INTRODUCTION

In traditional utility planning, expansion needs were defined by the cost-based pricing environment. Utility planning focused on finding the lowest cost alternative to serve all customers. In addition, as a sole provider of electric service the utility assumed that it had an obligation to determine and implement the least-cost use of energy and other resources. In a deregulated power industry, this situation will change very little for the distribution planner. The local distribution company will still be regulated, and prices for delivery (if not power) will still be cost-based. Instead of an obligation to serve, local distribution company will have an obligation to connect, or more specifically an obligation to provide sufficient capacity. Under retail wheeling, some other company’s power may be flowing through the distribution system (DS) to the customers, but the distribution company is still required to provide sufficient capacity and to do so at the lowest possible cost.

The optimal distribution system planning is recognized as a very complex problem because of large number of variables and candidate network configurations, related with the characteristics of geographical area and the consumer loads served. The activity of planning may be categorized in the following three categories: expansion planning, operation planning (to choose the optimal configuration (e.g. the set of switching operations) in order to improve efficiency and reliability with (possibly) no investment costs), and emergency planning (to attenuate the effects of the contingency).

There have been many approaches to the planning problem taken in recent years. Large network problems have been addressed for linearized objective functions. Branch and bound applications can be found in [1,2,3], mixed-integer programming in [4] together with Bender’s decomposition [5] and with branch exchange [6,7]. Dynamic programming approaches have been taken in [7,8]. Surveys on classification and applications of the distribution system planning can be found in [9,10]. More recently, evolutionary computation techniques have also been proposed [11,12]. Those are string genotype approaches to small-size network problems. For large networks the combinatorial nature of decision making turns such genetic algorithms (GAs) into computationally expensive approaches.

In this paper we present Geographical Information System (GIS) supported evolutionary approach developed to address large-scale link structured distribution network expansion planning problems with multiple HV/MV transformer and switching stations. To our knowledge only two researchers [13,14] have devised methods suitable for the problem of open link DS design. However, these methods have some drawbacks: restructuring of the existing feeders is disregarded, switching stations are neglected, number of HV/MV substations is limited, etc. We propose operational methodology used by Croatian Distribution Utility Companies and which is based on the software tools collectively referred to as ADDin (Computer Aided Design of Distribution Networks) each aimed at a specific part of the planning procedure (e.g. data preparation an interpretation module, optimization module, spatial load forecasting module). In this paper the role of the proposed method is recognised in the search for strategies based on robust decisions, in the uncertainty and multiple criteria framework, driven by the consideration of the risk concerned.

DISTRIBUTION FEEDER LAYOUT WITH COMPLETE CONTINGENCY SUPPORT

Underground urban systems are the most expensive type of power distribution, fulfilling the most difficult distribution task – delivering very high load densities at high reliability while keeping completely out of sight (the vast majority of primary feeders within Croatian distribution system in urban areas are built from insulated cables directly buried or pulled through concrete ducts in the ground). One of the main concerns in such distribution systems is their reliability of service. Digging into the street in an urban area, as would be required occasionally for new additions or repairs of direct buried cable, is very expensive. Such work requires permits (which are often not immediately forthcoming), and tight control of construction schedules. So repairs can require from several hours to a day or more.

For all DS the recommended practice is to have some way in which maintenance and replacement of every element in a system can be performed without causing lengthy interruption of electrical service to customers it feeds. Thus, alternate sources, paths and configurations of service must be planned allowing system reconfiguration in a case of contingency. With no doubt, one of the major aspects influencing selection of a feeders and substation transformers capacity, type, route and layout are alternative routes. However, the reliability of service has mostly being ignored in planning models (at least its detailed representation) because theirs mathematical formulation is highly complex. Some authors have been proposing models were reliability considerations are considered. In [15] author proposes, after obtaining the optimal radial network, building of new feeders (according several economical and technical criteria) for the closing of loops in order to allow network reconfigurations in case of contingency, increasing the network reliability. However, this procedure will not lead to an optimal meshed configuration. Another aspect that strongly influences the reliability of distribution systems is the switching policy (i.e. the optimal placing of switching equipment). A common policy is the
placement of switches in most lines in urban distribution networks. However, having manually operated or remotely operated switches has a large impact on distribution reliability and on network design. A convenient mix must be searched, and this is a complex problem itself. Therefore, generally this problem in considered a posteriori (i.e. after the solution for the distribution network is obtained).

