A Multi-objective Model for Sizing and Placement of Distributed Generation

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Abstract: - The traditional approach in electric generation is focused on centralized plants producing electricity which is transmitted and distributed over long distances through the networks. In contrast, using distributed energy resources, much smaller amounts of energy are produced by numerous small, modular energy conversion units, which are often located close to the point of use. Therefore, Distributed Generation (DG) can reduce transmission and distribution losses, as well as fossil fuel emissions, differ capital costs and improve distribution energy reliability in case of central power outage (Micro-Grid philosophy). This study presents a multi-objective approach to support selecting the location and size of DG in distribution networks, for a future integration in a Micro-Grid and Virtual Power Plant (VPP) method. The study uses a Soft System Methodology (SSM) for structuring the problem of DG planning and Genetic Algorithms (GA) to compute non-dominated solutions to the multi-objective programming model.

Key-Words: - DG, SSM, GA, Multi-objective Programming, Micro-Grid, VPP.

1 Introduction

Much of the energy generated today is produced by large-scale, centralized power plants using fossil fuels (coal, oil and gas), hydropower or nuclear power, with energy being transmitted and distributed over long distances to consumers.

There are a number of drawbacks associated with this type of system, such as the high level of dependence on imported fuels, the environmental impact of greenhouse gases and other pollutants, transmission losses and the necessity for continuous upgrading and replacement of transmission and distribution facilities [1, 9].

In contrast, in a power system composed of distributed energy resources, much smaller amounts of energy are produced by numerous small, modular energy conversion units, which are often located close to the point of end use. These units can be stand-alone or integrated into the electricity grid.

The models for planning the future architecture of electricity systems recognise that with increased levels of DG penetration, the distribution network can no longer be considered as a passive appendage to the transmission network - the entire system has to be designed and operated in an integrated manner. In addition, this operation of increased complexity must be carried out by a system under multiple management agents.

Three conceptual models have been envisaged: Micro (or Mini) Grids, Active Networks supported by Information and Communication Technologies (ICT) and an 'Internet' model - all of which could have application depending on geographical constraints and market evolution [1, 9].

The advent of new distribution paradigms and increased DG penetration in a single market brings new business opportunities. The communication systems required to operate the energy market will be open systems and an effective energy 'stock market' will be enabled. Such systems will require that uniform energy and information interfaces are

established, probably using internet based information networks.
Access to this information will allow new roles for energy brokers, the establishment of VPP and variable energy tariffs. The trading of energy futures and other financial instruments will be much widely used than today [1].
This new paradigm associated with the liberalization of electricity markets may force many public administrations in different countries to revise their energy development plans and, consequently, to decide how much generation can be accepted in their grid and where to locate it. Private promoters will be then called to bid for installing DG units.
The problem of sitting and sizing DG technologies in a given distribution network can be stated as a multi-objective planning problem. In fact, multiple, conflicting and incommensurate evaluation aspects are at stake for assessing the merit or solutions, such as investment costs vs. power losses avoidance. Multi-objective models have the capability to better reflect reality, incorporating objectives of distinct nature that are weighed by decision-makers and planning engineers to select good compromise solutions having in mind their practical implementation. These models enable to grasp the conflicting nature of the objectives and the tradeoffs to be made in order to identify satisfactory compromise solutions by providing a basis to rationalize the comparison between non-dominated solutions. A non-dominated solution is a feasible solution for which no improvement in all objective functions is simultaneously possible; that is, an improvement in an objective function can only be achieved by degrading, at least, another objective function value.
The mathematical model herein proposed involves both discrete and continuous variables as well as nonlinear constraints, namely related to power flow equations. Therefore, due to the presence of multiple objective functions, non-linear relations, and its combinatorial nature the model is hard to solve using mathematical programming algorithms. This was the motivation to resort to GAs to compute non-dominated solutions to the model developed [2, 8].
In the realm of optimization, GAs present a behaviour similar to natural evolution, in which a population of potential solutions evolves over successive generations with survival of the fittest. The suitability of GAs to deal with multiple objective problems has been widely recognized [3].
This paper presents an algorithm based on SSM for structuring the problem of DG planning [2, 4], helping to develop a multiple objective programming model in which several axes of evaluation are explicitly considered. GAs are then used to compute non-dominated solutions to the model.
Section 2 discusses the opportunity offered by Active networks, Micro-grids and the VPP methodology when DG is sited in distribution networks. In section 3, the main features of SSM are briefly reviewed. The main approaches for tackling multi-objective programming problems using GA are described in section 4. In section 5 the problem formulation is presented. The GA developed to compute solutions to the problem is analyzed in section 6. Section 7 reports some preliminary results of a case study. Finally, some conclusions are drawn in section 8.

