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Voltage Stability in Distribution Networks with DG

M. Alonso, H. Amarís

Abstract— **This paper presents a methodology for optimal placement of DG units in power networks to guarantee the voltage profile, maximize loadability conditions in normal and in contingencies situations. The methodology aims in finding the configuration, among a set of system components, which meets the desired system reliability requirements taking into account stability limits. Results shown in the paper indicate that the proposed formulations can be used to determine which the best buses are where the addition of small distributed generator units can greatly enhance the voltage stability of the whole network and power transfer capability under contingencies.**

Index Terms— **Distributed generation, genetic algorithm, voltage stability, contingencies.**

I. Introduction

In recent years, there has been an increasing interest in the production of electric energy from renewable energy sources, such as: wind, sun and water. Main reasons are: fuel saving, supplying remote places and environmental considerations.

Distributed generation (DG) is defined as small generation units with a maximum capacity from 50 MW to 100 MW that are usually connected to the distribution network. DG units are neither centrally planned nor dispatched. In spite of their advantages, DG has a great impact on power flow, voltage profile and stability of the power system.

Electric power planning with the presence of DG units requires the definition of several factors, such as: the best technology to be used, the number and capacity, the best location or the grounding connection. The installation of DG units at non-optimal places can result in high power energy losses implying higher costs. Moreover, optimal planning of DG units, like PV and wind turbine, is limited to few allocations available because it would depend on the energy resource location.

Recently, Distribution Operators have successfully applied metaheuristics optimization methods for planning issues. The reason is mainly because they can reach a satisfactory solution of the problem; they are very fast and they have low computation complexity. Genetic Algorithms (GA) are gaining increasing popularity in power systems planning because they are robust and they can find the global optimal solution in complex multi-dimensional search spaces [1].

The paper is organized as follows: section 2 presents the objective of the work; sections 3 and 4 present a brief review of voltage stability and Reactive Power Planning (RPP) methodology respectively; section 5 describes genetic algorithm technique that it is implemented on section 6. In section 7 numerical results are presented to prove the suitability of the proposed methodology. Conclusions are shown in section 8.

II. Objective

The objective of this analysis is to find the best allocation of different DG units, with VAR capability, in order to maximize loadability of the system. This study will be done for improving voltage stability under contingency situations using heuristic methods. The methodology is based on the application of the two following processes (Fig. 1):

- Optimal allocation process: The aim of this method is to optimally locate DG units with VAR capability on distribution network in order to maximize loadability conditions of the system and to provide potential candidates to the problem. For this task GA are used to evaluate possible solution of the optimization problem as is shown in Fig. 2.
- Evaluation of contingency situations: This second process evaluates the reliability of the distribution network with DG optimally located under N-1 contingencies. Voltage profile and voltage stability are evaluated.

III. Voltage Stability

Voltage Stability is defined as the ability of a power system to maintain steady-state voltage at all buses in the system after being subjected to a disturbance from a given initial operating condition [2]. In the literature, two voltage stability problems are analysed:

- Estimation of the maximum loadability.
- Computation of the critical power system loading that could lead to voltage collapse.

Voltage stability is usually represented by P-V curve. In Fig. 3 the noise point is called the point of voltage collapse (PoVC) or equilibrium point. At this point, voltage drops rapidly with an increase of the power load and

