VOLT/VAR CONTROL IN DISTRIBUTION SYSTEMS AS A MULTIOBJECTIVE OPTIMIZATION PROBLEM

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Abstract— The integrated control of voltage and reactive power (volt/var) on radial distribution feeder is formulated as a multiobjective optimization problem to be solved trough the Strength Pareto Evolutionary Algorithm (SPEA2), a relatively recent technique of recognized computational efficiency. Two objectives has been established: voltage level variation and power and energy losses including costs of losses and costs of equipments. The decision variable are localization of capacitor banks and regulator banks and operation schedule these equipments on different load level. Application to distribution system of a Brazilian utility company has been done. One among these studied cases is presented.

Keywords— Multiobjective, Integrated Control, Distribution Systems, SPEA2.

Resumo— O controle integrado de tensão e reativos (volt/var) em alimentadores radiais de distribuição é formulado como um problema de otimização multiobjetivo para ser resolvido via método *Strength Pareto Evolutionary Algorithm* (SPEA2), que é uma técnica relativamente recente, de reconhecida eficiência computacional. Dois objetivos são considerados: localização de bancos de capacitores e bancos de reguladores de tensão, bem como a programação de operação destes equipamentos em diferentes níveis de carga. As variáveis de decisão são a localização e os tap's de operação dos bancos de reguladores de tensão e de capacitores, suas localizações e programações de operação para três condições de carga. Aplicações a sistemas de distribuição de uma concessionária brasileira foram realizadas e um dos casos estudados é apresentado.

Palavras-chave— Multiobjetivo, Controle integrado, Sistemas de Distribuição, SPEA2.

1 Introduction

The integrated control of voltage and reactive power (volt/var) in radial distribution feeders (Grainger & Civanlar, 1985 & Kagan et al, 2004) is made applying automatic voltage regulator banks (Almeida et al, 2005) as well as fixed and switched capacitor banks (Ferreira et al, 2002).

The matter lies at determinations where the banks must be installed and how them must operate to control of voltage profile and, simultaneously, to reduce the power losses.

Considering the discrete characteristic of problem, on account of incremental adjustments of the voltage regulator and the busbars set where the capacitors banks can be installed, we have a combinatorial optimization problem, which involves multiple objectives equally important to be optimized.

There are different approaches to solve a multiobjective problem. By aggregation of the objectives into a single one (Steuer, 1986) maybe the most widely used one. The big issue about this approach is justly to choose the weights.

Multiobjective optimization techniques have been applied successfully in operation and planning problems to distribution systems (Hashimoto et al, 2005 & Milošević & Begović, 2004).

Here we successfully apply the Strength Pareto Evolutionary Algorithm (SPEA2) (Zitzler et al, 2002), that find or approximate the Pareto set for multiobjective optimization problems. This technique incorporates some of most recent multiobjective evolutionary algorithms, such as: an improved fitness assignment scheme, a nearest neighbor density estimation technique and new archive truncation methods to guarantee the preservation of boundary solutions. The objective functions are modeled as costs, but representing the technical criteria desired.

The approximation of the Pareto set, According Zitzler et al (2004), there may exist several optimal solutions representing different trade-offs between the established objectives, and then some knowledge can be applied about the solution set to choose the best compromise solution.

The adopted models to the radial distribution feeders, loads and voltage regulator bank are the same used in (Almeida et al, 2005). The load flow technique applied (Das et al, 1995) guarantee convergence until in several loads conditions.

The proposed algorithm has been applied to a 62 buses system equivalent to a Brazilian radial distribution system. Results are showed, like the optimal Pareto set and the corrections of voltage profile and power losses reduction associated to some of the solutions set are analyzed.

