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GIS Enhanced Long-Term Planning of MV Distribution Networks

ZLATKO ZMIJAREVIĆ SLAVKO KRAJCAR DAVOR ŠKRLEC

University of Zagreb
Faculty of electrical engineering and computing
Department of Power Systems
PP 148, 10001 Zagreb, Croatia
Tel: +385 1 6129 907; Fax: +385 1 6129 890
E-mail: caddin@zvne.fer.hr

Abstract

This paper outlines a methodology for long-term planning of MV power distribution networks. The optimization procedure within the proposed methodology is based on genetic algorithms for optimal routing of primary feeders in open-loop and link networks. A brief overview of the algorithms is given to emphasize the applicability and constraints of the methodology. The proposed methodology relies on geographically referenced data stored in an arbitrary Geographic Information System (GIS) and takes into account the existing network structure. For verification and exploitation, an extension to a successful commercial desktop GIS has been developed for preparing necessary data and for interpreting results. An addition to this paper is a short compilation of directions for the future based on experiences gained through the development of our tools and user feedback.

Keywords: Long-Term Distribution Planning; Geographic Information Systems; Genetic Algorithms.

1. Introduction

Many papers on the topic of distribution planning have been published and have proposed various optimization techniques involving many issues (comprehensive references may be found in [1,2]), but to our knowledge very few pursue open-loop or link network planning [3,4,5]. The majority of existing long-term planning methods deal with pure radial networks, although some allow loops [6]. Network reconfigurations by means of Distribution Automation (DA) for reducing losses or for providing alternate supply paths in emergency conditions elevate the appeal for open-loop and link networks. Reconfiguration is recently investigated to a great extent in construction design and short-term planning, but given the circumstances, long-term planning for open-loop and link structures is a widely open area for research.

The long-term planning described herein is based on an operational methodology used by Croatian electric utilities. Although improvements have been made to the genetic algorithms described later in this paper, the focus is on the functionalities and results shown in practice with the use of software tools collectively referred to as *CADDiN* (Computer Aided Design of DIstribution Networks). The development of the software attempts to match the research done by the authors and advances in computer standards and technologies since its genesis in 1989. A strategy that proved to be fruitful was the early adoption of Geographic Information Systems for handling data necessary for planning.

2. Outline of the proposed methodology

The goal of electric power distribution system planning is to meet the growing and changing electric power demand within the distribution system by expansion or reinforcement actions in a foreseeable future period satisfying operational constraints. The desired output of a planning procedure is optimal sizing and timing of a feeder or substation construction or reinforcement on an optimal location. An acceptable objective proposed by this methodology is least-cost planning minimizing overall expenditures (capital investments, technical and other losses and maintenance).

If eased from impacts of LV planning, medium voltage network planning strategies may include options concerning:

- MV network reinforcements with new feeders (on new or existing routes),
- construction of new HV/MV substations,
- reinforcements of existing HV/MV substations,
- construction of new switching substations (a facility for purposes of switching where the power supply is usually achieved by direct feeders to supply substations),
- converting switching substations to supply substations.

The methodology proposed herein may be used to assess possible options within the observed strategies. The backbone for the methodology is an optimization algorithm for finding optimal link or open-loop structures given the locations of load points and their forecasted power demand. The output of the optimization algorithm is compound and provides optimal feeder routes, position of tie-lines and supply areas of HV/MV substations.

Optimal feeder routing between supply and load points is a complex task due to the fact that it is a graph-related problem. For given demands in load points, the corresponding network structure must satisfy a number of technical or administrative constraints (thermal limits, voltage levels, reliability indices, etc.). Finding a structure acceptable in terms of investments and operating costs is always difficult, since the number of core constituting elements of any distribution system is overwhelming. Construction of new HV/MV substations is very rare in real life (especially in urban areas) and reinforcements of existing HV/MV substations are economically feasible only in significant steps. Given these facts, the number of available options is small so the optimization procedure may be performed for each scenario.

