DISTRIBUTION PLANNING OF LARGE URBAN NETWORKS: SOFTWARE, ALGORITHMS, PRACTICE AND EXPERIENCE

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Abstract *— Distribution planning comprises both the operational planning and expansion planning of distribution systems. Operational planning is to choose a new system configuration, out of the existing system, to meet the load profile in a better way, more reliably and with fewer losses. The expansion planning considers additions to the existing system. To evaluate the goodness of a new addition, one should know how the system would operate with that new addition included — hence an operational planning problem should be solved. Thus an operational planning problem should be solved for each expansion plan to be considered. In this paper, we present the development of and experience with an evolutionary computation approach to address, and to actually solve, the operational planning and expansion-planning problems for real-size distribution systems. Results for a 385-node, 442-branch network are presented.*

Keywords — Distribution planning, operational planning, expansion planning, software, algorithms, loss minimization, reliability, network reconfiguration.

INTRODUCTION

Operational planning is to choose a new system configuration, out of the existing system, to meet the load profile in a better way, more reliably and with fewer losses. This should be done to optimize the current situation or whenever the load profile changes. Expansion planning is to choose — for investment — new cables (and corresponding trajectories), new transformers, and new switching capabilities as a preparation to meet future loads.

Distribution systems for urban areas have many possibilities of reconfiguration: the branch-node ratio is about 1.15, a 15% branch redundancy. The operational planning problem alone, for a 300-node system, would lead to billions of solution possibilities. The expansion planning considers additions to the existing system. To evaluate the goodness of a new addition, one should know how the system would operate with that new addition included. Thus an operational planning problem should be solved for each expansion plan to be considered.

The large scale of the problem, the combinatorial nature of the solutions, and the dimensionality of the distribution network make the task of planning formidable, even for today's powerful computers. Our approach is based on concepts of evolutionary computation. However, it is especially designed for distribution systems and is coupled with specific heuristics and classical analysis of distribution systems. The software design takes full advantage of the fact that distribution networks operate radially. This allows fast evaluation for selection, appropriate feasible solution recombination, regeneration of population, and effective loop optimization.

Our approach has been implemented in an application program, DPlan, currently in use at Electricidade de Portugal. Before using DPlan, the planner would analyse *one* solution, make a few changes and analyse it again. DPlan selects the best solutions from billions of possible solutions, and shows them to the user. In this selection effort, DPlan analyses only a few thousand solutions, thanks to the special design of the approach taken. This paper describes the essence of the distribution planning problem, formulates it in an appropriate manner to make evolutionary methods work, outlines the key ideas behind the algorithms used, and presents actual results from the utilization of DPlan to solve real-world distribution planning problems.

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 [8-17].

PROBLEM STATEMENT AND FORMULATION

An electrical network at the distribution level is composed of hundreds of nodes, most of which correspond to power delivery points or load points, and hundreds of branches, most of which correspond to electrical cables. The other nodes correspond to switching points and feeder points. The other branches correspond to switching busbars. In normal operation, each load point or switching point is connected to a feeder point through a single path. Thus the network, when in operation, is radial, i.e. the network operates as a tree. The co-tree branches, about 15% of them, can be used to change the topology of the operating network so as to improve its performance, i.e. they enable the operator to choose a different tree for operation whenever that becomes necessary or desirable. To make this choice optimal is a subject matter of this paper.

It may also happen that even the optimal choice, technically termed optimal topological configuration, will not be satisfactory. In that case, new branches must be considered, thus leading to investment and installation of new cable and switching busbars — the so-called expansion planning of the network. Because many possible new branches may be considered, the dimensionality of the problem increases further. However, despite the consideration of investment and installation costs and the increase in dimensionality, the problem is still of the same form. Thus, expansion planning is a subject matter of this paper too.

Formulation

The problem stated in the previous paragraph may be formulated as follows:

Min f(u)
subject to $u \in U$

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 is unusual for the network-planning problem. It has evolved a long way since the problem formulation of [8]. It reflects our experience with the evolutionary model we have successively developed. Apparently, this formulation has a tremendous disadvantage: the set U is not known a priori, not easy to enumerate, list or even identify. However, this formulation has the following real advantages:

A1 Represents the problem accurately.

A2 Discrete variables are shown explicitly and compactly: u is a tree.