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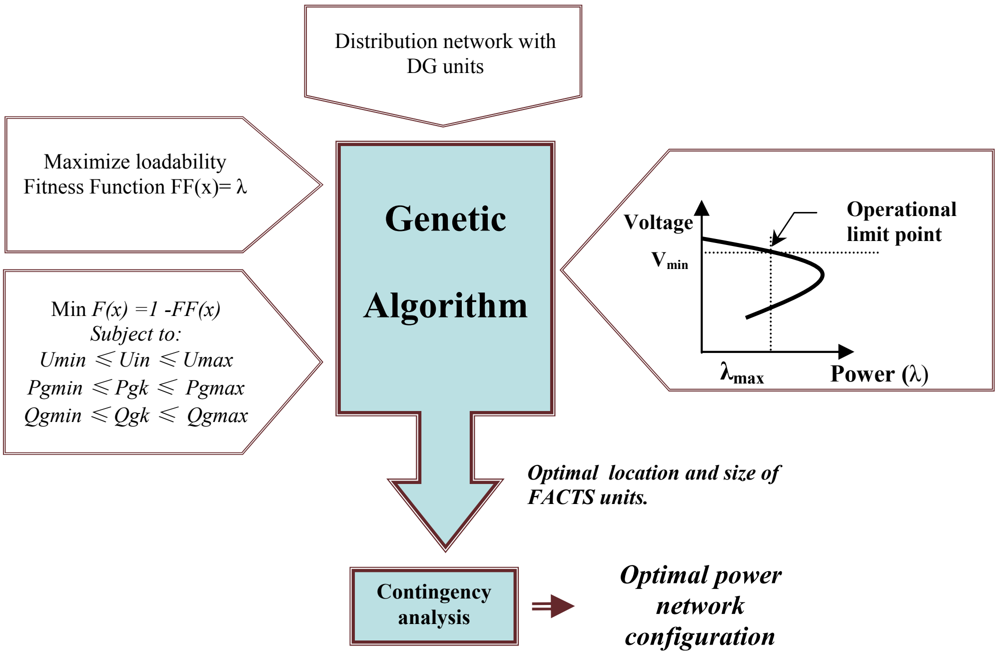

Fig. 1. Scheme of the algorithm

consequently, the power flow Jacobian matrix becomes singular. Classical power-flow methodologies fail to converge beyond this limit, which indicates voltage instability and can be associated with a saddle-node bifurcation point.

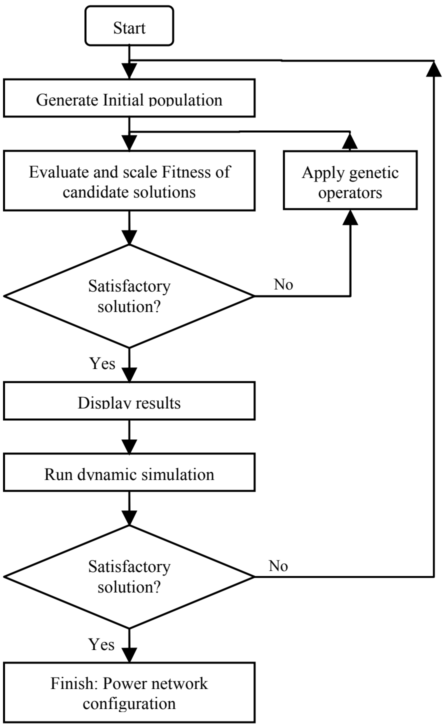

Fig. 2. Implementation of the optimization algorithm

Although voltage instability is a local phenomenon, the problem of voltage stability concerns the whole power system, and it is essential for its operation and control. This aspect is more critical in power networks, which are heavily loaded, faulted, or with insufficient reactive power supply.

Voltage Collapse is the process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system [2].

DG units can offer the ability of providing a very fast dynamic Var injection, so their optimal allocation in the power network could alleviate the voltage instability or even prevent the voltage collapse.

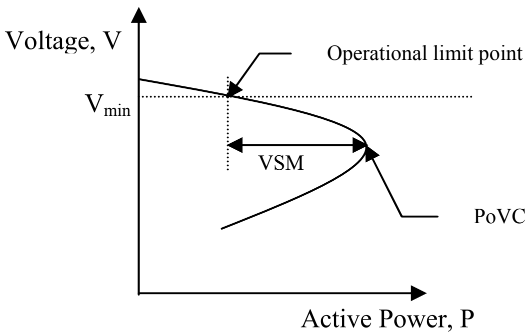

Fig. 3. P-V curve

IV. Reactive Power Planning survey

Optimal allocation of Var sources is one of the most challenging problems in power networks. The incorporation of shunt reactive power compensation devices in power networks provides voltage support, avoidance of voltage instability or voltage collapse. In the past years, locations of Var sources were determined by estimation or by approach; however, neither of both methodologies is effective.