2 Multiobjective Optimization Method

2.1 Definition

The multiobjective optimization problem can be defined as:

Optimize:

$$z = f(x) = (f_1(x), f_2(x), ..., f_r(x)) \quad (1)$$

subject:

$$g(x) = (g_1(x), g_2(x), ..., g_p(x)) \leq b \quad (2)$$

where:

$$x = (x_1, x_2, ... x_n) \in X$$

$$z = (z_1, z_2, ... z_r) \in Z$$

1. x is *decision vector* and X a *decision space*;
2. z is *objective vector* and Z a *objective space*;
3. $g(x) \leq b,\ b \in \Re^p$ are the restrictions to establish the feasible solutions in the *decision space* defined by $X^* = \{x \in X : g(x) \leq b\}$.

2.2 The dominance concept

A *vector* **a** $\in$ ***X*** is said dominate **b** $\in$ ***X*** (also written as **a** $\prec$ **b**), *if and only if*:

$$\begin{aligned} &\forall\ i \in (1,...,n), f_i(a) \leq f_i(b)\ \wedge \\ &\exists\ j \in (1,...,n) : f_j(a) < f_j(b) \end{aligned} \quad (3)$$

In other words, a solution dominates another one when it is less than or equal to (assuming minimization) with respect to all of its objectives, and it is strictly less with respect to at least one of them.

2.3 SPEA2

An improved version of the Strength Pareto Evolutionary Algorithm (SPEA2) for multiobjective optimization proposed in (Zitzler et al, 2002) has been used to solve the volt/var problem. SPEA2 uses two populations: a regular population, P_t and an archive, $\overline{P}_t$. The archive accumulates nondominated solutions and it is from there that individuals are selected to form a mating pool. Following the application of the genetic operators to the mating pool, the resulting offspring become the new regular population, P_{t+1}. The new archive, $\overline{P}_{t+1}$, is mainly constructed from the nondominated solutions in $P_t \cup \overline{P}_t$.

Binary tournament selection is used to fill the mating pool, and fitness assignment consists of two components: one based on the concept of Pareto dominance and the other on density information.

The purpose of the density component is to encourage a more even spread of solutions across the Pareto front. In more detail, the procedure for fitness assignment can be expressed as follows:

$$F(i) = R(i) + D(i) \quad (4)$$

where $F(i)$ is the total fitness value, $R(i)$ represents the raw fitness component, and $D(i)$ the density component. In order to calculate the raw fitness, each individual in P_t and $\overline{P}_t$ is assigned a strength value, $S(i)$, representing the number of solutions it dominates. The raw fitness, $R(i)$, for a particular individual, is then determined by adding together the strengths of all members of P_t and $\overline{P}_t$, which dominate that individual. The density value, $D(i)$, is based on the inverse of the Euclidean distance (in objective space) of the *k-th* nearest neighbor from individual *i*:

$$D(i) = \frac{1}{\sigma_i^k + 2} \quad (5)$$

where σ_i^k denotes the Euclidean distance sought. We set $k = \sqrt{N + \overline{N}}$. Environmental selection essentially copies all the individuals in P_t and $\overline{P}_t$ that are non-dominated, to $\overline{P}_{t+1}$, but at the same time, it ensures that the size of the archive remains constant at $\overline{N}$.To achieve this, solutions are deleted if $\overline{N}$ is exceeded and added when the archive size would otherwise fall below $\overline{N}$. A truncation operator is used to reduce the population by deleting those members considered too close to another individual in objective space. When the population needs to be increased, the best dominated individuals are copied from the previous archive and population.

3 Criteria For The Optimal Location

The principal criteria to locate the voltage regulators banks and the capacitor banks are:

1. To maintain the voltage in all buses, inside of acceptable limits;
2. To locate the voltage regulators banks in the main feeder;
3. Not to locate the regulators banks on buses where exists capacitors banks;
4. The regulator should support the power flows in the section where it, is located, which is of high magnitude in the first sections of the main feeder;
5. The capacitors should be located where can minimize of loss energy.

The attendances of those criteria demand an optimization method that is capable to contemplate the discrete characteristic of the problem and without approaches.

