The optimal distribution plan is the subject matter of this paper.

One can classify the activity of planning, hence the corresponding distribution plans, into the following three categories:

Expansion Plan
Operation Plan
Emergency Plan

An expansion plan is a plan to expand the distribution system, a plan to acquire and install new equipment so as to strengthen the system or to accommodate new loads. To choose an expansion plan means to choose the most appropriate set of investments from a set of all possible investments. A regular basis for the updating of an expansion plan should be a year.

An operation plan is a plan to operate the system satisfactorily, i.e. a plan to modify the configuration of the network so as to accommodate the load, satisfy the voltage and current requirements, improve efficiency and increase reliability of the system. To choose an operation plan means to choose the most appropriate network configuration (i.e. the set of switching operations) from a set of all possible configurations. Operation planning should be carried out seasonally, or whenever the load changes or the network changes due to maintenance reasons.

An emergency plan is a plan to operate the system following a contingency condition, a plan to attenuate the effects of the contingency and to lead the distribution system to a satisfactory, secure point of operation (if possible).

The planning problem is formulated as an optimization problem and the algorithms and software requirements are addressed. For each planning activity, the paper reports the benefits of optimal planning in increasing capacity, improving efficiency and reliability, and selecting investments.

Keywords — Distribution planning, operation planning, expansion planning, emergency planning, capacity, efficiency, reliability, investment, reconfiguration.
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Abstract — The paper addresses the optimal distribution planning and its importance in three different contexts of distribution utilities practice: expansion planning, operation planning, and emergency planning. The planning problem is formulated as an optimization problem and the algorithms and software requirements are addressed. For each practice context, the paper reports the benefits of optimal planning in increasing capacity, improving efficiency and reliability, and selecting investments.

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INTRODUCTION

This paper is on optimal distribution planning. What does distribution planning mean here? What is the meaning of optimal in the context of distribution planning?

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The paper presents illustrative results concerning each one of the foregoing distribution plans. However, the three plans can be presented and discussed within a common formulation — the object of next section.

Let us reference the approaches to the planning problem taken in recent years. There have been many approaches: quadratic programming and heuristics [1], by branch-and-bound and heuristics [2], branch-exchange and heuristics [3], neural networks [4], expert systems [5], and genetic algorithms [6-7]. Genetic algorithms have been found to be promising: they can accommodate complex objective functions, as required for a correct representation of the planning problem. However, they have been shown to be too slow to deal with large-scale problems [6-7]. References to our previous work include [8-18].

OPTIMAL DISTRIBUTION PLANNING
**Formulation**
The distribution-planning problem can be formulated as follows:

\[
\begin{align*}
\text{Min} & \quad f(u) \\
\text{subject to} & \quad u \in U
\end{align*}
\]

where \( U \) is the set of all possible trees of the network, and \( f \) is a function which maps each tree \( u \) onto a corresponding value \( f(u) \), a measurement of the cost of \( u \). The function \( f \) is usually very complex, does not follow an analytical expression, and its behavior cannot be assumed a priori. To evaluate \( f(u) \) one needs to run a full AC nonlinear power flow and analyse the network for power losses, reliability indices, structure patterns and other complex, user-defined performance criteria. The formulation presented here has evolved a long way since the problem formulation of [8]. It reflects our experience with the evolutionary model we have successively developed [8-18].

**Algorithms**
The problem formulated in the foregoing is an optimization problem, but it is not a conventional convex programming type of problem. Because of the nature of \( f \) and because \( U \) is a discrete set, the optimization problem is not susceptible to mathematical programming algorithms. Our experience has led, upon successive iterations, to formulate the problem as a problem of choosing the optimal tree. As a result, we have designed specific evolutionary-based algorithms to search for that optimal tree [12-13].

**Software**
From the many implementation issues, such as data structures for the evolutionary algorithm and network operation, and relationships with other techniques used (GIS), the following software results should be pointed out:

**R1 Investment decisions**
Investment decisions associated with the network branches: equipment and corresponding installation showing where new cables should be installed and existing cables replaced. The cables are selected from a specified set and the output shows the routes selected for new cables and identifies where common trenching (multiple cable route) is required. Similarly, for investment decisions associated with network nodes: equipment and corresponding installation showing new and replacing transformers, and additional switching capabilities for new connections.

**R2 Topological decisions**
These decisions comprise the selection of possible new branches, to connect disconnected existing branches, and to disconnect connected existing branches.

**R3 Voltage-current analysis**
A complete voltage-current analysis is carried out including the branches where cable current limits is exceeded and the nodes where system voltage levels are not satisfied.

**R4 Reliability: fault analysis and corrective switching.**
A fault can occur anywhere in the network, and the occurrence probability can be assessed from the fault rate statistics for each network branch. Following a circuit fault outage, in the majority of cases, supply restoration comprises a switching operation to a nearby feeder. A fault is simulated for each branch, and the feeder and corresponding switching operations are selected and the Expected Energy Not Supplied (EENS) is evaluated. Occasionally, even the best choice of switching may, due to cable current limits, prevent restoration of all power supplies. All these situations are analysed, the corresponding EENS value computed, and the selected switching reported. Other reliability indices (SAIDI, SAIFI, ASCI) are also computed.