Traditionally, the Reactive Power Planning (RPP) methodology is based on the definition of complex objective functions and network constrains, and on the use of optimization algorithms. In the literature, the following assumptions are usually considered while formulating the Var planning problem:

- The system is balanced.
- The active and reactive powers consider only the fundamental frequency component.
- The size of Var source is treated as a continuous variable.
- The reactive capability of a generator is portrayed by the conventional PQ diagram.

In this paper, optimal locations of DG units, with reactive power capability, are determined by using the proposed optimal reactive power planning model. The Genetic algorithms (GA) are used to solve the optimization problem. The methodology proposed can be applied to any DG-inverter unit offering reactive power capability (DFIG or PV). In the case of fixed speed wind turbines it is assumed that the Var injection is supplied by external Var sources located in the wind farm terminal (STATCOM or SVC).

V. Genetic Algorithms

Genetic algorithms (GA) are a family of computational optimization models invented by Goldberg (1989) and Hopgood (2001). GA [3] has been used for solving both constrained and unconstrained optimization problems modelled on a natural evolution process. It drives the biological selection, where the operators employed are inspired by the natural evolution process. The GA method modifies a population of individual solutions on each step (generation) of the algorithm according to genetic operators.

The main advantages of GA over conventional optimization methods are:

- They do not need any prior knowledge, space limitations, or special properties of the objective function about the problem to be optimised.
- They do not deal directly with the parameters of the problem. They only require codes, which represent the parameters and the evaluation of the fitness function to assign a quality value to every solution produced.
- They work with a set of solutions from one generation to the next, making the process likely to converge into a global minimum.

The solutions obtained are randomly based on the probability rate of the genetic operators such as mutation and crossover.

This technique is very useful for solving optimization problems, such as the proposal in this paper. The optimisation problem is formulated as:

Min F(x)

Subject to:

$$Aeq(x) = Beq$$
$$A(x) \leq Beq$$
$$x \in S$$

where:

- F(x) is the objective function to be optimised
- Aeq is equality constraints
- A is inequality constraints
- x is the vector of variables
- S is the search space.

A. Representation

A population is formed by a set of individuals that correspond with a possible solution of the problem. Each individual is represented by a set of the variables to be optimized, they are usually represented in a string form that is called chromosome.

The method of chromosome's representation has a major impact on the performance of the GA. There are two common representation methods for numerical optimization problems:

a) binary string representation method. The most important issue is to decide the number of bits used to encode the variables to be optimized;
b) vector of integers and real numbers. In this method each integer or real number represents a single variable.

Each element (bit, integer or real number) in a chromosome is called gene.

B. Initial Population

GA requires a group of initial solutions to start the process of optimization instead of a single one. This initial population can be created in two ways. The first one consists of using randomly produced solutions created by a random generator and it is used in those cases in which no prior knowledge existed. The second method employs a set of known solutions that satisfied the requirements of the problem. This method requires a previous knowledge about the optimization problem and converges to an optimal solution in less time than the first one.

C. Fitness Evaluation Function

The formulation of the fitness function (FF) is a very important aspect of the optimization problem. FF assigns a quality value to each individual of the population depending on how well the solution performs the desired functions and satisfied the given constraints. It allows to determinate which individuals of the population survive for the next generation. The fitness values of individuals in a given population are employed to drive the evolution process. In the case of a GA, this calculation must be automatic and the problem is how to devise a procedure which computes the quality of the solution. These characteristics enable the GA to present excellent results even when optimizing complex, multimodal or discontinuous functions.

D. Genetic operators

After application of fitness function, three basic genetic operators are applied to the population in order to create a new population, such as: selection, crossover and mutation. All of them are inspired by nature but it is not necessary to employ all the operators in a GA. The choice or design of the operators depends on the problem and the representation scheme employed.

Selection: The aim of the selection procedure is to copy individuals whose fitness values are higher than those whose fitness values are low in the next generation. This operator allows transmitting the best individual's genetic material in the next generations in order to drive the search towards a promising area and finding good solutions in a short time.

Crossover: This operator is considered the most important one of GA method because it is responsible for the genetic recombination. It is used to create two new individuals (children) from two existing ones (parents), they are picked from the current population through the selection operator. There are several ways of doing this. Common crossover operations are; one point, two point, cycle and uniform crossovers.