<table>
<tr><th colspan="16">Capacitors</th><th colspan="4">Regulator</th></tr>
<tr><th colspan="4" rowspan="2">Bus</th><th colspan="12">Unit of capacitors to load:</th><th rowspan="2">Bus</th><th colspan="3">tap to load:</th></tr>
<tr><th colspan="4">p</th><th colspan="4">i</th><th colspan="4">s</th><th>p</th><th>i</th><th>s</th></tr>
<tr><td>7</td><td>15</td><td>29</td><td>58</td><td>1</td><td>0</td><td>1</td><td>0</td><td>2</td><td>1</td><td>3</td><td>0</td><td>3</td><td>2</td><td>3</td><td>2</td><td>15</td><td>8</td><td>7</td><td>3</td></tr>
</table>

Figure 1 - Structure of decoded chromosome in decimal representation.

4 Formulation of The Problem

The volt/var problem of the location and adjustments of voltage regulators and capacitors banks in distribution systems is formulated here as a problem of combinatorial optimization to be solved using multiobjective optimization algorithm (Zitzler, 2002).

4.1 The codification

The codification is made here in binary representation to facilitate the control to avoid imperfect chromosomes. A decoded chromosome in decimal representation, showed in figure 1, is passed to computational routine where are calculated the two objectives f_1 e f_2. The computation of f_1 e f_2 occurs after the load flows (Das et al, 1995) be calculated in three load levels.

The code part referent the capacitor allocation is divided in four parts. The first part gives the bus numbers where capacitor banks are placed. The three following parts give the number of capacitors operating in each load level (peak, intermediate and soft level). In the soft load level, only the fixed capacitors are used.

The code part referent the voltage regulator allocation is divided in two parts. The first one gives the bus number where the bank is placed. The second part gives the numbers of taps operating in the load level: peak, intermediate and soft, respectively.

Two advantages may be noticed by using this chromosome structure: a more compact way of storing data and possibility to avoid producing imperfect chromosomes when processing crossover operations.

4.2 The fitness function

Two independent fitness functions (f_1 and f_2) formulated to solve the problem integrated control of. The fitness function associated to reactive power control, f_1, represent the power losses costs and the fitness function to voltage profile control, f_2, represents the costs of operation to maintain the voltage busbars inside of range allowed regulation.

The costs of equipments were considerate in both fitness functions.

Capacitors

The fitness function to reactive power control (f_1) is formulated, to be minimized. Here, includes the total cost with the installation of fixed capacitors and switched capacitors and the power losses costs:

$$f_1 = K_p \Delta p + K_E \Delta E + K_C (n_f, n_c, c_{inst}) \quad (6)$$

Where:

- f_1 is annual losses costs to be minimized, (\$/year);
- Kp annual medium cost of power losses at peak level (\$/kW/year);
- K_E medium cost of energy losses at integral period (\$/kWh);
- Δp annual power losses at peak level (kW);
- ΔE annual energy losses (kWh);
- K_C investment, a function of: installation costs (c_{inst}), number of fixed (*nf*) and switched capacitors (*ns*).

Voltage Regulators

The fitness function of voltage profile control is formulated to be minimized too. It is based in costs, but also take in account maintain the busbars voltages nearest to a reference voltage.

The idea is to considerate the costs of busbar voltage control, by the follow way: the cost is null when the voltage values is equal to desired voltage value. When the busbar voltage deviates, the cost of busbar voltage control also is increased. Therefore, a second degree polynomial function was interpolated, taking the deviate of voltage busbar related of voltage reference, in follow way:

Table 1 – Used criteria to set the voltage control cost function.

Δ_v (pu)	0,0	0,03	0,15
Cost *fp* (% C_{reg})	0	5	100

$$fp(\Delta_v) = a\Delta_v^2 + b\Delta_v + c \quad (7)$$

Where:

- fp represents the percentual of busbar's voltage control costs;
- C_{reg} is the cost of voltage regulator;
- *a, b, c* are the coefficients of the polynomial function;
- Δ_v represents the difference between the reference voltage and the busbar voltage, in p.u.