A3 Continuous variables such as node voltages and branch currents are not shown explicitly — nonetheless they have to be computed for the evaluation of f(u).

A4 Continuous variables are dependent variables: for an assumed tree u, the voltages, currents, performance indices and other quantities can be computed by electrical analysis and conventional optimization techniques.

A5 Is appropriate for the use of evolutionary computation techniques, for the reasons shown in the next section.

ALGORITHMS

Why Evolutionary

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.

An evolutionary approach is appropriate for the following reasons:

R1 The solution space is discrete and the problem is a large-scale combinatorial problem. The set U is of very large-size.

R2 The problem is not a highly constrained problem. As presented, it only has a constraint set — even though this constraint may be hard to satisfy. For conventional methods is very hard; for evolutionary methods, specific procedures are required to ensure that the constraint is always satisfied, i.e. that each individual is a tree.

R3 The cost function is of great complexity. To evaluate f(u) many procedures may be called. For example, power flow, reliability analysis, pattern evaluation. Such a cost function is inappropriate for conventional optimization methods.

R4 The user needs several good solutions in the end, not just the optimal one. The user is interested in viewing more than one solution, because there are always personal preferences as well as technical preferences that could not be specified a priori. These preferences however should be felt only upon a set of good solutions, thus after the specification requirements are satisfied. For this purpose, several final solutions should be close from the point of view of performance, but should not be close from the point of view of configuration, i.e. the user would like to have some quite different configurations with similar performance. Conventional optimization algorithms would not provide the user with those multiple different solutions.

Difficulties Encountered

When applying evolutionary algorithms to the problem, we encountered the following difficulties:

D1 When crossing two solutions, the resulting solutions would often lose performance, or even become infeasible. That happened because the genetic string was a string of branches. When two such strings are partitioned and crossed, the resulting two strings may not necessarily represent trees. If a resulting string does not represent a tree, the corresponding solution is infeasible.

D2 When convergence was achieved, one could still improve the solution by inspection and use of conventional network analysis. That indicates that the population saturated without reaching local connections that could be exchanged for benefit of the solution.

D3 The end solution could be far from optimal. That indicates that the whole solution space has not been searched properly. Using a larger population would still not solve the problem if the problem were a large-scale problem.

D4 There was not enough diversity in the final population. After 30 generations or so, the solutions tended to be alike; individuals corresponding to very different trees, though fit, would vanish and not reappear in later generations.

Procedures Developed

To overcome those difficulties, we have developed the following two procedures:

P1 Crossover is based on network path exchange.

This procedure can be summarily described as follows: (i) Choose two nodes, say node n1 and node n2. Individual I1 has a path between these two nodes, say path p1. Individual I2 has a path p2 between n1 and n2. (ii) Exchange paths, i.e. provide I1 with p2, and I2 with p1. For details of this procedure, see [12, 13].

This procedure ensures that the new individuals (after crossover) are both feasible and technically sound. Thus, this procedure overcomes difficulty D1.

P2 Whenever two (or more) individuals are identical, the second (and third, ...) undergoes an operation to become better (if possible). This operation is based on heuristics and conventional optimization techniques.

This procedure can be summarily described as follows: (i) Heuristics detect two weak points of the network. (ii) Starting from those two weak points, a loop is sought. (iii) The loop is then closed (by using a co-tree branch). (iv) A conventional minimization procedure is run to search for the loop branch that should open. (v) If the loop branch to be opened is the co-tree branch, the solution remains the same (of course); if not, the solution is improved. For details of this procedure, see [14, 15].

This procedure overcomes difficulty D2. Indeed, convergence is achieved when this procedure cannot improve the repeated solutions. And if the solutions cannot be improved is because they are locally optimal.

This procedure, together with procedure P2, overcomes difficulties D3 and D4. Indeed, the newly-operated individual, even though only with a single branch removed and another one added, may look (and be) substantially different from its twin (i.e. its original version). Why? Because many branches may change predecessor by that operation. What if heuristics fail? Heuristics are used to detect weak points; if weak points are not properly detected (this is unlikely to happen), the procedure will slow down, since it will not benefit from that information.

This procedure regenerates the population. Procedures P1 and P2 together sweep the whole solution space effectively, and yield solutions that experience has shown the planner can hardly improve upon.