In Croatian distribution systems, to mitigate the widespread of interruptions whenever any equipment failure occurs, both feeder and transformer level contingency supports are espoused. This means that besides using modern reliability-indexes as optimization attributes, the traditional approach of contingency coverage perspective (i.e. layout interaction on contingency support) is introduced as one of the major planning criteria. In other words, DSs in urban and suburban areas are operated as open loop (European distribution layout) and open link (Fig.1). The contingency back-up is simply implemented (single zone scheme) – it involves building feeders in pairs (i.e. as two “halves” of one loop or link) and operating them with open tie between their ends. This way, service to most customers on the outaged feeder is restored with between two to four switching operations. However, to achieve feeder and transformer level contingency support, such DSs must be upgraded to a significant portion. But this almost equally applies to multi zone contingency backup schemes if the distribution network layout is arranged to support transformer outages [16]. Namely, although multi zone contingency backup schemes require almost no additional cost for line segment reinforcements to achieve feeder level contingency backup, these gains become scant at the cost of greatly increased operational complexity, if the transformer level contingency backup is adopted. Still there are several aspects, as listed bellow, which attenuate the increase of reinforcement costs:

1. There is usually large difference (e.g. 70-100% of economical loading) between the economical and full thermal load ratings for any particular line type.
2. During contingencies voltage drop and load limitations are relaxed substantially.
3. Due to the relatively short feeder lengths, and relatively large cross sections in standard inventory of approved cable types, voltage drop is seldom, if ever, an issue in contingency planning.

4. Major distribution substations consists of two or more HV/MV transformers which are designed to provide full service to group of feeders served by any single transformer or buses out of service.
5. Simple in concept and very structured design makes use of standardized unit HV/MV substations, loops and links, and therefore this type of circuit proves very easy to layout, engineer and build.

This paper will focus attention to the problem of open link structured DS expansion planning. For detailed information on open loop DS expansion planning refer to [17].

THE ROLE OF GEOGRAPHICAL INFORMATION SYSTEM

In the past the need to deal with massive quantities of information was one, if not the most important constraint in the DS planning. The need of dealing with huge amounts of information is related, not only to the characteristics of the problem itself, but also to the recognition of the fundamental importance of the use of GIS in distribution network planning. For planning purposes GIS may provide huge volumes of geo-referenced data (urban zones, road networks, other distribution networks, etc.) useful in detailed decision making.

Architecture (modularity) of the proposed method

The network of allowable feeder routes within the GIS may be assembled from various line objects (e.g. road centre lines or some other lines related to road networks, property boundaries, existing cable routes, etc.). Direct distribution system expansion planning using the corridor network requires substantial effort since besides large number of existing cables, delivery and demand points there is a huge number of connecting nodes rising form breaking intersected line object (e.g. existing cables & centrelines) in the corridor network. What is the level of complexity involved in the process of proposing optimal strategy verify the data given in Table 1. Here the numbers of GIS nodes and links contained in the corridor network are given for the problem studied in the computational results section. Obviously, the planning procedure faces myriad – often literally millions – of possible ways to combine segments into feeder plans. Building such monumental software within the GIS proves to be too
Preparing necessary data

Analyzing the existing system

The expansion planning of the distribution system is necessary to satisfy:

- the new loads load,
- the load growth,
- to improve the overall efficiency and reliability of the system.

Priory to any planning effort the existing system should be analyzed - the capability of existing facilities is compared to long term needs. If capacity falls short of need, alternative options (e.g. introduction of new supply substations, dismantle and remove existing substations, reinforcement of existing supply substations, adding new feeders, introduction of switching stations, etc.) are defined which are further studied in the optimization procedure to determine expansion plan which will “correct” the situation in a best manner. The long term load forecast is primarily an input – it is used to compare with existing capacity to determine if and where projects could be initiated.

