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Coordinated Tuning of a Group of Static Var Compensators Using Multi-Objective Genetic Algorithm

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Abstract

The optimal coordinated tuning of a group of *Static Var Compensators* (*SVC*), in steady state, allows the *Power Electric Systems* (*PES*) to operate close to their overload limits, maintaining the voltage stability in several operating conditions. The mentioned tuning problem was considered as a *Multi-objective Optimization Problem* (*MOP*) with three objectives to optimize: the financial investment for acquiring the set of compensators, the maximum voltage deviation and total active power loss. The *Genetic Algorithm* (*GA*), which belongs to the group of Evolutionary Algorithms, was utilized and adapted for *MOP*, obtaining a *Multi-Objective GA* (*MOGA*). The parameters to be adjusted in each compensator are: the reference voltage and the minimum and maximum reactive power injected to the system. In this work, the number of compensators and their locations were calculated using the *Q-V* sensitivity curve, from the *Load Flow* algorithm, based on *Newton–Raphson* method. The proposed coordinated tuning method will be validated considering an example of *PES*, where was located and tuned a specific set of compensators. Time simulations were made for dynamic performing the steady state coordinated tuning.

Keywords: Static Var Compensator, Coordinated Tuning, Multi-Objective Optimization Problem, Multi-Objective Genetic Algorithm.

1 Introduction

This paper is an extension of work presented in [1], where it was described the optimal robust tuning of the *SVC* parameters, considering a few operating conditions, in steady state. So, in this work, it was implemented an optimal coordinated tuning procedure for adjusting several compensators, simultaneously, considering different critical operating scenarios, in order to overcome the voltage stability, in steady and dynamic state. Then, the compensators adjusted optimally allow to any *PES* studied operates close to their overload limits, maintaining a good level voltage for any disturbance.

The *SVC* devices belong to the *FACTS* group (*Flexible AC Transmission System*), which combine the digital electronic and the *AC* (*Alternative Current*) electric circuits and power electronic, and offer high speed response and large operational reliability [2]; because of those attractive characteristics, the compensators are largely utilized in protection and voltage stability of *PES* and require minimum financial investment to evaluate and locate [3].

This reactive compensation problem is solved, commonly, in two steps: a) Financial procedure, where the compensator parameters are adjusted and, b) operational procedure, where the feasibility of the tuned parameters is verified applying the *Optimal Power Flow* (*OPF*) method. If the parameter values, calculated in the financial step, do not satisfy the design requirements, in operational procedure step, the necessary reactive power is determined for injecting in the system, in order to satisfy the requirements. This reactive power value calculated, in the operational step in order to satisfy the voltage stability, is called as *virtual reactive power*. Then, considering the *Bender Decomposition*, new parameters are calculated in the financial step, taking into account the parameter values of the previous iteration, and the new parameters obtained are validated again. This iterative procedure is repeated until the *virtual reactive power* approaches to zero [4–5].

Nowadays, the *GA* is going to be used in reactive compensation problems. In reference [6], is detailed a reactive location method based on *GA*, and in reference [7] was utilized the *MOGA* in order to locate and calculate capacitor banks in a determined *PES*, used as a test.

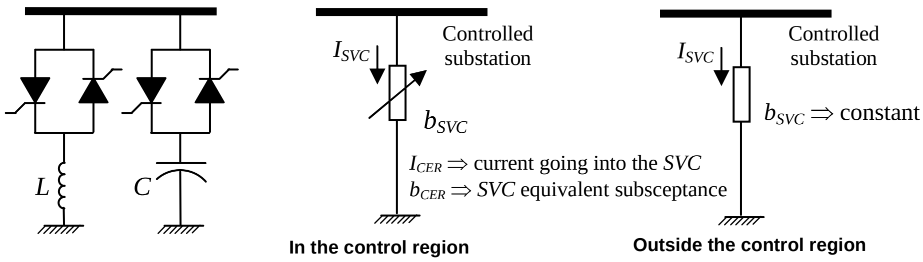
In this work is proposed a coordinated tuning procedure for calculating the optimal parameter values of a group of compensators, based on the search technique of the *GA*, considering several operating conditions in steady state. It was used the *GA* because its recognized efficacy in global optimization of complex and large industrial problems [8]. The parameters to be adjusted for each *SVC* are: a) the reference voltage of the *Automatic Voltage Regulator* (*AVR*) of each *SVC*, b) minimum reactive power, and c) maximum reactive power, to be injected to the system by each *SVC* devices.