Mutation: In this procedure, all individuals in the population are checked gene by gene and the gene value is randomly reversed according to a specified rate. This operation introduce new information in the algorithm in order to forces the algorithm to search new areas. This operator helps GA avoiding premature convergence due to genetic material that has been lost during the selection operation. Besides, it helps to find the global optimal solution.

E. Control parameters

The most important control parameters of a simple GA are:

- Population size: It allows a better exploration of the solution space during the search so that the probability of convergence to the global optimal solution is higher.
- Crossover rate: It determines the frequency of the crossover operation. It is used to discover a promising area at the start of the simulation.
- Mutation rate: It controls the mutation operation. In general, an increase in the mutation rate helps the GA to reach the global solution avoiding the local minimum. However, if this mutation rate parameter is very high, there could be high diversity in the population and the global solution is not reached.

VI. Optimization Methodology for Optimal Allocation and Reactive Power Planning

A. Encoding

In this paper, value encoding of chromosomes has been used where the placement problem is modelled by using real numbers. The target is where to locate "n" Var sources. Each chromosome has (1 + 2 n) genes that represent the variables of the system. The first one represents the loadability parameter of the system (λ); the other ones represent the bus number location in which DG units could be connected and the Var injection from each DG unit.

B. Fitness Function

According to this paper, the fitness function deals with the loadability of the system. For this purpose, a load change scenario is considered, in which P_D and Q_D can be represented as:

$$P_D(\lambda) = P_{D0}(1+\lambda K)$$
$$Q_D(\lambda) = Q_{D0}(1+\lambda K)$$

Where:
- P_{D0} and Q_{D0} are the original power load (base case).
- K is a multiplier designating the rate of load change.
- λ represents the load parameter.
  (λ =0 corresponds to the base case).

In this scenario of load change, λ_{max} corresponds to the maximum power transferred under voltage constraints.

To maximize the loadability of the system through the load parameter λ, The FF function used is:

$$FF(x) = \lambda$$

Where:
- x is a vector of variables: load parameter, bus connection and VAr injection.
- λ value depends on voltage constraints violation.

C. Constraints

The main constraints that are considered in the optimization process are the following:

- Voltage level at all buses should be held within established limits.
- Active and reactive power generation are limited by the generator capabilities.

D. Optimisation Formulation

According to the fitness function objective and constraints equations, the optimization problem can be formulated as:

Min F(x) =1 -FF(x)

Subject to:

$$U_{min} \le U_i^n \le U_{máx} \qquad n=1,2,\ldots,N$$
$$P_{gmin} \le P_g^k \le P_{gmáx} \qquad k=1,2,\ldots,K$$
$$Q_{gmin} \le Q_g^k \le Q_{gmáx} \qquad k=1,2,\ldots,K$$

VII. Case Studied

In this section, the proposed GA has been applied to a distribution network, such as the modified IEEE 34 node test feeder [4]. Two different situations have been considered.

A. Optimal allocation of DG units with VAR injection.

In this case, several DG units of 2 MW and maximum VAR injection capability of 3.5 MVAr had been connected to the power system. Initially (base case) there are no any DG unit connected to the distribution network (Fig. 4). The GA will indicate the optimal allocations of DG units and their VAR injection. Connection of DG units has been computed in consecutive iterations steps at different DG penetration levels.

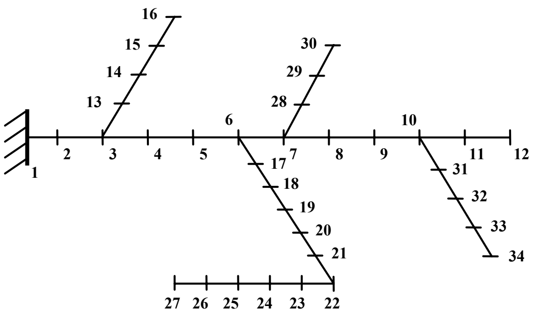

Fig. 4. Modified IEEE 34 bus system

Four DG penetration scenarios are considered as shown in Table I:

TABLE I.
PENETRATION SCENARIOS

	DG penetration %	DG units
Case 0	Base Case	
Case 1	23,9%	1 unit 2 MW
Case 2	47,8%	2 unit 2 MW each
Case 3	71,7%	3 unit 2 MW each

Table II shows the results obtained by the algorithm; the bus number where each DG unit is located, the reactive power injected and the maximum loadability, for low limit operational voltage (λmáx). Fig. 5 and Fig. 6 show the voltage profile and the maximum loadability of the case studied, respectively, at the base case and after the application of the optimisation algorithm.