Preparing necessary data

Priory to the planning missing distribution system data (i.e. stored in external databases) must be supplied and adequately prepared (converted or calculated). Besides, the following planning criteria and requirements of the optimization procedure must be defined within GIS.

- Supply region for the observed distribution network.
- Possible optimized network layout (i.e. link, loop). Namely, the planning procedure relies on the planner to specify substations pairs connected with feeders. This feature is especially important because besides supply substations optimization algorithm, that allows planner to specify permissible pairs of substations, is capable of designing link distribution systems that comprise switching stations as well. Namely, in the case of switching station planner can specify exactly one or two neighbouring supply substations that will be connected with this station.
- Operational voltage (e.g. adopting new primary voltage), minimal cross section of existing cables, possible sizes of new supply transformers, possible locations of new supply/switching substations, maximum number of feeders drawing power form each supply/switching substation.

Evaluating alternatives

Each alternative in the optimization procedure (evolutionary algorithm) must be evaluated against both criteria and attributes. Criteria are requirements and constraints the alternative must meet, including: voltage drop (as established by electric utility – in Croatia 2-8% during normal state operating conditions and 10-12% during outage conditions), loading limits, contingency margin rules, network layout. To stimulate the creation of alternatives acceptable on the account of loading limits and of a better reliability related costs, to the previous conventional list we have added the following two specific constraints:

- The total load associated with each link must be within the specified limit. The maximum meaningful value of this limit equals to the contingency thermal rating of new feeder segments since the size of all new sections is uniform. In some cases planner might specify lower value to ensure the reserve in feeder’s capacity for the future load growth.
- The maximum number of load points per link is limited by 15-30. An attribute is quality that is to be minimized (or maximized) while still meeting all criteria. Traditional power delivery planning (i.e. deterministic case) is single attribute planning, in that only one attribute (cost) is to minimized where cost is a multi-dimensional attribute (equipment, site costs, labour, operations and maintenance, losses, energy not supplied).

Present worth analysis is used to put present and future values on a comparable base. The feeder system usually represents two thirds to three quarters of the total cost of the distribution system, and is the cause of between one half and two thirds of service interruptions [16]. Many approaches to optimal feeders routing require prior knowledge of candidate locations of feeders. This simplifies the problem but can not give the optimum solution. In CADDIN method we use a different approach – no prior knowledge of candidate feeders’ locations is required and the GIS spatial analysis is used to accurately estimate feeders’ costs.

Feeders generally follow roads, highways and property boundaries. This means that feeders are restricted to routing along a grid of corridors (i.e. corridor network). The estimation of feeders’ cost is based on cost per meter defined on allowable route. Presuming a network of allowable feeder routes (corridor network) exists in GIS, each route segment may have different cost per meter. This cost per meter in CADDIN includes all present worth expenditures related to installation and maintenance of a feeder segment during the observed planning period (operating and reliability related costs are calculated within the optimization algorithm). Bearing in mind that the cost of excavating trenches, permits, legal fees, site preparation, labour, and so forth aggregated may be several times higher than the actual cable cost, in addition to specifying installation costs for a specific cable type on a particular route, our approach may utilize large savings related to the following aspects: instantaneous routing of parallel underground cables, using previously constructed...
ducts (e.g. reuse of obsolete cables), integrated utility planning (e.g. electricity & gas or electricity & telecommunications). This is especially important in central cores of major cities where municipal restrictions or codes limit the utility to major construction in an area only once every five years, etc. As a result, making sudden changes to accommodate load growth is simply not possible. Contrarily, by assigning higher costs to some allowable route segments, planner may hinder theirs usage in the automated planning methods.