The proposed methodology uses a formulation of the Capacitated Vehicle Routing Problem (CVRP) to model the MV network routing problem as described in detail in [5]. In brief, supply substations are depots, load points are customers and feeders are vehicle routes. The objective for a CVRP is to find optimal routes for a number of vehicles supplying a designated set of customers. The constraints of CVRP (vehicle capacity, vehicle range, customer demand, depot reserve) are easily translated to constraints on feeder routes (thermal limits, voltage drops, power demands, transformer sizes). The analogy between vehicles and feeder routes makes the model ideal for open-loop and link structures. Single-stage distribution network planning is possible by using a cost between two points representing fixed and variable expenditures for such a link during the planning period [5]. The expenditures converted to present worth values are related to investments, technical losses (resistive losses in feeders) and maintenance. Existing operational feeders are valuable assets and must be pondered by the planning procedure. The methodology proposed in this paper takes the existing network into account by formulating a different cost for using an existing feeder. The use of an economically defined cost for routing allows the optimization algorithm to simultaneously expand and reconfigure the distribution network.

To insure the desired level of serviceability in urban distribution MV networks, each load point is connected in a way that power supply can be reached through at least two unique routes. This may not be true for every load point, because in some circumstances reliability is not an issue or is already high (such load points are referred to as laterals). A meshed structure allows more flexibility in outage events, but the "cleaner" structure of an open-loop or link structure is more fitting for protection or DA, and is less expensive. Feeder serviceability refers to serviceability during a feeder segment outage, and likewise transformer serviceability refers serviceability during a supply substation outage. Feeder serviceability is achieved in open-loop networks by routing feeders (properly capacitated) through a number of load points and looping back to the supply substation. Link networks have a higher level of serviceability providing transformer serviceability in addition to feeder serviceability by routing feeders through a number of load points starting from one substation and ending in another substation.

3. Genetic algorithms for routing

The complexity of a Multiple Depot CVRP in comparison with a Single Depot CVRP is much higher, so it is no surprise that two distinct algorithms are used for routing - one for open-loop and the other for link networks.

The algorithm used for link networks within the current version of CADDiN is suited for solving Multiple Depot CVRP and is described in detail in [7]. Most GA generate initial populations randomly, sampling the total solution space uniformly. The used Genetic Algorithms performs population initialization by constructing routes picking nearby load points. This heuristic improvement in the population initialization proved to increase the convergence rate with no deterioration in quality. The recombination operator ER (*Edge Recombination*) introduced by Whitley's GENITOR algorithm [8] has been modified to create offspring. The applied mutation operator is the well-known 3-opt path improvement technique for the Traveling Salesman Problem.

Open-loop network are optimized with a GA fully presented in [9] similar to the genetic algorithm described first for solving link networks. It uses similar chromosome coding techniques and utilizes the same heuristic improvements for population initialization and recombination.

Significant research has been conducted regarding GA for optimizing link networks. Some of the shortcomings of the GA outlined previously have been overcome by a novel GA [10,11]. The most important improvement was an alternative chromosome representation. In addition, extensive investigation of various crossover and mutation operators was carried out.

4. Objective and constraints

The objective of the optimization algorithm is to find a network structure with the minimum sum of costs related to individual routes between all load and supply points. Using the adopted analogy between distribution network planning and Capacitated Vehicle Routing, some technical constraints are easily adopted by the optimization algorithm, while others are incorporated through penalty factors in the cost function. Constraints imposed by technical limitations, incorporated in the optimization are:

- thermal limits of individual routes,
- voltage drop in normal conditions (voltage levels at tie-links),
- voltage drop in worst-case feeder segment outage,
- capacities of feeders and supply substations needed for maintaining serviceability levels during outages.

An important modeling issue involves permissible paths between substations in link networks. Both GA (the old [7] and new [10]) rely on the planner to specify substations pairs connected with feeders. This is a feature useful in large networks where additional factors prohibit feeders linking certain substations (a typical example is the distribution network of Rijeka where the city is stretched between the Adriatic coastline and steep slopes of hills rising over the Kvarner bay). This feature is especially important for networks with switching substations. Direct lines emanating from supply substations to switching substations must be excluded from the optimization procedure, but may influence capacities of the supply and switching substation. The new GA described in [10] has introduced a new constraint imposed on the link network structure by limiting the number of feeders emanating from each substations.