The coordinated tuning problem was considered as a *MOP* with three objectives to minimize: a) *Financial Investment* for acquiring the set of compensators, b) *Maximum Voltage Deviation*, and c) *Maximum Power Loss*. Then, the *GA* described in [8] was adapted in order to optimize several objective functions, simultaneously, obtaining a *Multi-Objective GA* (*MOGA*). The main methodology for adapting the *GA* for *MOP*, described in details in this paper, is the *Pareto Dominance* rules; where, several optimal solutions are classified and saved on a group of optimal solutions. The group of optimal solutions is classified in each iteration of the *GA*. This algorithm gets a family of optimal solutions [9], at the end of its execution.

In order to compare the performance of the *MOGA*, based on *Pareto Dominance* rules, it was also implemented the *Weighted Sum Method* for adapting the *GA* for *MOP*, where the global evaluation function, or *Fitness*, is calculated by the weighted sum of several objective functions to optimize. This algorithm gets a unique optimal solution, at the end of its search procedure. In addition, this paper presents numerical results, which validate the proposed coordinated tuning procedure. The *PES*, used as a test, corresponds to an academic *IEEE PES* with fourteen buses (substations) [10]. Time response simulations were made in order to evaluate the dynamic performance of the group of tuned compensators, using standard values for dynamic parameters of the *AVR*, of each *SVC* device.

2 Mathematical Model

In this section, it is described the steady state mathematical model of the *SVC* device, such as described in Fig. 1.



(a) *SVC* structure. (b) *SVC* representations in different operating regions.

Figure 1. *Steady State* model of the *Static Var Compensator*.

According Fig. 1 (a), the compensator is composed by switching reactor L and capacitor C banks, controlled by thyristors [2], and they are connected in series. In Fig. 1 (b), a linearly susceptance represents, mathematically, the performance of the *SVC* device operating in the control region. However, the susceptance is a fixed value outside that region.

The susceptance is associated to the reactive power injected to the system in order to maintain the voltage level between suitable limits, in the *controlled substation*[1]. Fig. 2 describes the mathematical expression regarding to the voltage level of the controlled substation with the reactive power injected to the system.

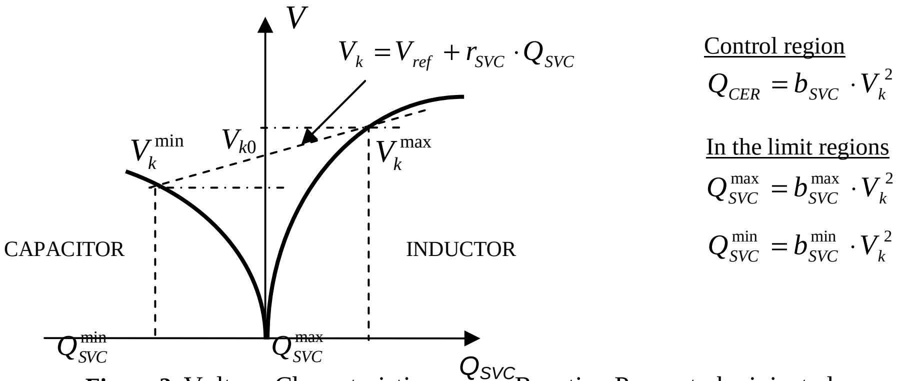


Figure 2. Voltage Characteristics versus Reactive Power to be injected.

Fig. 2 describes the relationship between the voltage value, in the controlled substation k, and the reactive power, Q_{SVC}, injected to the system; where, r_{SVC} is the slope of the characteristic curve. The b_{SVC} varies linearly in the control region, but is a fixed value in the limit regions, because it has achieved the capacitive or inductive reactive power limit. These limits are associated to the capacity of the capacitor and reactor banks.