The primary analytical method for estimating cost (finding routing corridors) of connecting pairs of substations is the shortest path algorithm (which is usually provided by GIS software) with a (previously addressed) corridor segment costs as a weight. The total “investment & maintenance” part of service costs assigned to some feeder segment in the distribution network is calculated (within GIS) by simply adding together costs emanating on each “shortest path” corridor between a pair of substations. Obviously for a part of a corridor used by an existing cable the installation cost equals zero (i.e. there are only maintenance and operational cost).

Such economically and technically defined costs for routing allow the optimization algorithm to simultaneously expand, reconfigure and reinforce the existing distribution network – although the preference is given to the usage of the existing feeder segments there is no guarantee that they will be selected in the shortest path analysis. This heavily depends on costs per meter assigned to theirs routes in the corridor network.

THE NEED FOR A STRATEGY

Multistage problem dynamics

Although the evolutionary algorithm described in the next section is in essence single stage planning tool, it can be used to solve multistage problems (in the last case under the pseudo-dynamic methodology). The pseudo-dynamic planning methodology should be divided into two phases, where in the first phase the distribution system is regarded as static in nature (load remains constant at its projected level at horizon year). The objective of this phase is to design a system that can serve this particular load demand in an optimal manner. Then, in the phase two, the effect of load growth is explicitly considered. For each intermediate year between the base and the horizon it is necessary to determine an optimal intermediate system. The intermediate system utilizes the existing as well as the set of equipment that has been specified from the horizon year static optimum system. After advancing through each of the intermediate years, for all equipment from phase one results decision is made about timing of the investments. The resulting strategy, as such, consists of a set of coordinated long-range plans that cover all possibilities of network development. Such multi scenario planning reduces the risk because it recognizes that there will be a need to change direction once the uncertainty is resolved and it plans for that. However, here it must be stated that both at the end of first and second GA run engineering judgment (supported by some multi-criteria decision making method (e.g. successive amplification method [11])) has to be applied in order to determine ideal for each path and the final decision strategy. Minimizing the regret is just a way of determining the robust expansion strategy. The approach proposed in [12] also relies on scenario representation (continuous representation of uncertainties (i.e. fuzzy sets) is not used). However, some differences in comparison to [11] approach exist. This method strongly relies on the assumption that for the fist stage of the planning horizon one could have good forecasts of the uncertain parameters. Namely, after the “family” of solutions is determined for each scenario by means of evolutionary algorithm, the objective of the proposed method is to find the best first stage investments that minimize the expected future and actual costs. Still, the author claims that for the expansion problems where the “catastrophic” types of scenarios are taken to represent uncertainty, risk-like formulations should be used.

Common to all these methods is the creation of the set of non dominated solutions (no matter if it is the requirement of fuzzy multi objective and/or multi scenario expansion planning). Therefore the evolutionary algorithm (version with no uncertainties involved is briefly described in the following section), seems extremely adequate to be adopted in some of...
the previously addressed methodologies. Namely, by adopting multicriteria framework and comprehensive representation of uncertainties (fuzzy sets and/or tree of futures) it provides the subsequent decision making tool with a set of possible non-dominated link distribution network expansion plans.

EVOLUTIONARY ALGORITHM

We decided to use evolutionary algorithms (EA) as they naturally give a set of solutions and can accommodate complex objective functions as required for a correct representation of the planning problem. Driven by difficulties in handling topology (radiality) constraints, inherent to majority of previously published methods especially those using binary representation, we developed both genotype and operators able to process meaningful topological information – link layout and connectivity is a genetic transmissible property [20].

Chromosome coding

Different link distribution networks are defined by the order of load points (as given on Fig.3 evolutionary algorithm approaches the problem as a sequencing problem). Before evaluating the fitness of some chromosome two-step decoding procedure converts these orders into real link distribution network (Fig.3). In the first step, for each load point in turn the “closest” (in terms of costs determined in GIS) feeder ending is determined and then in the second step, when all load points are connected to their corresponding feeders, the “closest” feeder endings are found with regard of predefined permissible supply/switching substations pairs.