SOFTWARE

From the many implementation issues, such as data structures for the evolutionary algorithm and network operation, and relationship with other techniques used (GIS), the bus splitting should be pointed out. Bus splitting is a simple means of achieving a great diversity of solutions and providing for profound modifications in the network. Consider all possible connection choices between two split nodes for a possible cable route: there are 9 possible choices with one cable, and 12 choices with two cables. Thus, the number of topological solutions to explore the network becomes much greater.

DPlan results can be grouped as follows:

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, additional switching capabilities for new connections, and internal busbar switching.

R2 Topological decisions

The topological decisions comprise to install new branches, to connect disconnected existing branches, and to disconnect connected existing branches (these are shown as dashed lines in Fig 1).

R3 Voltage-current analysis

A complete voltage-current analysis is carried out including the branches where cable ampacity is exceeded and the nodes where system voltage levels are not satisfied. Losses are computed by branch, feeder, and globally.

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 ampacity limits, prevent restoration of all power supplies. In these situations, the corresponding EENS value, branch id and selected switching are reported. See Table 2.

R5 Other performance indices

Another performance index that experience has found interesting is an index for the network pattern: complex configurations are penalized in favor of simple networks. Typically this index conversely affects loss minimization; nevertheless they can balance each other.

Multistage Horizon and Multiple Scenario

DPlan has capabilities to handle decisions along successive stages of the planning horizon, since not all investments may necessarily be scheduled to take place in the same year. Together with a wider horizon (ie multiple years or multiple stages) comes the issue of uncertainty, uncertainty about load growth and new loads, equipment prices and installation costs. Above all, one must consider uncertainty about expansion possibilities such as possibilities for new feeder substations in future stages. DPlan accepts uncertainty by means of multiple scenarios of possibilities. The investment decisions selected by DPlan are robust, they are hedged against all possible scenarios set up by the user. For details of how DPlan accomplishes this hedging against uncertainty, see [10, 17].

Interface

DPlan has to interface with the technical and geographical data, and with the user. A few words about the user interface. It relies on a major window with continuous zooming and panning capabilities. Three main menus can be chosen: View, Edit, and Filter (see Fig. 1). The View menu is for viewing all quantities (input data and results) related to a selected node or to a selected branch. The Edit menu is for editing the expansion possibilities of the network and for entering or modifying input data for a selected node and branch. Whereas the View and Edit menus refer to a particular item selected, the Filter menu refers to the whole view of the network. Filter can be applied for symbols, ids, voltages, currents, flows, loads, investments, and reliability indices. Filters also comprise colored patterns designed for investment, voltage, current, loss, reliability, and for feeder configuration. Filters can be superimposed on one another.

PRACTICE AND EXPERIENCE

DPlan has consistently provided good results. It has simplified and optimized investment decisions on the selection of new cables and connections. In the operational planning mode, DPlan has provided an easy-to-follow operation structure, improved system reliability and reduced distribution system losses.

Experience has demonstrated the importance of some of DPlan's special features for the success of distribution planning. These features include the following:

F1 Electrical analysis, network reconfiguration and investment plans are considered simultaneously in the optimization process. Each investment plan is evaluated for the optimal network operation configuration.

F2 EENS is evaluated by simulating faults in every network branch, according to branch specific failure rates, repair times and reconfiguration times. The user sets the rate and time values according to experience.

F3 For each particular fault, there are frequently several possible corrective switching actions. Every possible corrective switching is scrutinized for cable ampacity violations and the corresponding EENS is reported. Post-fault configurations are analysed for every branch fault.

F4 Each network node at a transformer site can be specified as single or double. A double node comprises a node for the load and network connections, and an extra