The formulation of the second objective is:

$$f_2 = \left(\sum_{n=1}^{nl} \sum_{i=1}^{nb} fp(\Delta_i) \right) . \frac{100}{(nb.C_{reg})} \quad (8)$$

Where:

- f_2 is the percentage medium cost to correction of voltage, (%);

nl	is the number of levels used to the segmented duration load curve;
Δ_i	is the difference between the voltage reference and the voltage at busbar i;
n_b	number of bars of the feeder.

The f_2 function represents the operational cost to correct the busbar voltages. Not necessarily to higher the voltage, but to maintain it inside the desired wide. The implemented fitness function has the same costs, in a symmetrical way, for voltages below or to the reference voltage.

For example, to a 1.0 pu reference voltage, a busbar with 1.05 p.u. will have the same cost to correct the voltage of 0.95 p.u. of other busbar. The reduction search space approach of to allocate technique to voltage regulator, successfully implemented in (Almeida et al, 2005) also has been adopted here.

According the definitions to multiobjective optimization problem and applying to volt/var problem:

Minimize:

$$z = f(x) = (f_1(x), f_2(x)) \tag{9}$$

subject:

$$g(x) = (g_1(x), g_2(x)) \leq b \tag{10}$$

where:

$$x = (x_1, x_2) \in X$$

$$z = (z_1, z_2) \in Z$$

The objective functions f_1 and f_2 represents the reactive (var) and voltage (volt) problems, respectly. The x vector represents a solution possible to installation banks of capacitor fixed and switched (x_1) plus voltage regulator (x_2) according of codification, showed in the item 4.1.

The restriction to volt/var problem are:

$$g_1(x) = N_{md}$$

$$g_2(x) = \Delta_{vm}$$

where:

1. N_{md} is the maximum number of capacitive modules;
2. Δ_{vm} is the maximum deviation of busbars voltages.

5 Implementation

A Matlab© implementation has been made in a microcomputer with Athlon XP 3500 processor. A distribution feeder of 13.8 kV and 62 buses, presented in figure 2, whose line and load data are found in Appendix.

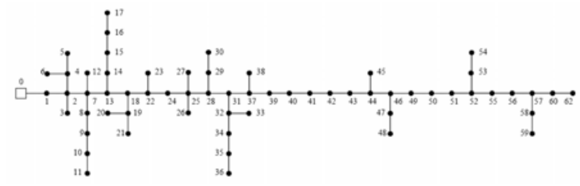

Figure 2 - Radial distribution system used in implementation.

The algorithm is flexible to let the amount buses to locate capacitors banks as well the unit standard of kvar is chosen. It has been considered the number of four buses of feeder and capacitors bank modules of 200 kvar. The values of parameters used in fitness function f_1 are: K_p = \$180/kW/year, K_E = \$0,04/kWh, $K_{C\ (\text{switched unit})}$ = \$240 and $K_{C(\text{fix unit})}$ = \$200.

A limit of power flow equal to 414 kVA, through the installation point of the regulator. A power factor equal to 0,85 was used to all loads and the data related of the load duration curve are showed in table 2.

The adopted parameters are showed in table 3 and a limit of 3000 generations was established as the stopped criterion with a total execution time of 89 minutes. The restrictions were: $N_{md} = 30$ capacitive modules and $\Delta_{vm} = 0{,}05\ pu$.

Table 2 – Parameters of segmented load duration curve.

Level	1 - Peak	2 – Intermediate	3 - Soft
Load Factor	0,67	0,52	0,43
Duration (h)	5,83	10	8,17

Table 3 – Parameters of SPEA2.

Population	Archive	Rate of	
		crossover	mutation
100	35	70 %	2 %

The figure 3 shows a chromosome of the non-dominated solutions (archive), after the convergence of the implemented method. The annual energy losses had an expressive reduction of 49.1% related of the initial, condition how showed in table 4.