In order to represent each *SVC* device, operating in different regions, in the *Load flow* algorithm, based on the *Newton-Raphson* method, the corresponding *Jacobian* matrix is modified. Then, in the *Jacobian* matrix, the *SVC* entries as a control function where the variable parameter is $\Delta x_i = Q_{i,SVC}$ [11], and $i \in \{1, 2, \ldots, p\} \mid p$ is the number of compensators considered in the group, as indicated in equation (1).

$$\begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta y_1 \\ \vdots \\ \Delta y_p \end{bmatrix} = \begin{bmatrix} \ddots & \cdots & \frac{\partial \Delta P}{\partial x_1} & \cdots & \frac{\partial \Delta P}{\partial x_p} \\ \vdots & \ddots & \frac{\partial \Delta Q}{\partial x_1} & \cdots & \frac{\partial \Delta Q}{\partial x_p} \\ \frac{\partial \Delta y_1}{\partial \theta} & \frac{\partial \Delta y_1}{\partial V} & \frac{\partial \Delta y_1}{\partial x_1} & \cdots & \frac{\partial \Delta y_1}{\partial x_p} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial \Delta y_p}{\partial \theta} & \frac{\partial \Delta y_p}{\partial V} & \frac{\partial \Delta y_p}{\partial x_1} & \cdots & \frac{\partial \Delta y_p}{\partial x_p} \end{bmatrix} \cdot \begin{bmatrix} \Delta \theta \\ \Delta V \\ \Delta x_1 \\ \vdots \\ \Delta x_p \end{bmatrix} \tag{1}$$

Capacitive Limit:

$$\frac{\partial \Delta y}{\partial V_k} = -2 b_{\max} V_k;\ \frac{\partial \Delta y}{\partial x} = 1;\ \frac{\partial \Delta Q}{\partial x_1} = -1; \cdots ; \frac{\partial \Delta Q}{\partial x_p} = -1;$$

Inductive Limit:

$$\frac{\partial \Delta y}{\partial V_k} = -2 b_{\max} V_k;\ \frac{\partial \Delta y}{\partial x} = 1;\ \frac{\partial \Delta Q}{\partial x_1} = -1; \cdots ; \frac{\partial \Delta Q}{\partial x_p} = -1;$$

Control Region:

$$\frac{\partial \Delta y}{\partial V_k} = -1;\ \frac{\partial \Delta y}{\partial x} = -r_{CER};\ \frac{\partial \Delta Q}{\partial x_1} = -1; \cdots ; \frac{\partial \Delta Q}{\partial x_p} = -1;$$

The components of the *Jacobian* matrix, associated to the *SVC* group, set to different numerical values according to the operating condition, such as indicated in equation (1). All components, regarding to the *SVC* control function with the angle and the active power with Δx_i, are equal to zero.

[1] *Controlled substation* is the substation where the *SVC* device is installed. Then, the compensator injects the necessary reactive power, throughout the referred substation, in order to maintain the voltage level in the whole system between suitable limits.

3 Proposed Tuning Procedure

The coordinated tuning of parameters of a *SVC* group was considered as a *MOP* with three objective functions to be minimized, such as indicated in equation (2):

Minimize $F(\mathbf{x}) = \left[F_1(\mathbf{x}) \quad F_2(\mathbf{x}) \quad F_3(\mathbf{x}) \right]$

subject to the following restrictions:

$$\begin{aligned} & PG_j - PL_j - \sum_{\substack{j\in\Omega \\ i\neq j}} P_{ij} = 0 \\ & QG_k + b_{SVC} \cdot V_k^2 - QL_k - \sum_{j\in\Omega} Q_{ij} = 0 \\ & QG_j - QL_j - \sum_{\substack{j\in\Omega \\ i\neq j \\ j\neq k}} Q_{ij} = 0 \\ & V_{k0} - V_k + r_{SVC} \cdot b_{SVC} \cdot V_k^2 = 0 \end{aligned} \tag{2}$$