TABLE II.
RESULTS OF GA

Case	**DG bus location**	**Q_{inj} (MVAr)**	**$\lambda_{máx}$**
Case 0	-	-	0
GA solution case 1	27	2.77	0.06
GA solution case 2	11	2.95	0.30
	25	2.79	
GA solution case 3	10	2.15	0.74
	23	2.45	
	26	2.71	

It is shown that optimal location of DG units with reactive power capability in distribution networks enhance the voltage profile and increase the maximum loading of the system. In the particular case of adding three DG units to the power network the maximum loading of the system for operational voltage limit is increased 74% (Fig. 7).

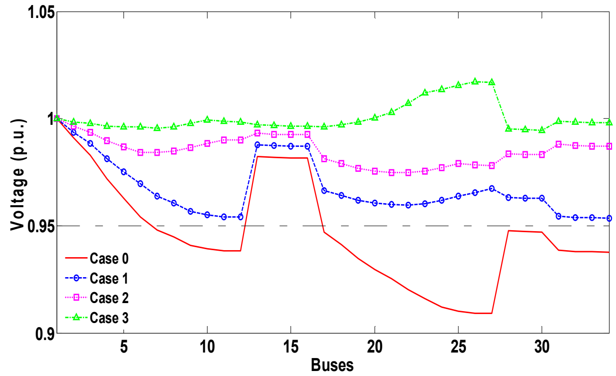

Fig. 5. Voltage profile of the modified IEEE 34 bus system

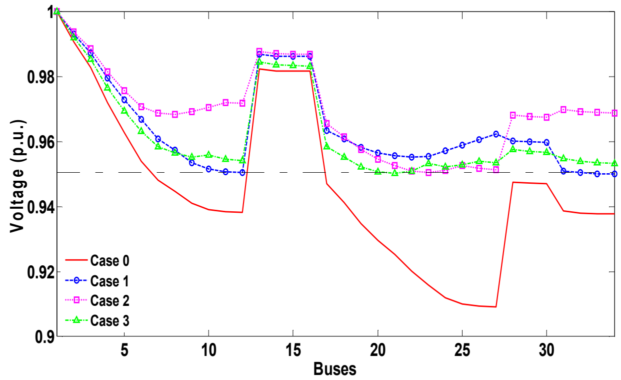

Fig. 6. Maximum loadability voltage profile

B. Voltage profile

Classical network are designed to work under electric power flow through the generator to the load. Incorporation of DG units to distribution networks modify power flows and could derivate in under or over-voltage on the network. Installation of DG technologies, with VAR injection capability, can have different influence on voltage profile, despite of appropriate DG allocation. For that reason, allocation and sizing of DG units in distribution networks have great importance.

Voltage profile and reliability studies are performance with PowerWorld® and Matlab®.

C. Contingency analysis

Contingency analysis is one of the most important tools to determine preventive or corrective actions in the power system. In this paper a single line outage (N-1 Contingency) has been studied in the modified IEEE-34 bus power network by using PowerWorld®. Determination of the severest contingencies scenarios were done based on the overloaded lines and bus voltage violations. The worst situation corresponds to the disconnection of line 10-31.