The chromosome representation of the distribution network allows exactly two feeders attached to one load point. This is a graph-related constraint of open-loop and link networks. Lateral branches may be removed in order to clean the network structures by adding the total power demand of load points on the lateral to the load point from which the lateral is branching and excluding the corresponding structure of the lateral from the optimization process.

Serviceability levels in link and open-loop structures produce short durations of outages. Consequently, expected outage costs are relatively minor. This relieves the optimization process and planning model of a relatively complex issue of reliability. Although no reliability calculations are performed of indices evaluated, the GA optimization considers reliability by defining the maximum number of load points per feeder.

Providing serviceability levels in link and open-loop structures implies indirectly a constraint that simplifies the planning procedure: new feeder segments are of one type (cross-section) only. Although some authors have addressed the topic of optimal conductor selection [12], their findings are focused on radial networks. To emphasize serviceability provided by open-loop and link structures, an additional optimization criteria is introduced: maximum feeder power limit. Specifying a limit lower than the thermal limit or a new segment ensures a reserve in the feeder's capacity for future loads. Another fact that advocates the use of a single standard feeder is that such a principle cuts overall costs in terms of maintenance, acquisitions, storage etc.

5. The GIS enhanced planning process

Geographic Information Systems may be viewed as the result of combining Computer Aided Mapping and database technology [13]. The ability to input, store, manipulate, analyze and display information on objects with real world geometry is the principal feature of GIS. Linking geographical data and alfa-numerical data for objects, in respect to spatial relations (topology) between dis7tinctive objects enables GIS to be an effective tool for managing resources and supporting decision making by means of numerous types of queries and analyses.

Distribution network planning heavily depends on GIS due to the natural (georeferenced) representation of substations and lines in contrast to connectivity schematics used for operations. GIS, since its performance is not aimed for real-time analyses, may provide voluminous geo-referenced data valuable for planning purposes (urban zones, road networks, gas and water networks etc.). In combination with statistically derived data (i.e. power demand per square km, population density) the planning process becomes less impaired.

The CADDiN software consists of several modules providing a set of tools for planning each aimed at specific parts of the planning procedure. The optimization algorithms for routing are enclosed in a stand-alone module, while data preparation and graphical interpretation are provided by a specially developed extension to a proven commercial GIS tool. Planning methodologies must be impartial to vendors and technologies. This doctrine always has been present during the development of CADDiN so the planning procedure described later may be used for any arbitrary GIS. The GIS tool used by CADDiN is the globally famous CAD tool AutoCAD extended with GIS capabilities named AutoCAD Map. The enhancements brought by CADDiN may be perceived as additional to AutoCAD, meaning the functionality of AutoCAD is intact (results of the planning procedures are at the same time ready for design).

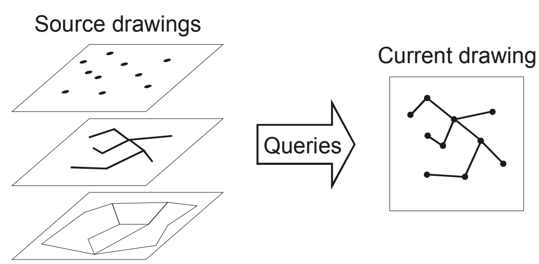

Figure 1. Extraction of data from source drawings

AutoCAD works with *drawings*, but for GIS analyses an alternative approach is used as shown in Figure 1. *Source drawings* contain objects with attached data records and represent the complete GIS database. A user extracts data from the *source drawings* into the current *drawing* by using *queries*. These *queries* can be typical GIS or database queries using location or data criteria for extraction, but may also use the CAD properties of objects in *drawings*. Object may or may not retain their links to their original within the *source drawings*. If such links are retained, changes on objects in the current drawing are transferred to the *source drawings*. This scheme is very helpful in the planning process due to the fact that many scenarios may exist using many alterations in the planning data. Extracting data for obtaining up-to-date data is necessary, but retaining links with *source drawings* is not sound, since the planning process may involve changes in the data (capacities, load data, location modifications, etc.) and new data (new load points, new lines, etc.) which generally is not allowed in a enterprise wide database.