2 Active Networks, Micro-Grids and VPP

Active networks have been specifically intended as facilitators for increased penetration of DG and are based on the recognition that new ICT technology and strategies can be used to actively manage the network.
The model is based on two main concepts: i) *Provide connectivity*; ii) *The network must interact with the consumer*. The structure of this model is based on increased interconnection as opposed to the current mostly linear / radial connections, relatively small local control areas and the charging of system services based on connectivity. The active network has some analogies to telephone networks and requires active management of congestion unlike conventional passive systems that rely on Ohm’s law to determine power routing. With increased distribution of power input nodes due to DG, bi-directional energy flow is possible and new technologies are emerging that can enable direct routing of electricity. New power electronics systems offer ways to control the routing of electricity and also provide flexible DG interfaces to the network. Electricity transmission in the system is not dependent on a single route so failure due to a single component problem is reduced.
The greatest change in the active network model is at the local control area level where each area defined has its own power control system managing the flow of power across its boundaries. The system would be then ICT-based with management enabled by remote actuators controlling it. The central area control computer would ‘negotiate’ with neighbouring areas on exchange of power. If an area was isolated then the system would react by disconnecting enough load or generation to maintain

the correct power balance. This could lead to considerable improvements in the reliability of the supply system as a whole. This model requires relatively little further investment in infrastructure, except to reinforce some areas of the network to provide increased interconnection and investment in automated switch gear [1, 2].

Micro-Grids are small electrical distribution systems that connect multiple customers to multiple distributed sources of generation and storage. Micro-grids are typically characterized by multipurpose electrical power services to communities. These hybrid systems have also the potential to: i) provide reliable power supply to remote communities where the connection to the transmission supply is uneconomic; ii) prevent outages or local blackouts by isolating the faulted area and permitting independent islands [1].

A VPP is typically a multi-fuel multi-location and multi-owned power plant composed by several types of DG units (solar, micro-turbine, …). This concept is not itself a new technology but a method of organizing decentralized generation in a way that maximizes the value of the generated electricity to the utility. VPPs have the modularity potential to replace conventional power step by step until a sustainable energy mix has been reached [1].

3 Soft systems Methodology

The need for a problem structuring phase to improve the perception of complex situations in different decision contexts has been recognized as a first step into the development of a decision support model.

SSM explores a problematic situation by identifying its nature and all stakeholders involved and their relations. Activity models for relevant systems are developed, according to the perception that each actor has of the real-world. These models are compared with the real-world, resulting in a set of possible changes to be implemented to improve the situation [4]. By enabling to structure a mesh of inter-related problematic issues, SSM also unveils the evaluation aspects, which contribute to assess the merit of different courses of action, therefore helping to shape the criteria to be used in decision support models.

One of the main stages of SSM is the “finding out” stage, where a description of the problem situation is made.

SSM uses the following three basic steps:

- *Finding out about the problem situation*. In this phase, it is necessary to characterize the actual situation and all its relevant components. With all the information collected from the real-world, a flow of events and ideas is defined.
- Naming relevant human activities and building conceptual models. In this phase, fundamental evaluation aspects and constraints of distinct nature (technical, economical, environmental, etc.) are unveiled. This effort lays the foundations for the development of the multi-objective programming model.
- Taking action in the situation to bring improvement. This phase involves, in the framework of our model to support planning decisions, to identify the actions (solutions) resulting from the mathematical programming model, instantiated with the relevant data collected throughout the process, integrating the Decision Maker (DM) interactively in the solution search process.

4 Genetic Algorithms in Multi-objective Programming

Multi-objective optimization is a very important topic because most real world problems require the explicit consideration of multiple, and incommensurate evolution aspects to assess the merit of potential solutions. The solution to a multi-objective problem generally consists of a set of non-dominated solutions, a Pareto front. The Pareto front yields many candidate solutions, from which the DM can select the one as a satisfactory compromise plan, underlying a trade-off between the objectives according to different methodologies to support user intervention [3].

