BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Tomul LVII (LXI), Fasc. 4, 2011
Secţia
ELECTROTEHNICĂ. ENERGETICĂ. ELECTRONICĂ

EMERGENT CONCEPTS IN DISTRIBUTION NETWORK OPTIMAL PLANNING

BY

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Received, June 23, 2011
Accepted for publication: September 16, 2011

Abstract. The current development of distribution systems towards the smart grid paradigm is sided by the reformulation of the classical objective functions for distribution system operational and expansion planning. This reformulation takes into account the increasingly significant role of distribution automation and distributed generation (DG) connected to the distribution systems, as well as the possibility of formulating multi-objective optimization problems. This paper recalls the key aspects of the evolution in progress as presented in the recent literature, and illustrates some basic concepts referring to the DG location and sizing by means of the results obtained on a tutorial example.

Key words: distribution systems; optimization; planning; multi-objective; distributed generation.

1. Introduction

Most of today's electricity distribution networks have been designed and are operated according to criteria suitable for technologies and application practices used some decades ago. Likewise, the objective functions for distribution system optimization (*e.g.*, for network reconfiguration and

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planning) are still close to the ones based on the distribution network operator (DNO) point of view. Emergent concepts and paradigms such as Microgrids and Smart grids are now *in auge*, with diffuse deployment of smart metering and distribution automation. In a smart grid perspective, the various stakeholders operating in the electricity distribution field follow their own individual objectives, aiming at scoring profits from energy management and exploitation of local resources and external energy network connections (Driesen & Katiraei, 2008; Chicco & Mancarella, 2009). These objectives may conflict with the traditional DNO ones, aiming at reducing costs of grid investments and operation. In this context, the traditional objective functions adopted for distribution system optimization need to be revisited to include aspects linked to operational efficiency, cost-effectiveness, multi-generation, environment-compliance, system vulnerability reduction, service quality improvement, customer service enhancement, and the corresponding economics (Chicco, 2010; Fan & Borlase, 2009).

This paper contains a synthesis of the concepts referring to distribution system optimal planning. Optimization is addressed by considering distribution systems without or with distributed generation (DG). The illustrations are presented with reference to the current literature and with the illustration of a simple tutorial example to highlight basic aspects for effective application of some of these concepts.

2. Optimization Approaches to Distribution System Planning

Distribution system optimization addresses *reconfiguration* problems in normal conditions or in emergency conditions (service restoration), as well as *planning* problems at constant load (operational planning) or at variable load (expansion planning). For these problems, the objectives to be optimized can be of technical and/or economic nature, ranging from the classical system losses to different types of costs (*e.g.*, for investment, operation and maintenance, selling/buying electricity), up to reliability and power quality indicators (Carpinelli *et al.*, 2005; Tsai & Hsu, 2010; Ochoa *et al.*, 2006; El-Khattam *et al.*, 2004).

Focusing on distribution system *planning*, generally the optimization problems involve the choice of the best values of the decision variables among a specified set of alternatives, taking into account planning actions referring to structural changes or to the addition of new resources in the distribution system, such as distributed multi-generation, demand response and distributed storage. The objective function is usually driven by economics, with the current trend to incorporate interactions with other energy networks and environmental issues (Mancarella *et al.*, 2011; Favuzza *et al.*, 2007). Indeed, nowadays many approaches to optimal distribution system planning formulate multi-objective problems. Once defined the multiple objectives to be considered, the typical approaches to solve the optimization problems resort to the creation of an aggregated single-objective function (for instance, the weighted sum of the individual objectives), or exploit the potential of different numerical techniques to find the non-dominated solutions forming the Pareto front. The non-dominated points in the solution space correspond to compromise solutions appearing with two or more conflicting objectives.