where P_{Gi}, Q_{Gi}, P_{Li}, Q_{Li} correspond to the active and reactive power generated and demanded in the substation i, such $i \in \{1, 2, \ldots, nsubs\} \mid nsubs$ is the number of substations of the *PES*. The index k identifies the *controlled substation*; so, V_{k0} corresponds to the reference voltage of the *AVR* associated to the compensators installed in substation k. In addition, there are restrictions which limit the active and reactive power generation, in those substations where are installed a group of generator machines: $PG_{\min,i} \leq PG_i \leq PG_{\max,i}$, $QG_{\min,i} \leq QG_i \leq QG_{\max,I}$; and restrictions which limit the voltage level in substations regarding to load zones: $V_{\min,j} \leq V_j \leq V_{\max,j} \mid j \in \{1, 2, \ldots, nbL\} \mid nbL$ is the number of load centers in the *PES*.

3.1 Decision Variables

The *GA* handles the vector of parameters (decision variables) such as shown in equation (3), and it was used the float point codification for representing each of them [12]:

$$\mathbf{x} = \left[V_{REF}^1 \quad Q_{\min}^1 \quad Q_{\max}^1 \quad \cdots \quad V_{REF}^p \quad Q_{\min}^p \quad Q_{\max}^p \right] \tag{3}$$

Such as described before, the parameters to be optimized for each *SVC* device are: a) the reference voltage, V_{REF} (where, $V_{REF} = V_{k0}$), of the *AVR* associated, b) the minimum reactive power to be injected, $Q_{\min}$, and, c) the maximum reactive power to be injected by each *SVC* device, $Q_{\max}$. Each parameter value belongs to the following search space:

$$\begin{aligned} & 0{,}95\,p.u. \leq V_{REF} \leq 1{,}05\,p.u. \\ & -200MVAr \leq Q_{\min}^{SVC} \leq 0MVAr \\ & 0 < Q_{\max}^{SVC} \leq 200MVAr \end{aligned} \tag{4}$$

3.2 Objective Functions

In the *MOP*, for coordinated tuning of a group of *SVC*, there are three objective functions to be minimized: a) the *Financial Investment*, $F_1(\mathbf{x})$, for acquiring the set of compensators, b) the *Maximum Voltage Deviation*, $F_2(\mathbf{x})$, and, c) the *Maximum Total Active Power Loss*, $F_3(\mathbf{x})$, calculated by considering all selected critical operating scenarios.

$$\begin{aligned} F_1(\mathbf{x}) &= \sum_{i=1}^{nSVC} B_i \cdot \left|\Delta Q_{SVC,i}\right| \\ F_2(\mathbf{x}) &= \left\|\mathbf{V}^{esp} - \mathbf{V}\right\|_\infty \\ F_3(\mathbf{x}) &= \left|\sum_{g=1}^{ng} PG_g - \sum_{bc=1}^{nbc} PL_{bc}\right| \end{aligned} \tag{4}$$

In equation (4), $F_1(\mathbf{x})$ is directly proportional to the compensation capacity of each *SVC*, where B_i is the monetary value for each *MVAr* of the *i-th* compensator; and, n_{SVC} indicates the number of compensators to be adjusted in the *PES*. In this work, each B_i = 1.0 monetary/*MVAr*. In addition, *ng* and *nbL* correspond to the number of substations with a group of installed generators and substations associated to the load zones, respectively.

3.3 *GA* Adapted for *MOP*

In this subsection will be described the two proposed algorithms, based on *GA*, adapted for *MOP* and applied for optimal coordinated tuning of parameters belonging to the group of compensators.

3.3.1 MOGA based on Pareto Rules

Considering the coordinated tuning problem of compensator parameters of a group, the *Dominance Pareto Rules* are described through the following mathematical expressions [9]:

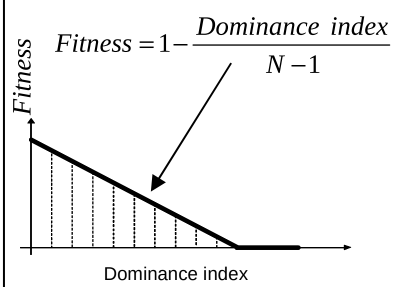
i) $F_k(\mathbf{x}_r) \leq F_k(\mathbf{x}_s)$, where r and $s \in (1, 2, \ldots, N) \mid r \neq s$ and N indicates the population size in the *GA*, and $k \in \{1, 2, \ldots, f\}$, such f corresponds to the number of objective functions considered in the optimization procedure;

ii) $\exists\, i$, such that, at least one of the entries satisfies $F_i(\mathbf{x}_j) < F_i(\mathbf{x}_k)$.

