Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Optimal Location of Pilot Buses by a Genetic Algorithm Approach for a Coordinated Voltage Control in Distribution Systems

O.Richardot, Y. Bésanger, *Senior Member IEEE*, D. Radu, N. Hadjsaid, *Senior Member IEEE*

***Abstract*-- Large scale integration of distributed generation in distribution networks causes voltage quality problems, but also may be able to provide means to solve theses problems if correctly controlled. A possible way to take advantage of distributed generation is to use it to perform a coordinated voltage control that would maintain voltage to its set-point value at the substation and some other specific nodes called pilot buses. This paper proposes a method for optimal location of these pilot buses in order to ensure the coordinated voltage control performances. For this purpose, we developed a hybrid software based on GAs (Genetic Algorithms). The proposed procedures are successfully tested on a typical distribution network with distributed generation units for several numbers of pilot buses.**

***Index Terms* -- ancillary services, voltage control, distribution system, genetic algorithm.**

I. INTRODUCTION

The actual power distribution systems are facing nowadays new challenges due to a large insertion of distributed generation (DG), and especially renewable sources. As DG penetration rate may notably increase over coming years, it seems necessary for power system's future reliability that, from negative loads they are considered as today, they become real actors of the power system.

DG units are usually considered too small to be able to provide any guaranteed service to the power system, such as fixed amount of active power, or voltage control, and to be dispatchable or observable by the distribution network operator (DNO).

Nevertheless, mutualisation and coordination of DG is a possible way to take advantage of a high DG penetration rate by making them able to provide ancillary services such as participation to voltage control. The transposition of transmission Secondary Voltage Control (SVC) and Coordinated Voltage Control (CVC) principles to the distribution system represent an efficient way for reactive power reserve managing, in order to support HV transmission network primary and secondary voltage controls, as shown in [1]. This paper mainly focuses on the determination of optimal location of pilot buses in such kinds of systems, from technical point of view, in order to provide an optimal exploitation of SVC and CVC principles. To carry out this problem, we employed a GA technique.

The outline of the paper is organized as follows: Section 2 reminds actual voltage regulation methods at transmission and distribution levels and presents an example of a secondary coordinated voltage control, in Section 3 is presented the pilot buses location problem as a bi-objective optimization problem, in Section 4 is shown the possible approaches which can be used, Section 5 describes a GA technique used, in Section 6 an example system is used to validate the proposed approach. Finally, section 7 presents the conclusions of the paper.

II. REGULATION METHODS

A. Actual voltage regulation methods

Transmission network voltage is actually controlled by a well known three-step control method [2], each step acting with a different time constant:

- Primary Voltage Control (PVC) is locally performed by Automatic Voltage Regulators (AVR) which maintain generators voltages at their set-point values. PVC response time is faster than one second.
- SVC is automatically performed on a large area scale, with a response time close to one minute. Its aim is to realise reactive power production-consumption balance. SVC is based on the measurement of voltage deviation at a pilot bus for each single area: a centralized corrector sends a reactive power participation level set-point to any generator which participates to SVC. Each generator produces then an amount of reactive power proportional to its available reserve called secondary reserve. The pilot bus is chosen so as to be representative for the whole area EHV voltage, and areas are assumed to be theoretically independent from each other (from the voltage point of view). That means that there is no significant permanent reactive power transit between adjacent areas.
- Tertiary Voltage Control (TVC) is manually performed with a time constant of 10 to 30 min at a country scale to lower reactive energy transfer between areas. It is based on optimization methods taking into account economical and technical aspects of power system operation.

Today, at the distribution level, connected DG do not yet

O. Richardot is with the Grenoble Electrical Engineering Laboratory (G2Elab), 38402 Saint Martin d'hères Cedex, France (e-mail: olivier.richardot@g2elab.grenoble-inp.fr)

Y. Besanger is with the Grenoble Electrical Engineering Laboratory (G2Elab), 38402 Saint Martin d'hères Cedex, France (e-mail: yvon.besanger@g2elab.grenoble-inp.fr)

D. Radu is with the Grenoble Electrical Engineering Laboratory (G2Elab), 38402 Saint Martin d'hères Cedex, France (e-mail: daniel.radu@g2elab.grenoble-inp.fr)

N. Hadjsaid is with the Grenoble Electrical Engineering Laboratory (G2Elab), 38402 Saint Martin d'hères Cedex, France, and with GIE-IDEA, 38402 Saint Martin d'hères Cedex, France (e-mail: nouredine.hadjsaid@g2elab.grenoble-inp.fr).

participate to voltage regulation, which is performed with other means, like tap-changers or capacitor banks. The aim of these devices is to maintain MV voltage within standard bounds.