A short summary of recent literature contributions on planning is provided in this section (without DG) and in the next section (with DG). For instance, strategies for improving the system reconfiguration in the operational framework may take into account multiple objectives, such as in the annual feeder scheduling addressed by Yin & Lu (2009) considering losses, interruption costs and switching operational costs in the presence of time-varying load models, with a solution proposed for feeder reconfiguration. Reconfiguration is further addressed by Tsai & Hsu (2010) with multiple objectives such as losses, maximum percentage voltage variation, load balancing index and total number of switching operations to change the system configuration with respect to the reference one, and by Santos *et al.* (2010) with minimization of power losses and number of switching operations to change configuration. For these problems, the multiple objectives are generally handled by defining as single objective the weighted sum of the individual objectives, in some cases incorporating additional penalty terms (*e.g.*, weighted sum of quantities depending on network loading, substation loading and voltage ratio, each term being activated if the corresponding threshold is exceeded (Santos *et al.*, 2010)). The optimization method also includes system constraints concerning radial distribution system configuration, thermal limits of the branches and voltage quality aspects (if not already considered among the multiple objectives). Different solution methods used for the optimization problems include binary particle swarm optimization (Yin & Lu, 2009), Gray correlation analysis (Tsai & Hsu, 2010) and evolutionary algorithms with node depth encoding (Santos *et al.*, 2010).

Concerning optimal distribution system expansion planning, with time horizon up to a couple of decades (or more, (Fletcher & Strunz, 2007)) and consistent with one or more successive expansion stages (Vaziri *et al.*, 2001), the objectives used are, generally, investment costs, reliability costs and sometimes the costs of losses. Minimization of economic cost and expected non-supplied energy is formulated (Ramirez-Rosado & Dominguez-Navarro, 2004; Carpinelli *et al.*, 2001). The reliability term is replaced by Carrano *et al.*, (2006) with a system failure index, while (Carrano *et al.*, 2007) deals with minimization of energy losses and investment in new facilities and distribution lines for design purposes. Again, various solution methods used include multi-objective Tabu search (Ramirez-Rosado & Dominguez-Navarro, 2006), an Immune system-based algorithm run on a single-objective function (Carrano *et* *al.*, 2007), and other algorithms aimed at finding the set of non-dominated solutions (Ramirez-Rosado & Dominguez-Navarro, 2004; Carrano *et al.*, 2006).

3. Optimal Planning with Distributed Generation

Planning problems referring to distribution systems with DG involve the location and size of given types of DG to be placed in the distribution network nodes. These problems are also known under the terminology *DG siting and sizing* (Carpinelli *et al.*, 2005, 2001; Celli *et al.*, 2005). Since different types of DG have different evolution in time (either due to ambient conditions or control strategies), planning with DG is meaningful when the distribution system is analysed by taking into account the evolution in *time* of the load and generation patterns. For this purpose, the load patterns can be represented through load profiles, each profile being associated to a category of consumers. In this way, different customer categories can be represented at each system node. Likewise, the different types of DG are represented by their generation profiles. Other approaches do not use load and generation patterns explicitly, resorting to other variables such as the capacity factor to analyse the effect of variable DG penetration on the system losses (Quezada *et al.*, 2006).

In a deterministic framework, a general sizing problem in which the DG can be located in any node without specifying its nature and with unlimited size is a practical nonsense. In fact, in such a case the solution of the sizing problem would be trivial, with the total DG pattern at each node exactly equal to the load pattern at any time. In this trivial solution, the distribution network would remain totally unused, that is, the branch currents would be null, in turn leading to null branch losses and voltage drops. Clearly, to obtain this solution there is no need to setting up an optimization problem with minimum losses and/or minimum voltage deviations as objectives, being the solution already known. Furthermore, in the trivial solution the objectives of minimum losses and minimum voltage deviations are clearly not conflicting to each other. This said, when is the formulation of an optimization problem needed in case of DG planning? The answer depends on the presence of various types of *constraints* set on the DG, concerning

a) *DG location*, assigning to each node the type of DG that can be inserted in that node taking into account availability of the primary source.

b) *DG nature*, represented by the evolution in time of the expected DG pattern, linked to ambient characteristics or control strategies of the prime mover.

c) *DG size limits*, with minimum and maximum values due to availability of the technological solutions; the maximum values (specified by the planning operator) can depend on modularity of technologies that can be installed in packages of different or multiple size, with possible future expansion.