The *Pareto Rules* are applied on each solution of the *GA* population, in order to determine how many numbers of solutions are better than other one. This number defines the *Dominance index* for each feasible solution. The individual (solution), which *Dominance index* is null, is considered as an optimal solution. This classification method is made in each generation of the *GA*. Then, in each generation all optimal solutions obtained by the *Pareto Rules* are saved in a group, called the *Pareto Front* (*PF*); and, it is also actualized in each generation.

In Fig. 3 is shown a pseudocode of the *GA* adapted for *MOP* by using the *Dominance Pareto Rules*.

```
1. t ← 0;
2. Generate Initial Population: P(t);
3. Evaluation of each solution of P(t);
4. WHILE t < t_max
   4.1.   Apply Dominance Pareto Rules.
          i)   F_k(x_i) ≤ F_k(x_j) | i y j ∈ {1, 2, …, N} y k ∈ {1, 2, 3};
          ii)  ∃ k | F_k(x_i) < F_k(x_j).
          These rules are applied on each solution, and then are compared with the
          rest of population, in order to determine how many solutions are better
          than the corresponding solution, defining its dominance index.
   4.2.   Actualize the optimal solutions in PF(t)
   4.3.   Calculate the Fitness of each classified solution;
   4.4.   Apply GA operators: Selection, Crossover and Mutation [7],
          obtaining a new population P(t+1);
   4.5.   Evaluate each new solution of P(t+1);
   4.6.   Do P(t) ← P(t+1);
   4.7.   t = t + 1;
   END WHILE
5. RETURN FP(t) // print the last actualized group PF(t).
```



(b) *Fitness* evaluation

Figure 3. *Pseudocode of the MOGA based on Dominance Pareto Rules.*

All optimal solutions, which are obtained by applying the *Dominance Pareto* rules, are reproduced, in each generation, inside the $PF(t) \mid t$ is an iteration counter. The $PF(t)$ is actualized in each generation. In the mathematical expression, the *Fitness* calculation is directly associated to the *Dominance index* of the individual, such as indicated in Fig. 3 (b). The *GA* adapted for *MOP* using the *Dominance Pareto Rules* is called as *GADP*.

3.3.2 MOGA based on Weighted Sum Method

In this case, the *GA* such as described in [8] was adapted for *MOP* according to equation (5):

$$Fitness_i(\mathbf{x}_i) = a_1 \cdot F_1(\mathbf{x}_i) + a_2 \cdot F_2(\mathbf{x}_i) + a_3 \cdot F_3(\mathbf{x}_i) \quad (5)$$

The coefficients of equation (5) correspond to the normalization factors, where $a_q = c_q / F^{max}{}_q$ and $q \in \{1, 2, 3\}$. $F^{max}{}_q$ is the maximum value of the *q-th* objective function, and the coefficient c_q is any value such that $c_q \geq 1$, this methodology avoids certain objective functions dominate over the rests [9], carrying to a local optimum [9].

3.4 Initial Population

In this work, $N - D$ feasible individuals are generated randomly, where $N = 50$ individuals. The remaining D individuals are estimated through equation (6), varying the reference voltage, $V_{REF,i}$, and then is calculated the necessary reactive power to be injected into the system, in the corresponding *i-th controlled substation*, which also defines the initial reactive compensation capacity of the *i-th SVC* device.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{bmatrix} \cdot \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix}, \Rightarrow \Delta Q = \left[\left(\frac{\partial Q}{\partial V} \right) - \left(\frac{\partial Q}{\partial \theta} \right) \cdot \left(\frac{\partial P}{\partial \theta} \right)^{-1} \cdot \left(\frac{\partial P}{\partial V} \right) \right] \cdot \Delta V \Bigg|_{\Delta P = 0} \quad (6)$$

The equation (6) describes the *Q–V* sensitivity curve, obtained by the matrix equation of the active and reactive power deviation of the *Load Flow* algorithm [2]. Each compensator is located in a substation, associated to the load zone, where is required a high reactive power value in order to maintain the associated voltage module in 1 p.u. So, this methodology also defines the *i-th controlled substation*.