B. Coordinated secondary voltage control

CVC systems adjust the voltage of several pilot buses located in the controlled area [3]. To do so, it computes a set of generator set-point values every 10 seconds by minimizing a constrained multi-objective function using a deterministic method [1] (this assumes that the initial set of unknown variables is close enough to the optimal set, which is realistic while there is no important event, since the algorithm works in nearly-real-time).

The CVC's three objectives are: minimization of voltage deviation at pilot buses; minimization of reactive power production ratio deviation; and minimization of generators voltage deviation.

As the different objectives may not be optimal for the same set of set-point values, they can be given relative importance with weighting factors. Maximum weight is generally given to pilot buses voltages as it is the main objective. Different weights can also be given to different nodes according to their relative importance or priority.

But the objective function includes reactive power management in order to make sure that each producer have approximately the same reactive power reserve (proportionally to their total capacities, and taking into account active power), or to manage reactive power reserve according to a particular strategy. It also includes generator voltage control to avoid too high voltage drops between generators, which could produce critical currents circulation and then, high line losses as consequences.

As we are now dealing with distribution network applications, let's introduce the appropriate acronym D-CVC for the following.

III. PROBLEM FORMULATION

A. Voltage map and pilot buses

We remind here that the D-CVC's function is to regulate pilot buses voltage in order to maintain the voltage map as smooth as possible in normal operation conditions. This means that voltage map should ideally not be disturbed by load variations or voltage variations in another regulation zone. In the case that concerns us, where D-CVC is applied in a distribution network, voltage map shouldn't be affected by voltage variations coming from transmission network.

Now, the previously described multi-objective function computation is subject to different constraints or strategies which can be of technical as well as of economical order. The main constraints concern voltage limits, voltage deviation limits, and reactive power limits. Voltage drop and line losses can also be taken into account, so as economical constraints like prime mover's energy availabilities and costs.

Therefore, to be efficient and reliable, CVC needs adequate gain and weighting factors. But it also needs that pilot buses are judiciously chosen. This is the object of the present paper. Indeed, real and reactive load and production variations cause significant voltage map disturbances. The relation between voltage variation on each node and power disturbances being sensitivity matrices related to lines impedances.

As the real power production is not an available mean of voltage regulation because it is fixed by the needs of active loads, we will only consider reactive power production for the purpose of voltage regulation.

B. D-CVC control law

D-CVC is based on the relation between reactive power and voltage variations at different nodes which are linked by the susceptance matrix of the network:

$$[\Delta Q/V] = [B]\cdot[\Delta V] \tag{1}$$

where $\Delta Q/V$ is a vector containing the reactive power variation dived by the actual voltage for each node; B is the susceptance matrix; and ΔV is the voltage variation vector.

Considering the different status of the generator buses (actuators), the substation (VAR generator, but not an actuator) and the load buses, equation (1) can be written as follows:

$$\begin{bmatrix} \Delta Q_g/V_g \\ \Delta Q_s/V_s \\ \Delta Q_l/V_l \end{bmatrix} = \begin{bmatrix} B_{gg} & B_{gs} & B_{gl} \\ B_{sg} & B_{ss} & B_{sl} \\ B_{\mathrm{lg}} & B_{ls} & B_{ll} \end{bmatrix} \cdot \begin{bmatrix} \Delta V_g \\ \Delta V_s \\ \Delta V_l \end{bmatrix} \tag{2}$$

where g represents indices of generator buses, s is the index of substation node, and l indices of load buses. As the substation generates reactive power in distribution network, it has to be placed into the generator buses list, even if not used in the control law. So let's name $V_{\tilde{g}} = \begin{bmatrix} V_g \\ V_s \end{bmatrix}$, then from (2), one can write:

$$\begin{aligned} \Delta V_l &= B_{ll}^{-1}\cdot[\Delta Q_l/V_l] - B_{ll}^{-1}\cdot\begin{bmatrix} B_{\mathrm{lg}} & B_{ls} \end{bmatrix}\cdot\Delta V_{\tilde{g}} \\ &= A\cdot[\Delta Q_l/V_l] + B\cdot\Delta V_{\tilde{g}} \end{aligned} \tag{3}$$

ΔQ_l is called disturbance vector, and $\Delta V_{\tilde{g}}$ is called control vector.

As we aim to control pilot buses voltage, we need to define a pilot buses observation equation:

$$\Delta V_p = P\cdot\Delta V \tag{4}$$

where p represents pilot buses indices and P is a (n_P*n_B) matrix with $P(p,i)$ equal to 1 if the node i is the p^{th} pilote bus and 0 otherwise. n_P is the number of pilot buses, and n_B is the total number of buses.