The solution strictly depends on the characteristics of the analysed application (system data and objective function specified), and there is no general solution to the DG planning problem. The characteristics and constraints on DG location (types of DG allowed at each node), nature and size limits of the alternatives of interest have to be fully specified. The DG sizes become the decision variables for the optimization problem.

4. DG Planning – A Tutorial Example

A tutorial DG planning analysis concerning the distribution system indicated in the Appendix is illustrated here. Hourly load patterns vary along a representative day ($H = 24$ h). Two locations (node *5* and node *9*) can host DG of variable size. For the sake of simplicity, the nature of DG is with flat generation profile (*e.g.*, a small run-of-river hydro plant, or a cogeneration system operated at full load). The alternative sizes are considered from 0 to 6 MW, discretized at 0.2 MW steps. It is assumed that the DG indicated at the two nodes does not violate the thermal limits of the network lines. This leads to a total of 31 size alternatives for each DG location, resulting in $31^2 = 961$ combinations to analyse with an exhaustive search approach (no need of resorting to heuristics).

The sets $\boldsymbol{N}$ and $\boldsymbol{B}$ contain the system nodes and branches, respectively. Two simple and widely used objective functions to be minimized are considered namely

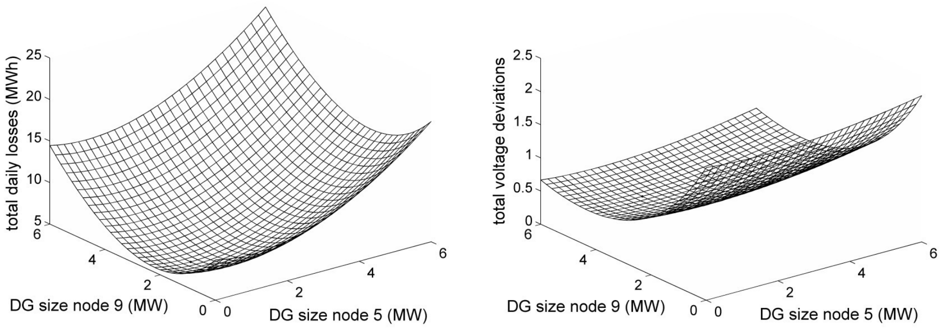
a) *Total daily losses*, calculated by summing up the losses, $\Delta P_b^{(h)}$, obtained in the branches $b \in \boldsymbol{B}$ by solving the power flow at each hour $h = 1,..., H$

$$L_{\text{tot}} = \sum_{h=1}^{H} \sum_{b \in \boldsymbol{B}} \Delta P_b^{(h)}. \tag{1}$$

b) Total relative voltage deviations (dimensionless), obtained by summing up the system relative voltage deviations in the nodes $n \in \boldsymbol{N}$ at each hour $h = 1,..., H$ (assuming the reference voltage V_{ref} equal to 1 per unit)

$$D_{\text{tot}} = \sum_{h=1}^{H} \sum_{n \in \boldsymbol{N}} \frac{\left| V_n^{(h)} - V_{\text{ref}} \right|}{V_{\text{ref}}}. \tag{2}$$

Running exhaustive search gives a global view on the possible solutions. The results are indicated in Fig. 1. For minimum total daily losses (5.0714 MWh), the optimal DG sizes are 1 MW at node *5* and 2.2 MW at node *9*, and the total relative voltage deviations are 0.7741. For minimum total relative voltage deviations (0.4909), the optimal DG sizes are 1.6 MW at node *5* and 4.4 MW at node *9*, and the total daily losses are 8.4867 MWh.



a *b*

Fig. 1 – Results with objective functions calculated from exhaustive search:
a – total daily losses; *b* – total relative voltage deviations.