**Interface**
Distribution planning software has to interface with the technical and geographical data, and with the user. The software makes use of cutting-edge graphic technologies to build up a friendly, fast geographical, multi-monitor multi-window user interface. It has capabilities for continuous, instantaneous analysis of the network — every change the user makes in the network (for example, a new connection, or an increase in load) makes an instantaneous change in all views of the network. Zooming and panning are readily available at all times, continuously and instantaneously. The interface also includes the following: easy-to-use, intuitive editing facilities; special filters for symbols, ids, voltages, currents, flows, loads, investments, and reliability indices; colored patterns for investment, voltage, current, loss, reliability, and for feeder configuration; automatically-scaled mapping facilities, and querying facilities.

**RESULTS**
We present a set of results concerning an urban distribution system of 385 nodes, 442 branches (Table 1). The results comprise the three types of planning: emergency, operation, and expansion. Results for larger networks are also presented in Table 1.

**Emergency Plan**
Consider the following major event: the outage of the main substation. The main substation is in the middle of the town (load center) and is the major power supply to the network. The other two substations play normally a secondary role. The key issue here is capacity, i.e. to maintain as much load as possible. Consider two plans: a simplistic plan, Plan P1, and the optimal plan. Plan P1 connects the feeders under outage to the neighboring feeders still in service. Some of those
connections heavily overload the circuits in service. The system can feed about 45% of the total load — system capacity is 45%. The optimal plan does provide for non-obvious, deeper connections within the system — the resulting system capacity increases to 88%. Fig. 1 depicts these results.

**Operation Plan**
Consider a distribution system operating satisfactorily, without problems, i.e. no voltage violations, no current violations. The question that may arise is whether the system is operating in the most appropriate configuration, i.e. is it optimal?

Fig 2 compares the performance of the “no problem” system with the optimal configuration system. Losses decrease to a much lower value; expected energy not supplied and duration of interruptions also decrease. Thus, an optimal plan may lead to a substantial improvement in efficiency and reliability.

[Note that the improvement in efficiency and reliability are with no investment costs, just reconfiguration costs.]

What about capacity — what are the capacity gains by reconfiguration? Fig. 3 shows the gains in capacity. Although the system load was causing no voltage and no current violations, they appear when the load profile is raised to 107% of the original load profile. For the optimal configuration (the same one that yields the results of Fig. 2), voltage or current violations only appear when the assigned load is 180% of the original load profile — a substantial increase in capacity.

**Expansion Plan**
Consider a distribution system that needs expansion to satisfy load growth. [Note that expansion of the system is always necessary to satisfy the new loads, may be necessary to satisfy the load growth (increase in capacity), and may be desired to improve the efficiency and reliability of the system].

Consider two plans: a simplistic plan, Plan P2, and the optimal plan. Plan P2 reinforces weak branches and provides local relief to the weakest areas of the system. The optimal plan selects from the set of possible new connections and reinforcements those that are more important to increase overall capacity, to improve overall efficiency and reliability. Plan P2 selects on the basis of local information, whereas the optimal plan selects on the basis of global, network-wide information.

Fig. 5 compares the performance of Plan P2 with the optimal plan. The investment costs are slightly higher. The losses decrease to a much lower value; expected energy not supplied and duration of interruptions also decrease. Thus, an optimal plan may lead to a substantial improvement in efficiency and reliability, with the same amount of investment.

As far as capacity is concerned, the new additions of Plan P2 provide for a capacity reserve of about 50%. The optimal plan leads to about 100% reserve (see Fig. 4).

[We note that gains in efficiency and reliability may justify investments; thus, the optimal system tends to have a considerable amount of reserve.]

**Complexity**
What is the level of complexity involved in the process of proposing an optimal plan? The complexity depends heavily on the scale of the problem, as given by the number of nodes, number of branches, number of possibilities for reconfiguration. Table 1 illustrates the level of complexity involved. Three networks are presented. Larger networks include rural areas – larger scale, fewer reconfiguration options. Note that thousands of full AC power flows are required, and millions of faults have to be simulated — and the corresponding corrective actions also simulated — to evaluate the solutions generated along the optimization process.

<table>
<thead>
<tr>
<th>Number (#)</th>
<th>Networks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
<td>385</td>
</tr>
<tr>
<td>Branches</td>
<td>442</td>
</tr>
<tr>
<td>Substations</td>
<td>3</td>
</tr>
<tr>
<td>AC Power Flows</td>
<td>7,040</td>
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<tr>
<td>Simulated Faults</td>
<td>2,464,200</td>
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<tr>
<td>Proposed Changes</td>
<td>12</td>
</tr>
<tr>
<td>Wall-Clock Time</td>
<td>80 s</td>
</tr>
</tbody>
</table>

**CONCLUSION**
Distribution planning — which include expansion planning, operation planning, and emergency planning — can be made optimal. The benefits of optimal planning in increasing capacity, improving efficiency and reliability, and selecting investments have been reported.
Fig. 1. Post-fault capacity after main substation outage — Plan P1 vs. optimal emergency plan.

Fig. 2. System indices — before vs. after optimal reconfiguration.

Fig. 3. Network capacity — Before vs. after optimal reconfiguration.

Fig. 4. Planned capacity — Plan P2 vs. optimal expansion plan.

Fig. 5. System indices — Plan P2 vs. after optimal expansion plan.
References