A theoretically perfect D-CVC should compute ΔV_g so as $\Delta V_p = 0$, whatever may ΔQ_l be. Then, from (3) and (4), one can write:

$$\begin{aligned} \Delta V_p &= P\cdot\begin{bmatrix} \Delta V_{\tilde{g}} \\ A\cdot[\Delta Q_l/V_l] + B\cdot\Delta V_{\tilde{g}} \end{bmatrix} \\ &= P\cdot\begin{bmatrix} 0 \\ A \end{bmatrix}\cdot[\Delta Q_l/V_l] + P\cdot\begin{bmatrix} I \\ B \end{bmatrix}\cdot\Delta V_{\tilde{g}} = 0 \end{aligned} \tag{5}$$

where I is the identity matrix, or :

$$\Delta V_p = P\cdot A_1\cdot[\Delta Q_l/V_l] + P\cdot B_1\cdot\Delta V_{\tilde{g}} = 0 \tag{6}$$

from equation (6), it results the D-CVC theoretical control law:

$$\Delta V_{\tilde{g}} = -C_1\cdot P\cdot A_1\cdot[\Delta Q_l/V_l] \tag{7}$$

where $C_1 = \left[\left(P \cdot B_1 \right)^T \cdot \left(P \cdot B_1 \right) \right]^{-1} \cdot \left(P \cdot B_1 \right)^T$.

Note that the rank of the matrix $\left[\left(P \cdot B_1 \right)^T \cdot \left(P \cdot B_1 \right) \right]$ is, by construction, less or equal to n_P, and its dimension is (n_G*n_G), n_G being the number of generator buses, therefore is at first sight not invertible. Then, an iterative method must be used to compute C_1. The method applied here is the *preconditioned conjugate gradient* (PCG) [4].

C. Objective function

The pilot bus for each regulation zone (for classical SVC) is historically chosen having a high short-circuit power because these buses are less sensitive to load variations and then, are quite representative of the voltage map. However, for a coordinated regulation with several pilot buses, their choice must satisfy two objectives [5]:

- the voltage map of the whole network must be the less sensitive to reactive power disturbance in steady state. Therefore it is necessary to control voltage on representative nodes: this is the *observability* criterion;
- pilot buses should also be chosen so as a small action of the actuators (DG reactive power production) is enough to control their voltage : this is the *commandability* criterion.

(1). Observability

Observability criterion can be expressed by the following way: for a given reactive load disturbance ΔQ_l, pilot buses must make the voltage deviation to be minimal.

Let the voltage deviation index be defined as:

$$J_O(P) = \sum_{i=1}^{n_B} \lambda_i \Delta V_i^2 = \Delta V^T \cdot \Lambda \cdot \Delta V \qquad (8)$$

where λ_i are weighting factors for each node, and Λ the weighting diagonal matrix:

$$\Lambda = \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \lambda_{n_B} \end{bmatrix} \qquad (9)$$

Rewriting equations (3) and (7) gives:

$$\Delta V = \begin{bmatrix} \Delta V_{\tilde{g}} \\ \Delta V_l \end{bmatrix} = \begin{bmatrix} -C_1 \cdot P \cdot A_1 \\ A - B \cdot C_1 \cdot P \cdot A_1 \end{bmatrix} \cdot \left[\Delta Q_l / V_l \right] \qquad (10)$$

and (8) can be written:

$$\begin{aligned} J_O(P) = \left[\Delta Q_l / V_l \right]^T \cdot & \begin{bmatrix} -C_1 \cdot P \cdot A_1 \\ A - B \cdot C_1 \cdot P \cdot A_1 \end{bmatrix}^T \\ \cdot \Lambda \cdot & \begin{bmatrix} -C_1 \cdot P \cdot A_1 \\ A - B \cdot C_1 \cdot P \cdot A_1 \end{bmatrix} \cdot \left[\Delta Q_l / V_l \right] \end{aligned} \qquad (11)$$

(2). Commandability

Commandability criterion can be expressed by the following way: for a given reactive load disturbance ΔQ_l, pilot buses must make the DG reactive power contribution to be minimal.