The voltage profile also has corrected and all voltage feeder busbars stayed in desired voltage range. In figure 4, it is presented the voltage profile to all busbars of main feeder before and after the volt/var control has been applied.

Table 4 – Annual energy losses

Condition	MWh	%
Initial	1457,2	2,55
After volt/var	970,89	1,71

Capacitors																Regulator			
Bus				Unit of capacitors to load:												Bus	tap to load:		
				p				i				s					p	i	s
39	51	57	22	0	1	2	0	1	0	1	3	3	3	3	3	18	9	6	3

Figure 3 – A solution present in the archive after the convergence of SPEA2.

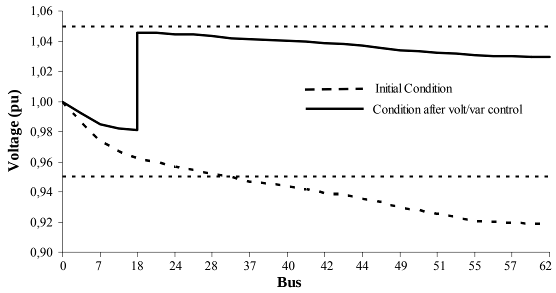

Figure 4 -Voltage profiles of main feeder to peak load condition.

The distribution of the solutions in the objective space, according the fitness functions are presented in figure 5, in the first and the last generation of SPEA2.

The coordinated axis scale which represents: the medium percentage costs (% C_{reg}) to voltage control, f_2, and cost of power losses, f_1, in $\$10^5$. We have notice a significant improvement in the objective minimization and also in the solution diversity.

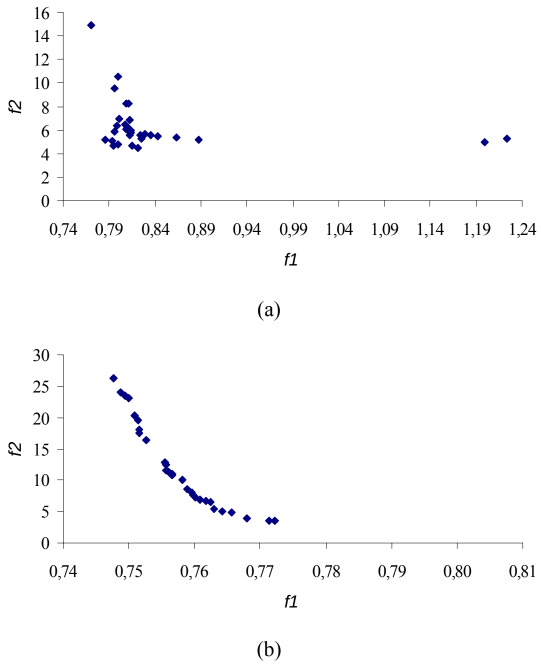

Figure 5 - Solutions on objective space of volt/var problem: (a) first generation; (b) last generation (3000) – Approximation of Pareto Set.

6 Conclusions

The volt/var control in distribution systems has been dealed here like a combinatorial optimization problem solved by multiobjective optimization technique (SPEA2). The final population of archive is a good approximation of Pareto Set for this problem. The implemented objectives functions with costs to produce solutions in the archive which satisfy the defined criteria to volt/var control. More objectives how installation of harmonic filters can be added at this method.

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Appendix

Data of radial distribution system (CZA03 – CEAL – Companhia Energética de Alagoas) used in implementation are shown on table A.1.