CADDiN is independent of data models since it creates its own data model by extracting only the required data from source drawings and than transforming the data to an acceptable format. Using features of AutoCAD Map an adequate model is constructed within the current *drawing* and a network is built to accommodate the optimization algorithm.

6. Details of the planning process

The CADDiN planning procedure is shown in Figure 2. Steps ① and ② are used to define the utility's data model and location of actual data. Selection of planning criteria in step ③ involves the selection of several CADDiN parameters and the definition of five *queries* for five types of objects:

1. substations,
2. load points,
3. existing cables that will be used throughout the planning period,
4. routes of abandoned cables or cables that do not match the planning criteria (routing is cheaper using these routes) and
5. allowable corridors for routing new cables (i.e. road centerlines, corridors on roads, ducts).

Through the use of *queries*, the planner is allowed very precise selection of objects through compound conditions on data, location or other properties. Typical selection of cables use data attributes like cross-section, insulation level, age, type, etc. The *queries* may investigate other data in order to produce objects that will enter the optimization process (i.e. a planner may user urban zones to exclude routes through certain areas). The queries are also used to decompose the planning problem into specific or smaller problems. A typical case is a city network, where the urban center link structured, while suburban areas are supplied by open-loop structures.

Step ④ is an automated process, which executes *queries*, transforms data and finally creates a network for the optimization process. Transformations of data are performed by data definitions - *expressions*. To emphasize the flexibility of this approach, routing costs using existing cables may be calculated using data fields in various tables (zone weight, road type, etc) or various variables (i.e. costs per meter). After data transformations, a network used for routing cables is created in terms of an AutoCAD proprietary topology model. Network segments are composed of line elements corresponding to existing cables and possible routes (old cables and allowable corridors). For each network segment a cost is calculated to represent expenditures related to investments and maintenance for the whole planning period converted to present worth values. The cost is differently calculated for the three types of line objects using AutoCAD map *expressions,* allowing flexibility in the planning model. The default *expressions* calculate the cost by multiplying the length of the cable with new cable cost per meter and a present worth factor. New cable cost per meter is uniform to the whole planning area or it may be obtained from a data field giving the planner an opportunity to specify higher (difficult terrain or constraints imposed by local government exist) or lower costs (ducts) of individual segments. It is important to notice that the network created is composed of segments so individual feeder segments of different electrical properties (cross-section, material, insulation, etc.) are naturally represented in this model.

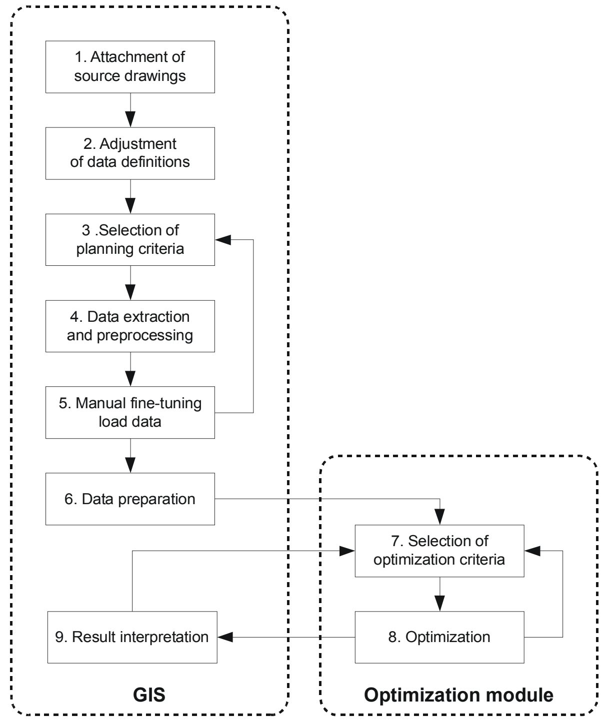

Figure 2. Planning procedure supported by CADDiN

In step ⑤ modifications may be performed on power demands of load points allowing experiments with load growth. The capacities of substations may be modified to allow reserve for excluded load points (due to decomposition or for supplying special customers).