Let the reactive power contribution index be defined as:

$$J_C(P) = \sum_{i=1}^{n_G} \Delta Q_{g_i}^{\ 2} = \Delta Q_g^{\ T} \cdot \Delta Q_g \qquad (12)$$

Rewriting the first line of equation (2) and equation (3) gives:

$$\begin{aligned} \left[\Delta Q_g / V_g \right] &= B_{gl} \cdot A \cdot \left[\Delta Q_l / V_l \right] \\ &\quad + \left(\begin{bmatrix} B_{gg} & B_{gs} \end{bmatrix} + B_{gl} \cdot B \right) \cdot \Delta V_{\tilde{g}} \\ &= D \cdot \left[\Delta Q_l / V_l \right] + E \cdot \Delta V_{\tilde{g}} \end{aligned} \qquad (13)$$

replacing $\Delta V_{\tilde{g}}$ from equation (7) in (13) gives:

$$\left[\Delta Q_g / V_g \right] = \left[D - E \cdot C_1 \cdot P \cdot A_1 \right] \cdot \left[\Delta Q_l / V_l \right] \qquad (14)$$

or :

$$\Delta Q_g = diag\left(V_g \right) \cdot \left[D - E \cdot C_1 \cdot P \cdot A_1 \right] \cdot \left[\Delta Q_l / V_l \right] \qquad (15)$$

and (12) can be written:

$$\begin{aligned} J_C(P) &= \left[\Delta Q_l / V_l \right]^T \cdot \left[D - E \cdot C_1 \cdot P \cdot A_1 \right]^T \\ &\quad \cdot diag\left(V_g^{\ 2} \right) \cdot \left[D - E \cdot C_1 \cdot P \cdot A_1 \right] \cdot \left[\Delta Q_l / V_l \right] \end{aligned} \qquad (16)$$

(3). Final objective function

Two objectives have been defined in order to find the optimal position of the pilot buses. Well, whatever the optimization method chosen, a mono-objective optimization is simpler to compute than a multi-objective. Therefore, we propose to define a final objective function J by a weighted mix of J_O and J_C :

$$\min_P J(P) = \left(J_O(P)^{K_O} \cdot J_C(P)^{K_C} \right)^{\frac{1}{K_O + K_C}} \qquad (17)$$

where K_O and K_C are the weighting factors respectively of the observability and the commandability criterions.

IV. POSSIBLE METHODOLOGY

The optimal location of pilot buses depends on actual voltage and load level of each node of the network. Hence, a possible method to determine general optimal pilot buses, taking into account different possible states of the network is described in three steps hereunder :

- the first step consists in defining some scenarii based on different load situations (for example global under-load, normal load and global over-load), and different load disturbances;
- in the second step, an optimal pilot bus set is computed using either deterministic or heuristic algorithm;
- in the third step, for each pilot bus set found in second step, the objective function is evaluated in each defined scenario. A satisfactory index is then calculated being the mean value of the objective function.

The best pilot bus set is the one with the best (in this case, the lowest) satisfactory index.

In this paper, the second step optimization is computed with genetic algorithms that are presented in next part.

V. DESCRIPTION OF GAS USED

A. Genetic Algorithms

The first step to do when a GA is developed is the *coding of problem* as a finite-length string over some finite alphabet. After this, an initial set of random solutions called *population* is generated. A population of candidate solutions, or *individuals*, is maintained, and individuals made to compete with each other for survival. Once *evaluated*, through the *fitness* function calculation, stronger individuals got a greater chance to contribute to the production of new individuals (*offsprings*) than weaker ones, which may not even contribute at all (*selection* procedure). Offsprings are produced through *recombination*, whereby they inherit features from each of the parents, and through *mutation*, which can confer some truly innovative features as well. In the next selection step (next *generation*), offsprings are made to compete with each other, and possibly also with their parents. Improvement in the population arises as a consequence of the repeated *selection* of the best parents, which are in turn more able to produce good offsprings, and the consequent elimination of low-performers. After several generations, the algorithm converges to the best individual, which hopefully represents the optimum or suboptimal solution to the problem [6].

Hence, to reach the aim of the optimization problem described in the *Section 3* we developed a hybrid GA, which we describe below.

B. *Individual representation*

As mentioned above, GAs require the parameter set of the optimization problem to be coded as a finite-length string over some finite alphabet. Since the goal of optimization was to locate the pilot buses into a distribution network, an individual is represented by a string of length n_P, where n_P is the number of pilot buses which we want to locate optimally in the power system. Therefore, in the individual string, one can find information about the location of the pilot buses in the power system. It contains integer numbers from 1 to n_B, where n_B is the total number of system buses.

In the Fig. 1 is shown, only for the exemplification purpose, an example of individual representation composed of five pilot buses on a sample distribution network.