Fig. 2 shows the hourly system losses and the hourly system relative voltage deviations in the two optimal solutions. The corresponding shapes are a direct consequence of considering flat DG power profiles in the system.

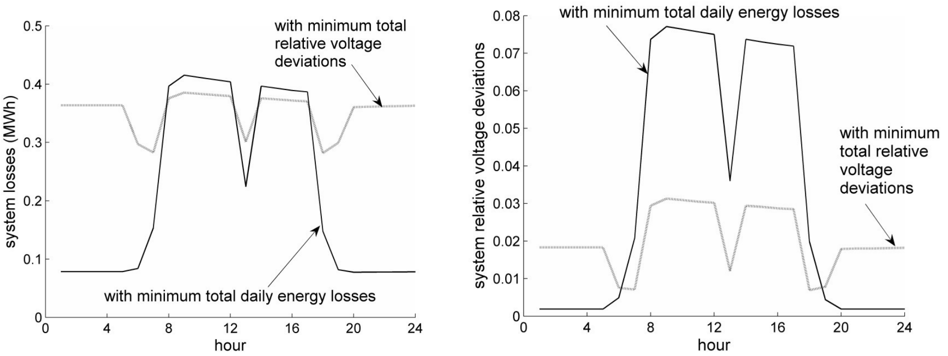


Fig. 2 – Hourly system losses and relative voltage deviation in the optimal solutions.

From the results from Fig. 1 one could argue that the solution domain for both objective functions is convex, so that gradient-based optimization techniques could be efficiently exploited. However, convexity of the solution domain in this tutorial example depends on the simple structure of the system analysed and on the absence of enforced constraints. For larger distribution systems and with multiple constraints, the solution domain is not so clearly defined, it could be non-convex and with several local minima. Hence, the adoption of heuristics methods aimed at global optimization may be effective.

Mutual consistency of the optimization objectives is evaluated through the correlation coefficient among the two solution surfaces. With DG sizes from 0 to 6 MW at both node *5* and node *9*, the correlation is poor (correlation coefficient = 0.0506), and remains low (0.1409) also restricting its calculation with a more local portion of the surfaces (with DG size at node *5* from 0 to 2

MW, and DG size at node *9* from 0 to 5 MW). As such, the two objectives cannot be deemed neither as equivalent, nor as conflicting, because with true conflicting solutions negative correlation among the local surfaces would occur.

More generally, each node can be associated to one or more types of DG sources, specifying a set of discrete sizes for each DG source. In this case exhaustive search on all the possible size combinations for each location may become impracticable, that is, the result cannot be reached in a 'reasonable' computation time. For instance, with 20 candidate nodes to host DG and 4 levels of DG size discretization (equal for all the nodes), the number of combinations for an exhaustive search is $4^{20} = 1.1 \times 10^{12}$. If each objective function is calculated, for instance, in 1 ms, the total calculation time becomes 1.1×10^9 s (over 34 years!). These numbers (although referring to relatively low numbers of candidate nodes and DG size steps) clearly indicate that exhaustive search may be indeed impracticable for real-size systems. Different methods providing pseudo-optimal solutions include genetic algorithms (Hong & Ho, 2005; Singh *et al.*, 2008), the ε-constrained method (Celli *et al.*, 2005; Carpinelli *et al.*, 2005), a multi-objective performance index (Ochoa *et al.*, 2006), iterative optimal power flow (Vovos *et al.*, 2005), improved Hereford-Ranch algorithm (Kim *et al.*, 1998), mixed integer linear programming (Keane & O'Malley, 2007), mixed integer non-linear programming (Atwa *et al.*, 2010), single-objective minimization with heuristic cost-benefit analysis (El-Khattam *et al.*, 2004), and an iterative method for DG allocation in the distribution system (Popovic *et al.*, 2005).