Table A.1 – Data of CZA03 feeder of CEAL Distribution System

from	to	C(km)	R (Ω/km)	X (Ω/km)	S(kVA)	Conductor
0	1	0,61	0,2006	0,4026	150	336,4_CA
1	2	0,77	0,1202	0,3592	337,5	477_CAA
2	3	0,2	1,3735	0,486	0	6_CU
2	4	0,36	1,3735	0,486	412,5	6_CU
4	5	0,24	1,3735	0,486	0	6_CU
4	6	0,47	1,3735	0,486	45	6_CU
2	7	0,48	0,1202	0,3592	420	477_CAA
7	8	0,37	1,3735	0,486	45	6_CU
8	9	0,02	1,3735	0,486	300	6_CU
9	10	0,42	1,3735	0,486	262,5	6_CU
10	11	0,22	1,3735	0,486	450	6_CU
7	12	0,34	1,3735	0,486	375	6_CU
7	13	0,33	0,1202	0,3592	150	477_CAA
13	14	0,17	0,2006	0,4026	45	336,4_CA
14	15	0,22	0,2006	0,4026	45	336,4_CA
15	16	0,64	0,2006	0,4026	45	336,4_CA
16	17	0,04	0,2006	0,4026	75	336,4_CA
13	18	0,16	0,1202	0,3592	0	477_CAA
18	19	0,1	1,3735	0,486	75	6_CU
19	20	0,05	1,3735	0,486	150	6_CU
19	21	0,08	1,3735	0,486	45	6_CU
18	22	0,28	0,1202	0,3592	187,5	477_CAA
22	23	0,2	1,3735	0,486	225	6_CU
22	24	0,14	0,1202	0,3592	45	477_CAA
24	25	0,2	0,1202	0,3592	75	477_CAA
25	26	0,08	1,3735	0,486	45	6_CU
25	27	0,27	1,3735	0,486	112,5	6_CU
25	28	0,27	0,1202	0,3592	262,5	477_CAA
28	29	0,16	1,3735	0,486	75	6_CU
29	30	0,16	1,3735	0,486	150	6_CU
28	31	0,16	0,1202	0,3592	45	477_CAA
31	32	0,18	1,3735	0,486	0	6_CU
32	33	0,52	1,3735	0,486	232,5	6_CU
32	34	0,18	1,3735	0,486	75	6_CU
34	35	0,28	1,3735	0,486	225	6_CU
35	36	0,31	1,3735	0,486	150	6_CU
31	37	0,36	0,1202	0,3592	225	477_CAA
37	38	0,1	1,3735	0,486	195	6_CU
37	39	0,23	0,1202	0,3592	30	477_CAA
39	40	0,23	0,1202	0,3592	157,5	477_CAA
40	41	0,24	0,2006	0,4026	112,5	336,4_CA
41	42	0,12	0,2006	0,4026	150	336,4_CA
42	43	0,22	0,2006	0,4026	75	336,4_CA
43	44	0,28	0,2006	0,4026	112,5	336,4_CA
44	45	0,2	1,3735	0,486	45	6_CU
44	46	0,28	0,2006	0,4026	150	336,4_CA
46	47	0,37	1,3735	0,486	270	6_CU
47	48	0,19	1,3735	0,486	375	6_CU
46	49	0,4	0,2006	0,4026	75	336,4_CA
49	50	0,33	0,2006	0,4026	75	336,4_CA
50	51	0,23	0,2006	0,4026	75	336,4_CA
51	52	0,27	0,2006	0,4026	262,5	336,4_CA
52	53	0,28	0,2006	0,4026	187,5	336,4_CA
53	54	0,19	0,2006	0,4026	675	336,4_CA
52	55	0,3	0,2006	0,4026	337,5	336,4_CA
55	56	0,08	0,2734	0,4264	225	2/0_CU
56	57	0,16	0,2734	0,4264	375	2/0_CU
57	58	0,08	0,2734	0,4264	225	2/0_CU
58	59	0,04	0,2734	0,4264	112,5	2/0_CU
57	60	0,17	0,2734	0,4264	600	2/0_CU
60	61	0,07	0,2734	0,4264	300	2/0_CU
60	62	0,28	0,2734	0,4264	337,5	2/0_CU