The ability to work in each generation with a population of potential solutions makes GAs well suited for multiple objective programming problems, namely combinatorial ones, in which a set of non-dominated solutions must generally be identified rather than a single optimal solution. The non-dominated frontier offers the DM a wider view of the compromises that can be established in different regions of the search space. GAs present a behaviour similar to natural evolution, in which a population of potential solutions evolve over successive generations. The evolution process takes place in several phases. Generally, the first one is the evaluation of individuals according to some objectives. A selection phase follows in which some potential solutions are chosen from the population, using a probability that is a function of the individual performance. Usually, a higher selection probability is given to the individuals with higher performance. Crossover and mutation operators are then applied to the selected solutions to give origin to the next generation. The process continues until some stopping condition is reached. These operations carried out in the realm of optimization problems are inspired on natural evolution, allowing for the exploration of the search space and striving for good solutions to the problem under study. The operators (selection, crossover and mutation) and an adequate fitness function allow for the evolution process to be carried out. Usually, the fitness of every individual in the population encompasses the evaluation in the several objectives under analysis and other issues that may be taken into consideration, such as changing the selection pressure.

The selection operator is responsible to generate duplicates of good solutions and eliminate bad solutions in a population. Some methods to achieve this purpose include tournament, proportional and ranking selection. The crossover operator is the main genetic operator once it has the potential of exchanging chromosome parts between individuals, thus creating different individuals hopefully more fitted. The mutation operator has the potential of bringing new genetic material into the population, thus forcing the search of new regions [3, 6].

5 Problem Formulation

The following formulation illustrates the effect of DG penetration on the actual load demand and voltage profile of the distribution feeder equipped with switched shunt capacitors. In radial networks, bus voltage decreases as the distance from the distribution transformer increases, and may become lower than the minimum voltage permitted by the utility. Utilities usually combat this problem by increasing the tap ratio of the distribution transformer, and/or by switching on the shunt capacitors. By providing a portion of energy on site, DG systems reduce branch current, which in turns leads to reducing losses and increasing voltage throughout the feeder.

The proposed planning tool deals with the location and sizing of DG units in order to obtain the benefits associated with minimizing the loss of total real power in the system and the investment costs of installation of DG units.

Hence, it can be formulated as the following optimization problem:

Minimize $[C_{inst}, P_{losses}]$

Subject to *Power flow Equations*
V, I Limits
Pollutant Emissions

Quality of service requirements of an acceptable voltage profile in customer points are included as constraints resulting from legislation.

The MO problem is a constrained non-linear optimization problem with mixed variables (due to the presence of modular sizes of DG units).

5.1 DG Installation Costs (C_{inst})

For installation cost minimization, the performance index $\mathbf{C_{inst}}$ is given by:

$$Min\ C_{inst} = \sum_{j,k,l,n,m,i} (CI^{jm}_{ikln} . x^{jm}_{ikln}).(1+d)^{-k} \quad (1)$$

where CI^{jm}_{ikln} represents the installation cost of the DG unit of technology *i*, of *j* kW nominal power, in year *k* of the planning period, installed on bus *l* (from the derived feeder *n* of the main feeder *m*). x^{jm}_{ikln} is a binary decision variable and *d* is the discount rate.

$$x^{jm}_{ikln} = \begin{cases} 1, \text{ if the DG technology is installed} \\ 0, \text{ otherwise} \end{cases} \quad (2)$$

5.2 Active Power System Losses (P_{losses})

This objective minimizes the real power losses arising from line branches.

$$Min\ P_{losses} = \sum_{m,l,n} r^m_{ln} \frac{(P^m_{ln})^2 + (Q^m_{ln})^2}{(V^m_{ln})^2} \quad (3)$$

where, r_{nl}^m is the ohm value of bus *l* (from the derived feeder *n* of the main feeder *m*), and P_{nl}^m and Q_{nl}^m are the corresponding active and reactive power flow.