3.5 *GA* Operators

A Stochastic Tournament *Selection*, with five individuals, was used in order to choose the probabilistic better solution for next generation. Then, it was utilized an *Arithmetic Crossover* [12], with probability p_c = 0,7, and *Mutation* operator, with a constant probability p_m = 0,01, for getting new individuals.

4 Experimental Results

4.1 Characteristics of Power System Test

The implemented coordinated tuning algorithms are applied on IEEE14 system [10], show in Fig. 4.

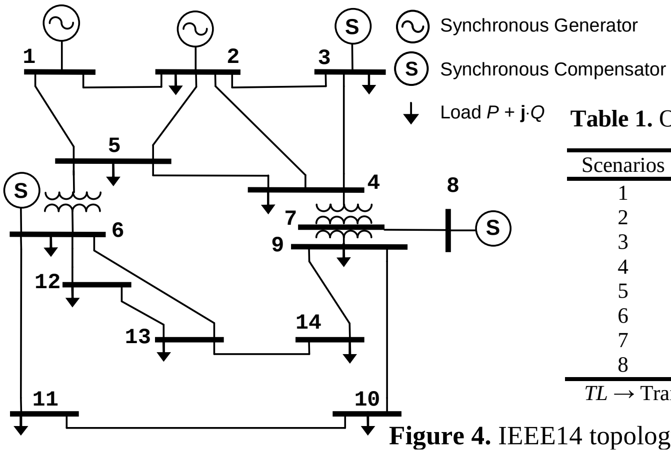


Table 1. Operating Conditions considered on IEEE14 system.

Scenarios	Description
1	Base case
2	Generator 2, out of service.
3	*TL* 6–13, disconnected.
4	*TL* 6–13, and *TL* 9–10, disconnected.
5	*TL* 6–13, and *TL* 9–14, disconnected.
6	Synchronous Compensator 3, out of service.
7	Synchronous Compensator 3 and 8, out of service.
8	All Synchronous Compensators, out of service.

TL → Transmission Line.

Figure 4. IEEE14 topology.

In this paper, the coordinated tuning methodology adjusts two compensators. The *Q–V* sensitivity curve, which procedure was described in subsection 3.4, determined the load buses 13 and 14 for installing each *SVC*.

4.2 Computational Environment

The *MatLab*® [13] was used for *Load Flow* implementation and *GA* adaptation for *MOP*. The *Power System Analysis Toolbox* (*PSAT*) [14] was used to evaluate the dynamic perform of each *SVC*.

4.3 Analysis of Numerical Results

The *GA*, based on *Weighted Sum* methodology (*GAWS*), was executed 5 times for each different *Fitness*. The different mathematical expressions for *Fitness* were obtained by modification of each coefficient, such as described in equation (5). In Table 2 are shown the different values considered for each coefficient, the best numerical result obtained by each *GAWS* execution, and the average computational time spent in each running.

Table 2. Numerical results obtained by *GAWS*.