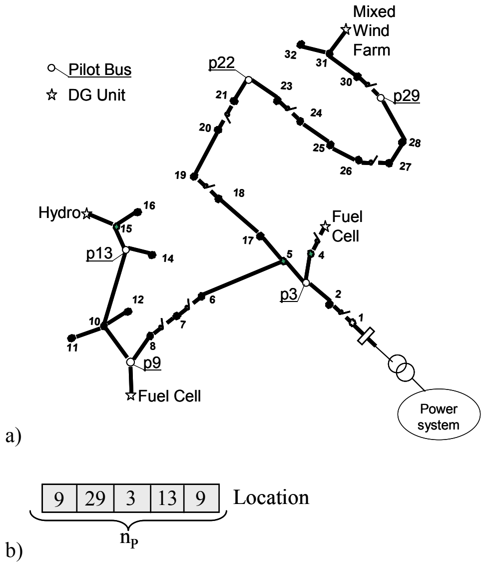

Fig. 1. Individual representation. (a) Power system. (b) Individual.

C. *Initial population*

A GA starts with an initial population of individuals, which is randomly generated. This population is built from a set of initial parameters such as: n_P the number of pilot buses which we want to locate optimally, n_{ind} the number of individuals in the population. Firstly, one assigns to the buses of the network numbers from 1 to n_B, after an individual is created. For this, among the n_B numbers, different n_P numbers are randomly chosen, and are placed in the individual string. This operation is repeated n_{ind} times to obtain the initial population.

D. *Fitness evaluation*

The next step in the GA, after the initial population generation, is represented by the evaluation of the objective function of the problem through the fitness function. In general, the fitness coincides with the objective function, if it is an unconstrained problem or an adaptation of this for a constrained problem. For the present work, the objective function presented in Section 3 becomes a fitness for the GA. More particularity, seeing that the GAs are designed for the search of a maximization problem solutions, in this work we employed as GA fitness the inverse of the objective function which has to be minimized. The procedure of fitness evaluation is performed for all the individuals of the population.

E. *Reproduction*

Reproduction is a process in which individuals are copied according to their fitness, which means that individuals with good characteristics have a higher probability of contributing one or more offspring in the next generation. The reproduction operator may be implemented in algorithmic form in a number of ways [6]. In this work, we considered Stochastic Universal Sampling (SUS) and Roulette Wheel Selection (RWS) methods [7], [8]. Furthermore, taking into account the characteristics of the fitness function, which doesn't have large variations from an individual to other, a fitness scaling technique has been employed. These can both maintain the population diversity among optimum and also prevent the premature convergence due to the "superindividuals". Among the fitness scaling strategies, we used the linear, rank based and sigma truncation fitness scaling [7], [8].

After applying the reproduction operator, the matting pool of the next generation is obtained.

F. *Crossover and mutation*

The main aim of crossover is to reorganize the information of two different individuals and produce a new one in order to promote the exploration of new regions in the search space. Therefore, with the matting pool obtained from the process of reproduction, crossover proceeds in two steps: in the first step individuals are mated randomly and in the second step to the mated individual couples crossover is applied, using coin tosses to select the crossing sites. There are several procedures to perform crossover, in this paper being applied the simple crossover and two-points crossover [8]. In the first case, one randomly selects one cut site along two mated individuals and exchanges the right parts of their, to generate offspring. In the second case, two crossing sites are picked up uniformly at random, along two mated individuals. After this, between the selected mated individuals, only the strings parts which are between the crossing sites are exchanged, elements outside these being kept to be part of the offspring [6]. The crossover may occur with a probability p_c which is generally close to 1.

Mutation is used to introduce some sort of artificial diversification in the population to avoid premature convergence to local optimum. Mutation alters one or more individual strings elements with a specified probability p_m. Every element of the individual string has an equal chance to be mutated. Mutation occurs with a lower probability at the initial generation and it is increased to the end of generations in order to diversify the population

G. Iterative process

Following reproduction, crossover and mutation, the new population is ready to be tested. For this, we decode the new individuals created by the GA and calculate the fitness function like mentioned above.

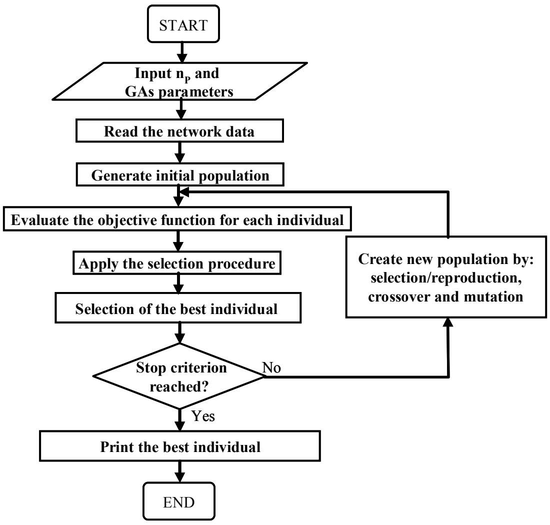

Fig. 2. Flow chart of the proposed GA

Hence, the operation of fitness evaluation, reproduction, crossover and mutation are repeated until the maximal number of generation, n_{gen}, is reached, this representing the stop criterion of GAs. The proposed GA is summarized in Fig. 5.