6 Solution Approach

A GA has been developed aimed at characterizing the non-dominated front for this problem of locating and sizing DG units in radial distribution networks. The outline of the algorithm proposed is based on the following steps:

1. Randomly generate the initial population satisfying the problem constraints;
2. Compute the fitness of each individual in the initial population;
3. Determine the initial secondary population obtained from the initial population;
4. Current Population ← initial population;

While (number of iterations is not attained) do

5. Build the next generation population;
   5.1 Apply elitism;
   5.2 Select individuals from the current population by binary tournament;
   5.3 Apply genetic operators;

6. Evaluate solutions; Apply dominance test;
7. Update secondary population;
8. Current population ← main population;

This procedure aims at finding a good compromise among the different non-dominated solutions for sizing and sitting of DG units in a distribution network. The aim is to provide the DM with information about the universe of potential (non-dominated) solutions and the underlying trade-offs, which could be used to support the choice of a satisfactory compromise plan.

7 Case Study

The methodology described in section 6 to characterize the optimal Pareto front, and provide decision support in the multi-objective model presented in section 5, has been applied to a distribution network with 94 nodes and 24 lateral feeders.

Five types of DG technologies are considered for possible installation (1-Solar, 2-Wind, 3-Micro-turbines, 4-Small-Hydro and 5-Fuel Cells).

The flexible characteristics of this approach enable the DM to make experiments with different parameter sets, adjusting them throughout the process.

The initial parameters are:

- Initial population size NP;
- Secondary population size NPS;
- Number of elite individuals EI introduced in the main population;
- Number of generations;
- Mutation probability *mp*;
- Crossover probability *cp*.

The algorithm uses a two-point crossover (with *cp*=1) and feasible non-dominated solutions only. After several runs the best results where obtained with: NP=32, NPS=42, EI=4, 6000 generations and *mp*=0.1.

Figure 1 displays the Pareto front, in the objective function space (objective function system losses and installation costs). This set of solutions on the non-dominated frontier is used by the DM as the input to select a final compromise solution.

For example, if the DM considers the solution marked with the circle as a good compromise plan according to the two conflicting objectives, the system losses are 25.559 KW and the installation costs are 25 Million Euros. The algorithm indicates the type of DG technologies to be installed at the following buses (table 1).

Where, only two types of DG units were chosen (type 2-Wind turbines and 3- Micro-turbines).

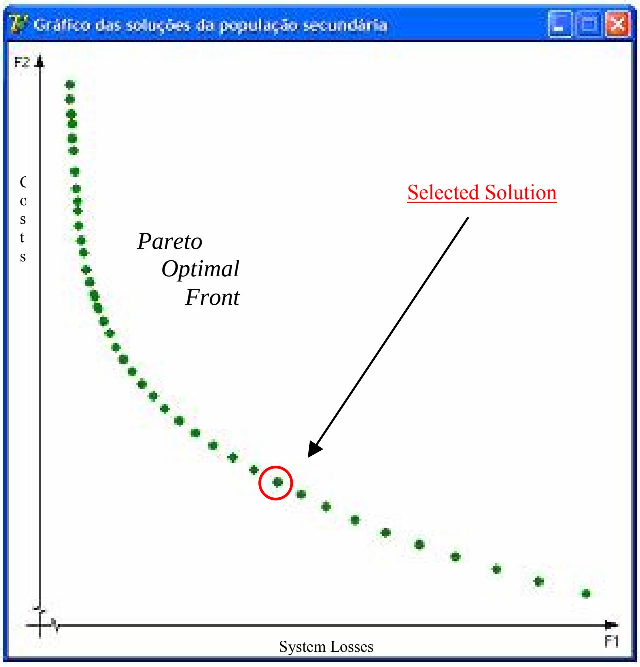

Fig. 1 – Final population with 42 solutions

BUS	13	23	24	26	28	31	40	49	52	54	58	62	65	66	67	77	78	79	90	92
DG	2	2	2	2	2	3	3	3	2	2	2	3	2	2	2	2	2	2	3	3

Table 1-Installed DG in network buses (solution 10).

4 Conclusion

In this paper, the problem of location and sizing of DG technologies in distributed networks has been modeled as a multi-objective problem. Two objective functions of technical and economical nature are considered in the model: minimization of total power losses and minimization of DG installation costs.

The algorithm developed is based on an elitist GA, characterizing the optimal Pareto frontier, that represents a set of distributed solutions which can be chosen by the DM for practical implementation. This algorithm is aimed to work as a way to obtain the input information (obtained from the output of a GA) necessary to develop a decision support system. This decision support system may be integrated in a traditional passive network or in an active network, Micro-Grid or may use a VPP method.

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