5. Conclusions

Key advances on the conceptual approach and on the solution methods for distribution system optimal planning are in progress. This paper has illustrated some aspects of these advances, also recalling some basic concepts referring to distribution system planning with distributed generation. Further evolution is needed to extend the concepts and methods in order to be used with uncertain data within a probabilistic framework, as well as to incorporate risk-related aspects and address the planning problems under a multi-criteria approach suitable for assisting decision-making in multi-year scenarios with high variability of the possible evolutions of the energy system structure, components and operation.

Appendix

Test System Data

A small tutorial test system is used to illustrate the concepts presented in the paper. The structure of the test system is shown in Fig. A1 *a*. The network has one slack bus (node *0*) and other 10 nodes. Data are provided in per units (pu). For the sake of simplicity, all network branches are equal, with impedance 0.01 + j0.01 pu and total shunt admittance j0.001 pu.

The loads are represented through their daily load profiles (Fig. A1 *b*), with residential, industrial and commercial load types. Normalized power is used for the representation, associated to a reference power for each node and each load type (Table A1). A constant reactive to active power ratio is considered for each load type, equal to 0.1 pu for the residential load, 0.5 pu for the industrial load and 0.4 pu for the commercial load.

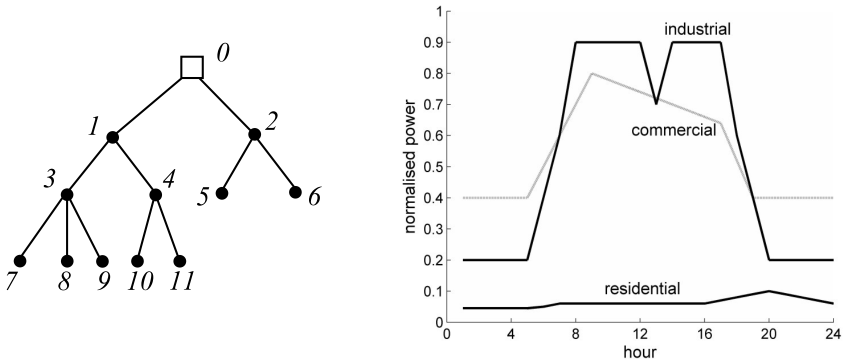
DG is assumed with flat generation profile along the day. A fixed generation of 0.1 pu is connected to node *6*. The DG units of variable size are connected to nodes *5* and *9*. The reactive to active power generation ratio is of 0.1 for distributed generation. The slack bus voltage is of 1 pu.

The backward/forward sweep method is used to solve the power flow, with tolerance 10^{-6}.

Table A1

Reference Power Values, [MW], *for Load Profiles of the Three Load Types at the System Nodes*

Load type	Node										
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
Residential	0.15	0.12	0.12	0.12	0.12	0.12	0.06	0.06	0.06	0.06	0.06
Industrial	0	0.5	0.5	0.5	0.5	0.5	0.85	0.85	0.85	0.85	0.85
Commercial	0	0.4	0.4	0.4	0.4	0.4	0	0	0	0	0



a *b*

Fig. A1 – Test system configuration and load profiles for the different types of loads: *a* – test system layout; *b* – load profiles.

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CONCEPTE EMERGENTE ÎN PLANIFICAREA REȚELELOR ELECTRICE DE DISTRIBUȚIE

(Rezumat)

Dezvoltarea actuală a rețelelor electrice de distribuție către paradigma rețelelor inteligente este însoțită de reformularea problemelor clasice de optimizare în studiile de exploatare şi dezvoltare optimă a rețelei. Această reformulare ia în considerare rolul tot mai important al automatizării distribuite şi generării distribuite (GD) prezente în rețeaua de distribuție, precum şi posibilitatea formulării unor probleme de optimizare multicriterială. Se prezintă aspectele esențiale ale schimbărilor în curs aşa cum sunt descrise în literatura de specialitate şi ilustrează unele concepte fundamentale cu privire la amplasarea şi dimensionarea surselor cu GD pe baza rezultatelor stabilite pentru un exemplu de calcul.