VI. SIMULATION RESULTS

A. Study case

For the validation of the proposed approach, we analyzed the pilot buses location problem applied to a radial distribution network. The distribution grid is a real French MV network, with five main feeders. The substation is connected to a node of the IEEE standard 39-bus-New-England transmission system via a small sub-transmission grid. Five DG units rated from 0.9 to 3.75 MW have been added in the distribution system for the needs of this study, randomly located as shown in Fig. 3.

The total load in the distribution grid is about 21.2 MW and 10.2 MVAR. The DG units provide a total amount of 11.6 MW, and consumes 1.35 MVAR (due to the asynchronous generators of the wind farm).

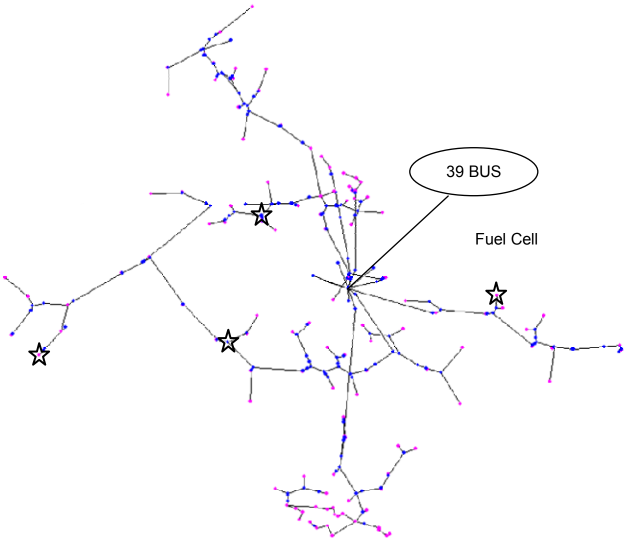

Fig. 3. Study case distribution network

B. Simulation results

The simulations were oriented into two directions; the first one was to find the optimal location of a given number of pilot buses in the studied network. In the second one, we studied the effect of the pilot buses number on the voltage control.

Therefore, for the considered network, the GA was applied several times in order to prove its capability to provide acceptable solution to the problem presented in the sections above. For all simulations, we considered the same set of parameters (an initial population having 60 individuals and a maximal number of generations equal to 200), the number of pilot buses chosen being equal to 3, 4, 5 and 7. The optimal location of these pilot buses is shown in Table 1 and Fig. 4.

TABLE I. OPTIMAL ALLOCATION OF PILOT BUSES

n_P	Location	Obj. function $*10^{-6}$
3	429 118 401	10.379
4	355 104 131 431	8.1960
5	130 352 410 413 342	6.8470
7	118 400 429 338 413 343 500	6.7801

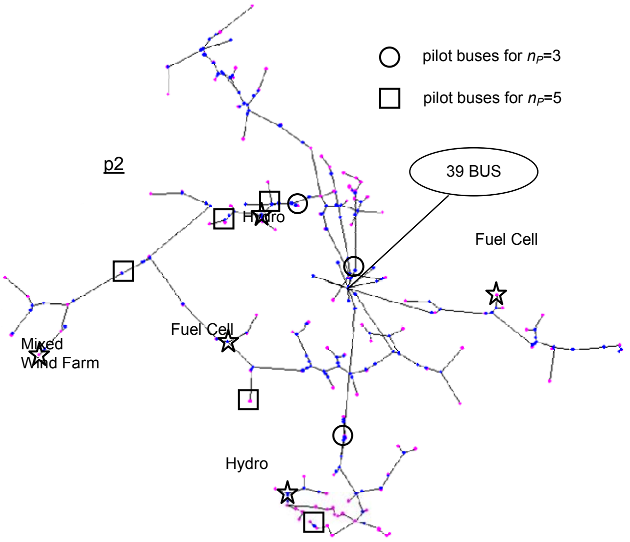

Fig. 4. Pilot buses location for the cases n_P=3 and n_P=5

For exemplification, the variation of the fitness function, giving the fitness of the best individual of each generation for the case n_P=5, among generations is shown in Fig. 5.