Step ⑥ exports data from GIS to files used by the optimization module, while optimal routing is carried out in steps ⑦ and ⑧ until an acceptable solution is found. In step ⑨, the results of the optimization are returned into the GIS so they may be cross-referenced with the geographical data. Figure 3. shows a typical solution for a planning problem within AutoCAD, where feeder routes (thick lines) may be checked using other geographical information (i.e. available routes shown as thin lines).

Although the current version of CADDiN is in essence a single-stage planning tools, solutions of a problem may be used as input for a new instance of the planning process, thus providing a pseudo-dynamic procedure. This of course cannot match pure dynamic models, but may provide insight for planners how their networks respond to load growth. The planning period must be divided into series of shorter periods, but not shorter than a period suitable for investing (3-5 years). Short periods are overwhelmed by investment expenditures and existing cables are used, but an interesting piece of information is the position of tie-links.

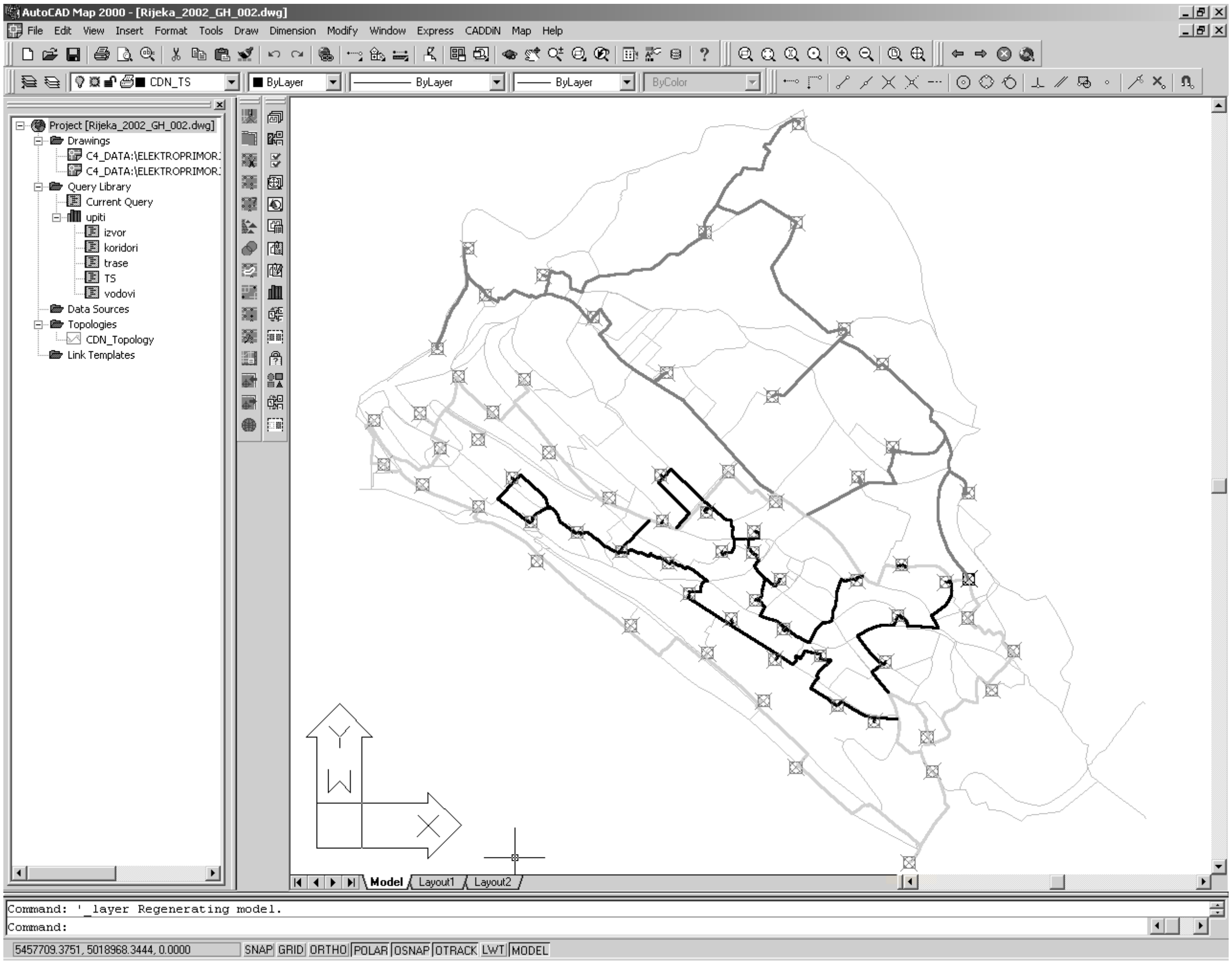

Figure 3. Solution to a long-term planning problem for 66 load points supplied by a single substation

Since the planner has the opportunity to evaluate various scenarios for the same area by changing load estimates and the number of load points in the planning area, great sensitivity is shown regarding load forecasting data for long periods.

7. Future plans

The development and research related to CADDiN seeks to enrich and develop planning practices by filling the voids in tools and methodologies present in the Croatian Electricity. The research done on CADDiN in the past had been oriented to various aspects of modeling existing networks and the use of GIS. Spatial forecasting has been also a field of research [14]. Two mayor topic are of current interest: 1) reliability and 2) timing of investments (dynamic planning).

GA proved to be and excellent tool for solving combinatorial problems, or in this particular case routing problems. As such, GA and Artificial Intelligence in general will be constantly investigated to improve approximation algorithms used in optimization problems related to distribution planning.

Concerning the development of CADDiN the following statements are of importance (based on experience and user feedback):

- Users must be able to manually revise the solution of optimization in order to a) help the optimization algorithm to leave a local optimum and b) to produce new solutions relatively similar to the computer generated solution but better according to other attributes.