line	a_1	a_2	a_3	$V_{REF,1}$ (p.u.)	$Q_{min,1}$ (*MVAr*)	$Q_{max,1}$ (*MVAr*)	$V_{REF,2}$ (p.u.)	$Q_{min,2}$ (*MVAr*)	$Q_{max,2}$ (*MVAr*)	F_1 (*MVAr*)	F_2 (*pu*)	F_3 (*MW*)	*Time* (*s*)
1	1,0	1,0	1,0	1,037	-94,7	1,2	1,034	-74,7	127,1	297,5	0,0154	18,05	193,2
2	1,2	1,0	1,0	1,036	-116,9	2,1	1,029	-97,6	59,6	276,1	0,0154	17,95	210,4
3	1,6	1,0	1,0	1,037	-81,6	9,8	1,034	-85,6	32,8	209,6	0,0154	17,94	205,7
4	2,0	1,0	1,0	1,034	-94,5	90,6	1,023	-74,6	57,9	317,4	0,0154	17,98	202,3
5	1,0	1,2	1,0	1,036	-126,5	52,2	1,037	-44,3	44,2	267,1	0,0154	14,25	186,4
6	1,0	1,6	1,0	1,034	-122,6	4,0	1,024	-66,9	80,1	273,6	0,0154	17,83	195,7
7	1,0	2,0	1,0	1,034	-122,6	4,0	1,024	-66,9	80,1	273,7	0,0154	17,83	195,7
8	1,0	1,0	1,2	1,039	-57,6	3,5	1,033	-92,6	47,3	201,0	0,0154	17,98	189,1
9	1,0	1,0	1,6	1,032	-128,8	84,4	1,030	-76,4	7,2	296,7	0,0154	17,86	201,8
10	1,0	1,0	2,0	1,038	-102,9	3,8	1,034	-94,1	82,7	283,5	0,0154	17,99	200,5

In Table 3 are shown the numerical results of *GA*, based on *Pareto Dominance* rules (*GAPD*).

Table 3. *Pareto Front* of the *GAPD* algorithm, obtained in one execution.

Individual	$V_{REF,1}$ (p.u.)	$Q_{min,1}$ (*MVAr*)	$Q_{max,1}$ (*MVAr*)	$V_{REF,2}$ (p.u.)	$Q_{min,2}$ (*MVAr*)	$Q_{max,2}$ (*MVAr*)	F_1 (*MVAr*)	F_2 (*pu*)	F_3 (*MW*)
1	1,039	-170,0	87,0	1.039	-198,0	79,0	534,0	0,0158	14,25
2	1,042	-142,0	11,0	1,042	-74,0	133,0	360,0	0,0163	14,26
3	1,035	-146,0	149,0	1,035	-27,0	90,0	412,0	0,0154	18,09
4	1,034	-173,0	137,0	1,034	-154,0	59,0	523,0	0,0154	18,07
5	1,033	-140,0	26,0	1,033	-72,0	197,0	435,0	0,0154	18,05
6	1,035	-146,0	149,0	1,035	-27,0	90,0	412,0	0,0154	18,09
7	1,039	-93,0	32,0	1,039	-61,0	1,0	187,0	0,0154	18,07
8	1,025	-146,5	26,0	1,025	-155,0	86,5	414,0	0,0154	17,87
9	0,992	-26,0	91,0	1,024	-128,6	89,3	335,1	0,0154	17,89
10	1,013	-86,0	70,9	1,016	-125,1	136,9	418,9	0,0154	17,70
11	1,003	-88,2	75,3	1,012	-141,0	87,7	392,2	0,0154	17,62
12	1,036	-87,8	93,4	1,019	-109,0	92,4	382,6	0,0154	17,99
13	0,995	-78,5	68,7	1,014	-120,4	64,4	331,9	0,0154	17,68
14	1,043	-101,4	99,1	1,023	-124,0	103,1	427,6	0,0154	18,14
15	1,036	-87,8	93,4	1,019	-109,0	92,4	382,6	0,0154	17,99
16	1,043	-101,5	99,1	1,023	-124,0	103,1	427,6	0,0154	18,14
17	1,035	-94,6	97,5	1,016	-112,9	49,0	354,0	0,0154	17,96
18	1,004	0,0	95,1	1,023	-109,1	98,8	303,0	0,0154	17,78
19	1,002	-93,7	76,7	1,013	-142,0	159,0	471,4	0,0154	17,64
20	1,000	-11,0	99,5	1,016	-109,9	119,1	339,5	0,0154	17,69
21	1,036	-106,5	130,9	1,027	-116,3	140,2	493,9	0,0154	18,03
22	0,962	-79,6	66,2	1,001	-192,0	126,7	464,5	0,0154	17,93
23	0,998	-98,9	80,1	1,005	-172,0	126,0	477,1	0,0154	17,55
24	0,998	-98,9	80,1	1,005	-172,0	126,0	477,1	0,0154	17,55
25	1,047	-96,3	116,3	1,010	-138,0	69,2	419,8	0,0154	18,24
26	1,048	-71,0	86,3	1,022	-71,4	126,3	355,0	0,0154	18,27
27	1,048	-71,0	86,3	1,022	-71,4	126,3	355,0	0,0154	18,27
28	1,021	-73,3	87,3	1,002	-190,0	111,5	462,1	0,0154	17,67
29	1,046	-143,5	139,0	1,032	-100,9	106,0	489,4	0,0154	18,27
30	1,005	-62,6	77,0	1,006	-174,0	121,4	435,0	0,0154	17,56