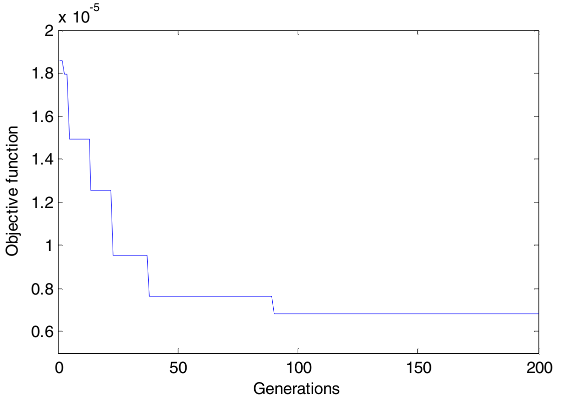

Fig. 5. Objective function evolution during GA run (for n_P=5).

Fig. 6 displays the dependence of the objective function to the number of pilot buses. It shows that the objective function, presented above in section 3, decreases when the number of pilot buses increases. But, an asymptotical value of the objective function may be observed. So there is a limit from which the pilot buses number increases the objective function's gain insignificantly with regard to the effort invested in the augmentation of pilot buses number.

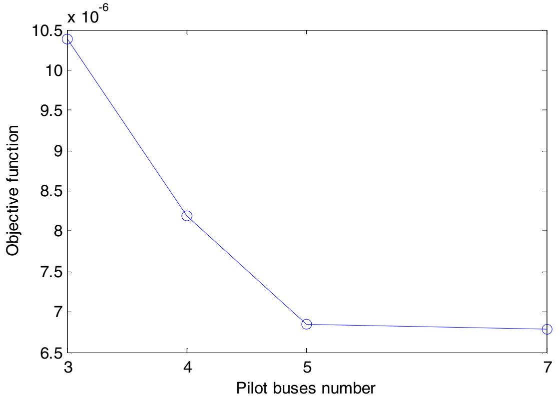

Fig. 6. Dependence of the objective function to n_P.

According to Fig. 6, the DNO can evaluate the number of pilot buses he will integrate taking into account both pilot buses installation costs and desired D-CVC performances. For instance, 5 is a good number of pilot buses, because adding one or more would not decrease significantly the value of the objective function.

C. D-CVC performances

In order to show the efficiency of pilot buses optimization, the D-CVC has been tested on the distribution network (Fig.4) with three pilot buses as an example (see fig. 4 for the placement of the pilot buses).

Fig. 7 displays the D-CVC response to a multiple voltage set-point step with pilot buses voltage deviation as sole objective, and Fig. 8 displays the complete D-CVC response to the same step. Dashed lines represent the set-points values for each pilot bus in the following figures.

One can see on Fig.7 that pilot buses voltages are very close to their set-points values.

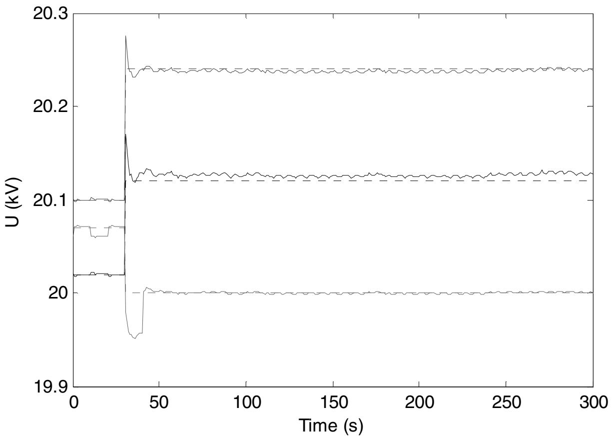

Fig. 7. Mono-objective D-CVC response to multiple set-point step

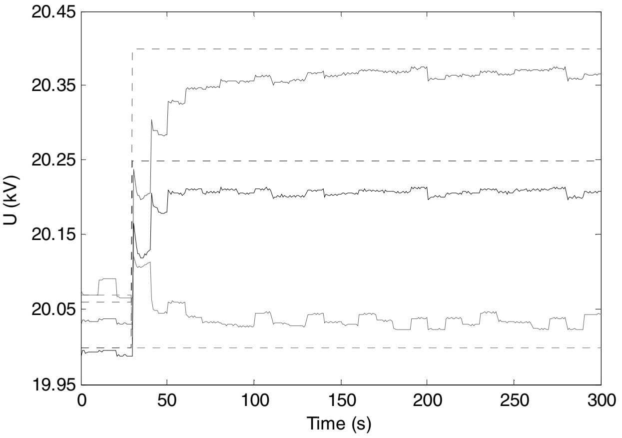

Fig. 8. Multi-objective D-CVC response to multiple set-point step

Taking into account generators' voltage and reactive power reserve (Fig.8) allows a better global operation, but pilot buses' voltages might not follow their set-point values with the same accuracy. This is a well known situation in multi-objective optimization problems: one objective can only be improved at the expense of at least one other objective. This is known as the Pareto theorem [9].