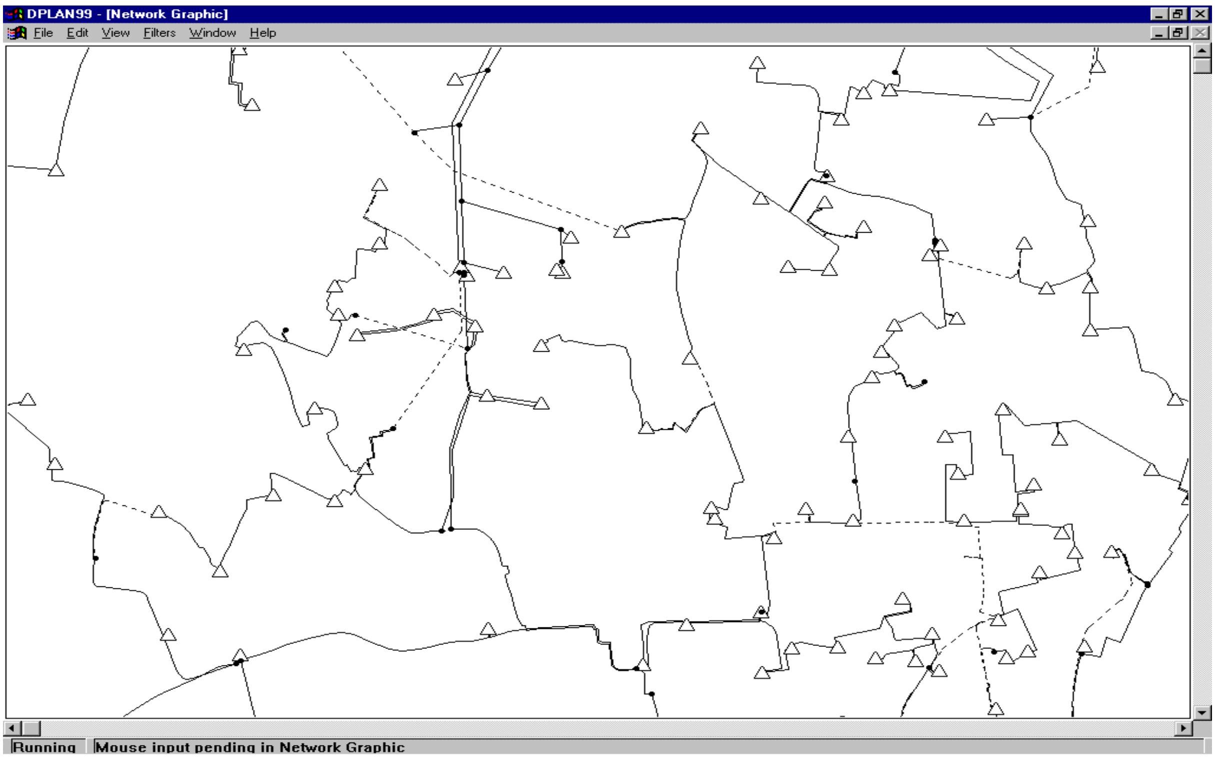

Fig 1 DPlan's window showing a partial view of the network

node for other network connections. Splitting a node into a double node is a common practice by network operation engineers and greatly increases the number of alternative network reconfigurations.

F5 The optimization can focus on loss minimization, EENS, cable ampacity limits, voltage levels or focus on any weighted combination of those objectives. Multiple objectives make DPlan useful for multiple network operational and expansion policies.

F6 The results are presented as a set of possible good solutions. The user in selecting a solution can accommodate subjective criteria, not accountable in the foregoing objectives.

F7 The program takes 1-2 minutes to produce a set of solutions, which comprises a complete analysis of 10-20 thousand possible plans and corresponding configurations (wall-clock time, Pentium 200 MHz). The execution time is thus fairly reasonable thereby allowing the planner to actively interact with DPlan's data and results.

Application

A 15kV distribution network, which supplies an important tourist urban area in Algarve, Portugal, has been selected to illustrate the application of DPlan. The network comprises two 60/15kV substations, 385 nodes (including 257 load nodes), 442 branches, 124km of cable and a 30MW peak load. Part of the network configuration is shown in Fig.1.

The system solution selected includes 17 new 15/0.4kV distribution substations; two new feeders in Al-240mm2 of about 2500m each; an existing feeder in Cu-25mm2 is disconnected -- its substations are connected to other feeders; 19 existing cables are replaced; 30 new cables and connections are selected. Overall, 2335m of cable are replaced and 15482m of new cable are installed, mostly of Al-240mm2 and Al-120mm2. The operational configuration of the system is substantially changed: 48 switches change status.

The structure of the network changes from a complex mesh to an easy-to-follow new structure incorporating new cables to connect and meet expected load. The reliability of the redesigned network is improved by 38% and system losses decrease by 50%. Some of DPlan's results for this study are shown in the following Tables. More results can be found in [16].