Handling problems constraints

The tendency of EA operators to create infeasible solutions was suppressed so as to increase the solution’s objective by using the penalty function when evaluating the quality of some infeasible solution. After testing several strategies [20] we decided to use Powell’s method [21] as it gave significantly better results when applied on highly constrained instances of the problem.

Crossover and mutation

Two things that are clearly important in ordering the load points that allow previously mentioned decoding procedure to build good links’ routes are the position and relative order of load points in the chromosome. This is the reason why we decided to use FRX and CX operators [21]. Comparing the three different mutation operators on a series of differently structured problems instances resulted in clear winner - the OBM operator [21].

COMPUTATIONAL RESULTS

To demonstrate the features of the proposed methodology in this section we present the results we have obtained for two considerably diverse future scenarios (dealing with different paths in a specified tree of future) in an artificial case study generated mostly from the data of distribution system of city Rijeka in Croatia. The area of city of Rijeka contains eight existing 30(35)/10 kV supply substations but for the purposes of this paper we have considered only a part of this system. It consists of three supply substations (SUSA, KRIM and NOVA_2 in Fig.4) having capacity of transformers (8+8 MVA) and 90 load points (some of which will be newly constructed or reinforced during the planning period). The tree of futures was used with planning horizon of 15 years. The initial load of all load points is 23 MVA and the final uncertain load range is 39-51 MVA. Lateral branches have been removed in order to clean the network structure by adding the total power demand of load points on the lateral (it supplies less priority load points) to the load points from which the lateral is branching. The two considerably different scenarios here presented comprise:

1. scenario (the largest load growth) one new supply substations (NOVA_1 in Fig.4) is going to be constructed and one existing (KRIM in Fig.4) reinforced to capacity of 40 MVA

2. scenario (the smallest load growth) one new supply substations (NOVA_1 in Fig.4) is going to be constructed, one existing (KRIM in Fig.4) reinforced to capacity of 40 MVA and the other one (NOVA_2 in Fig.4) becomes switching station

In the planning procedure the following planning criteria were presumed: operational voltage 10 kV, coincidence factor 0.5, costs of energy not supplied 3$/kWh, XHE 49 A with 150 mm² cross section to be used for new feeder segments and 150 mm² as the lower bound of existing feeder segments cross-section (all other existing feeder segments were treated as abandoned cables’ routes). Due to the fact that the observed area comprises only a part of distribution system of city of Rijeka (several feeders emanating from the supply substations supply load points outside the observed area) limitation on a number of feeders emanating from supply/switching substations was decreased accordingly to 7. In Fig.4 the resultant link network expansion plan obtained for the first scenario in regard of minimal facility investment costs is depicted with tick lines representing feeder routes and available routes (representing centre lines of routing corridors, existing and obsolete cables routes) shown as thin lines. In Fig.5 in a same manner the link network expansion plan obtained for second scenario is depicted.

Fig.3. Chromosome coding and decoding
Due to the page limitations only solutions that are the best acceptable in terms of investment costs are given (costs given in Fig.4 and Fig.5 represent the feeders costs only). However, in the planning process, as the results of different evolutionary algorithm runs for each observed expansion option and corresponding scenario, representative sets of non-dominated expansion plans are determined each of them being best acceptable in regard of some optimization attribute (e.g. investments, power losses, reliability, load balance between feeders and/or supply substations, etc).

CONCLUSIONS

The ability to supply consumers of an urban area without any longer interruption during a feeder or substation transformer outage is assured by the link network configuration. Evolutionary algorithm based method has been proposed in this paper as a useful technique for computing set of non-dominated link distribution network expansion plans based upon many practical issues not only in an economic sense but also in a sense of technical criteria and physical routing constraints. Fuzzy sets and tree of futures concepts to model uncertainties and decision making guided by a paradigm of multi-criteria risk analysis can be easily adopted in CADDIN method. The GIS has been recognised as a source of huge volumes of geo-referenced data useful in decision making. Extensions to commercial GIS and CAD software have been developed for analyzing the existing distribution system, preparing necessary data, evaluating different expansion alternatives, interpreting and analyzing the expansion planning results (strategy).

REFERENCES

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