In order to improve the D-CVC performances in distribution system operation, it is possible to calculate the pilot buses' voltage references using an Optimal Power Flow (OPF) with estimated load and production curves. The OPF optimization criteria may be the minimization of active power losses on the concerned distribution system.

VII. CONCLUSION

This paper deals with the introduction of a new method to determine the optimal location of pilot buses in a distribution network with a wide area voltage control.

A Genetic Algorithm approach was used to solve the combinatorial problem of pilot buses optimal location.

The case studies are carried out using a radial distribution network. The results show that the proposed method can produce the optimal placement, but also the optimal number of pilot buses. Using also an OPF to calculate the voltage references of pilot buses, the D-CVC represents a complete an effective way to make voltage control in distribution systems.

VIII. REFERENCES

[1] O Richardot, A. Viciu, Y. Bésanger, N. HadjSaïd, C. Kieny, "Coordinated Voltage Control in Distribution Networks Using Distributed Generation", in *Proc. IEEE-PES Transmission and Distribution meeting*, Dallas, Texas, USA, may 2006.

[2] P. Lagonotte, J.C. Sabonnadiere, J.Y. Léost, and J.P. Paul (EDF) "Structural Analisys of the Electrical System: Application to the Secondary Voltage Control in France", *IEEE Trans. on Power Systems*, 4(2): pp. 479-484, May 1989.

[3] H. Lefebvre, D Fragnier, J. Y. Boussion, P. Mallet and M. Bulot, "Secondary coordinated voltage control system: feedback of EDF", in *Proc. IEEE Power Engineering Society Summer Meeting*, 290-295 vol. 1, Seattle, WA, 2000.

[4] P. Lascaux, R. Théodor, *Analyse numérique matricielle appliquée à l'art de l'ingénieur*, Paris, Masson, 1997.

[5] A. Conejo, J.I. de la Fuente and S. Göransson, "Comparison of alternative algorithms to select pilot buses for secondary voltage control in electric power networks", in *Proc. IEEE 7th Mediterranean Electrotechnical Conference*, 940-943 vol.3, 1994.

[6] D. Radu, Y. Bésanger, "A Multi-Objective Genetic Algorithm Approach to Optimal Allocation of Multi-Type FACTS Devices for Power Systems Security", in *Proc. IEEE-PES 2006 General Meeting*, Montréal, Canada, June 2006.

[7] D. E. Goldberg, *Genetic Algorithms in search, optimization, and machine learning*, Addison-Wesley Publishing Company, Inc., 1989.

[8] M. Gen, and R. Cheng, Genetic Algorithms & engineering design, John Wiley & Sons, Inc., 1997

[9] D. Büche, *Multiobjective Evolutionnary Optimization of Gas Turbine Components*, Ph.D dissertation, Swiss Federal Institute of Technology, Zurich, 1999

IX. BIOGRAPHIES

Olivier Richardot obtained his Electrical Engineering Diploma and his M.Sc. from the National Polytechnic Institute of Grenoble (INPG), France, in 2001. He has completed his Ph.D. concerning distributed generation integration in distribution networks in 2006. He is now a research engineer at AREVA T&D.

Yvon Bésanger (SM'06) was born in 1967 in Brive, France. He received the Ph.D in Electrical Engineering from the Grenoble Institute of Technology (Grenoble INP) in 1996. He is currently Associate Professor at Grenoble INP, at the National Superior School for Energy, Water and Environment (ENSE3) and the Grenoble Electrical Engineering Laboratory (G2ELab). His research interests are FACTS devices, distribution networks operation and reliability and power system dynamic security..

Daniel Radu was born in 1975 in Bucharest, Romania. He obtained a Ph.D. degree in Electrical Engineering, in 2004, from the University "POLITEHNICA" of Bucharest, Romania. From 1998 to 2004 he has been assistant professor of Electrical Engineering at the same University. Then, he has been a post doc researcher at the G2ELab, France. He is now a research engineer at SCHNEIDER ELECTRIC.

Nouredine Hadjsaid (SM'04) received his Ph.D degree from Grenoble INP in 1992. From 1988 to 1993, he served as a research and teaching assistant at the Associate Professor at the National Superior Electrical Engineering School of Grenoble (ENSIEG) and the Power Engineering Laboratory of Grenoble (LEG). He is presently a Full Professor at INP) in 1996. He is currently Associate Professor at Grenoble INP, at the ENSE3 and the G2ELab. He is also Manager of GIE-IDEA, a research consortium whose partners are Grenoble INP, Electricité de France and Schneider electric. His research interests are power system operation and security.