Table 1 - Topological Decisions

Branch Id	**Decision**
PTM869-PN352	Install
PN352-PN354	Install
PTM0145-PTM0111	Connect existing
Id039-PN353	Connect existing
PTM0046-PTM0088	Connect existing
...	...
PN346-Id004	Disconnect
PTM0046-PTM0007	Disconnect
PTM0007-PTM0375	Disconnect
...	...

Table 1 shows the topological decisions corresponding to the solution proposed. For an existing branch, the decisions are Connect or Disconnect the connections. For a possible new branch, the decisions are to install and connect (Install), or not to install (not shown).

Table 2 identifies those sections of the network where, for a fault at Fault Branch Id and upon optimal corrective switching to a near feeder by using branch Switch Branch Id, the cable ampacity is still exceeded. The corresponding EENS value is also shown.

Table 2 - Fault Analysis — EENS for best single-switch reconfiguration

Fault Branch Id	**Switch Branch Id**	**EENS (kWh/year)**
SE01-Id087	PTM0046-PTM0007	1004.1
Id087-PTM0185	PTM0046-PTM0007	101.4
...	...	...
SE01-PTM240	PTM0359-Id005	59.8
...	...	...

As for the performance of the evolutionary procedure, consider Fig. 2. Note that the quantity shown (which is part of the cost function f) falls steadily as the generations evolve, until convergence (saturation) is reached at generation 60.

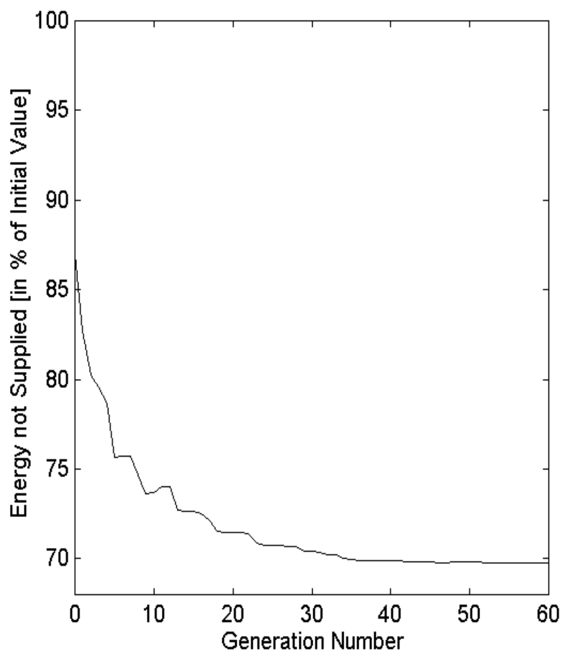

Fig 2 A reliability index, the overall expected energy not supplied, decreases as the evolutionary process proceeds. The values shown are for the best solution (tree) for each generation.

This behavior is not typical of genetic algorithms, it is a result of the special procedures described in this paper.

CONCLUSION

An approach to deal with the problem of operational planning and expansion planning of power systems has been presented. The paper shows that a proper problem formulation invites the utilization of evolutionary methods. Nonetheless, those methods cannot be applied straightforwardly. The difficulties encountered and the special procedures to overcome those difficulties have been reported. These procedures play a crucial role in making evolutionary methods work effectively and fast enough.

The procedures are implemented in a program, DPlan. The principal benefits of using DPlan are as follows:

B1 Reduces losses, thus decreasing energy operation costs

B2 Improves reliability, thus bettering the quality of supply

B3 Improves configuration in accord with desirable patterns, thus decreasing staff operation cost

B4 Optimizes investments, thus decreasing investment costs

B5 Provides high-quality technical information to support strategic decisions

B6 Reduces labor effort and speeds decision making

A few words more, related to B6. Traditionally, the planner selects an investment plan and then subjects it to an analysis program. The selection is made empirically. Then, for each plan selected, the planner has to select a new configuration. Again, the selection is made empirically. Those selections are selections in large-scale problems. Computers and numerical methods are most needed for large-scale problems, problems with a large diversity of solutions. To avoid the empiric selection of plans, to avoid the empiric configuration for each plan, and to allow the planner to concentrate on feasibility and evaluation of the options, not on the dimensionality of the problem, that is DPlan's *raison d'être.*

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