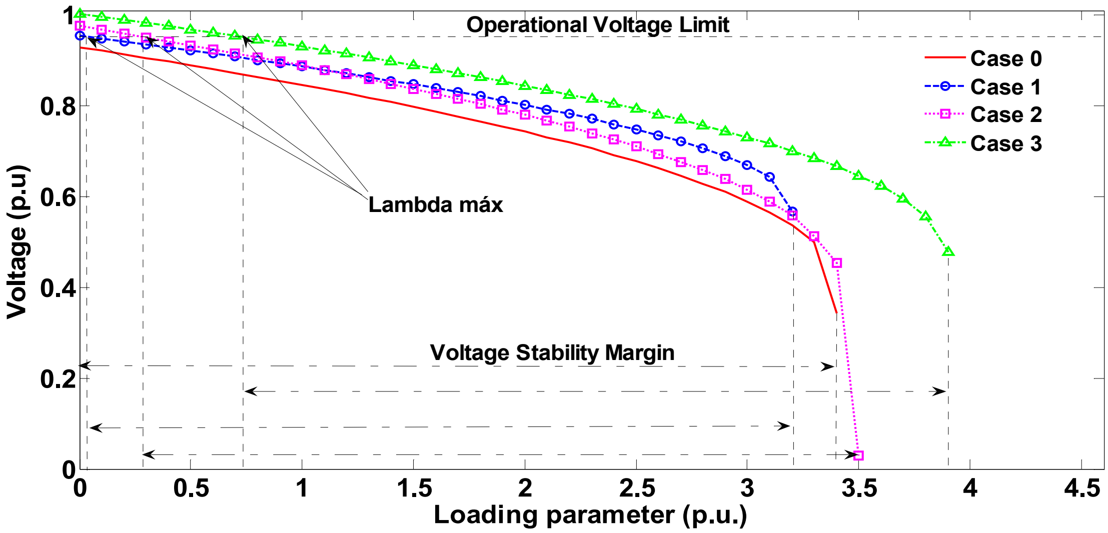

Fig. 7. Maximum loading parameter and voltage stability margin

This failure produces an overcharge of lines 22-21 and 22-23 of 104% and 109 % respectively. Fig. 8 shows the voltage profile of the power network under a single N-1 contingency considering the base case (without GD and VAr injection) and case 3 (three GD units with VAr capability in the connection point). Fig. 9 shows the post-contingency voltage profile for maximum loadalibity. It can be seen how the installation of optimally located DG units, with VAR injection, improve the reliability of the system after contingency N-1.

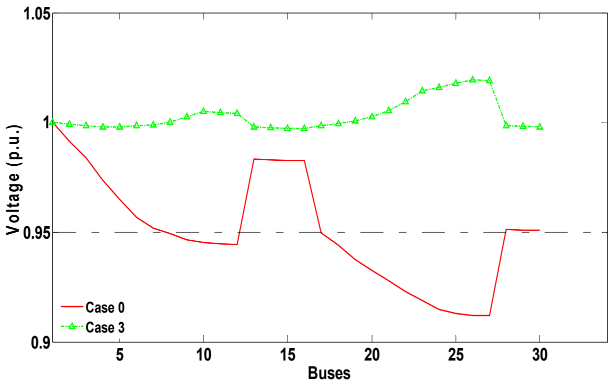

Fig. 8. Voltage profile under single N-1

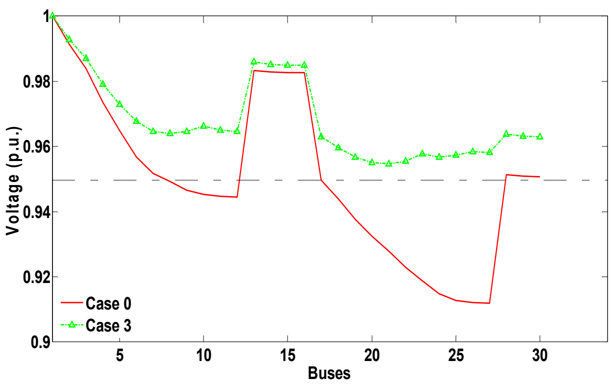

Fig. 9. Maximum loadability voltage profiles under single N-1 contingency

VIII. Conclusions

In this paper, a method based on GA for optimal placement of DG units with SVC or reactive power capabilities has been successfully developed to maximize the loadability of the system and to improve the security of the power network under single N-1contingencies. GA has been tested in distribution networks and it has been proved its ability to reach the global optimal solution for the allocation of several DG units. The results of the algorithm show that the optimum allocation of DG units, with reactive power capability in power networks can enhance voltage stability and maximize voltage stability margin in the whole network.

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Biographies

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