- Calculation of additional attributes of distribution networks (i.e. reliability indices) must exits for purposes of multi-criteria selection of various scenarios.
- Data and planning parameters must be easily transferred from one workstation to another.
- User manuals and training data are preferred in contrast to on-site training or distance learning.
- Data models must be flexible and easy to upgrade. Object oriented technology is a perfect way to solve this issue, but selection of software tools may be difficult and consequences of a wrong selection are usually visible late in the project.

- Tools must be impartial as possible to vendors and technologies. Third-party tools must be easily utilized during certain steps in the planning process.
- The software development must keep pace with mainstream trends in computer sciences and practices (adoption of new standards must be done promptly).
- The planning process intensely benefits from GIS since it is an essential part of a Utility's IT infrastructure. The Utility's data must be appropriately modeled and easily accessed.
- Planning software and the underlying algorithms must be flexible to incorporate new details used in planning.

8. Conclusion

A methodology for long-term planning of medium voltage networks has been developed using Genetic Algorithms for optimal routing and Geographic Information system for handling more accurate geo-referenced data. The methodology proved to be successful for creating long-term plans in practice. Solutions obtained by other methods or tools, especially short-term oriented may use the solutions provided by CADDiN to coordinate long- and short-term planning decisions. The ability of CADDiN to take existing cables into consideration is the basis for such a strategy.

The authors recognize that this methodology and accompanying software must grow with respect to three issues. *Timing* of investments must be considered by the planning methodology due to the fact that decisions are crucial in the early stages of the planning period. *Reliability* is yet to rise as a pressing issue in Croatia, since liberalization and deregulation are still in their primordial state. However, reliability calculations will be incorporated in CADDiN since users desire a planning tool for all network structures (open-loop, link, radial and meshed) with the ability to force network evolution from one structure to another. The problems of timing, sizing and locating investments are particularly dependent on *load forecasting* data which is unreliable due to many uncertainties brought by the future, lack of data and its stochastic nature.

9. Acknowledgements

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