In Table 2 and Table 3, the first *SVC* parameters correspond to the compensator installed in the 13^{th} substation, and the second parameters belong to the compensator located in the 14^{th} substation. Such as shown in Table 2, the set of *SVC* parameters, located on the 8^{th} *line*, corresponds to the best solution obtained by the *GAWS* algorithm. The main computational time, spent by each *GAWS* running, is approximately equals to 198 s, but, it produces a unique solution at the end of its execution.

In contrast, the *GAPD* got a family of optimal solutions in a single run of the algorithm, according to the results shown in Table 3, and spent approximately 241 s for obtaining the solution set. The referred computational time, spent by the *GAPD* algorithm, is greater than the execution time of the *GAWS*, mainly due to the classification process of the optimal solution set, applying the *Pareto* rules, made in each generation and saved on the *Pareto Front* group. The 7^{th} individual regards to the best solution in the *Pareto Front* of the *GAPD*. This solution is associated to the less financial investment, the identical voltage deviation and the same order of the active power loss value, comparing with the best numerical solution obtained by the *GAWS* algorithm.

The voltage values in the substations of the IEEE14, without any *SVC* installed and obtained by the *Newton–Raphson Load Flow* algorithm for each operating conditions described in subsection 4.1, are shown in Table 4.

Table 4. Voltage values in the IEEE14 system, without any *SVC* installed.

Substation	*Base case* (p.u.)	*2^{nd} Scenario* (p.u.)	*3^{rd} Scenario* (p.u.)	*4^{th} Scenario* (p.u.)	*5^{th} Scenario* (p.u.)	*6^{th} Scenario* (p.u.)	*7^{th} Scenario* (p.u.)	*8^{th} Scenario* (p.u.)
4	1,0177	1,0097	1,0161	1,0172	1,0185	1,0112	1,0040	0,9889
5	1,0195	1,0113	1,0188	1,0193	1,0190	1,0155	1,0109	0,9953
7	1,0615	1,0579	1,0573	1,0606	1,0654	1,0586	1,0302	1,0019
9	1,0559	1,0524	1,0479	1,0544	1,0636	1,0531	1,0332	0,9984
10	1,0510	1,0480	1,0441	1,0254	1,0576	1,0486	1,0322	0,9928
11	1,0569	1,0554	1,0532	1,0435	1,0606	1,0557	1,0473	0,9984
12	1,0552	1,0549	1,0331	1,0346	0,9767	1,0550	1,0535	0,9959
13	1,0504	1,0498	0,9980	1,0015	0,8752	1,0500	1,0470	0,9910
14	1,0355	1,0332	1,0077	1,0130	0,8215	1,0337	1,0210	0,9760

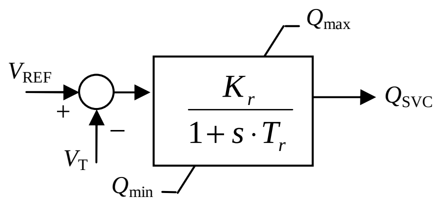
The voltage module of the substations 13^{th} and 14^{th} are the most sensitive to any disturbance in the system, such as indicated on Table 4. Therefore, the voltage drop, in the referred substations, is higher. However, the voltage values in the whole system are corrected by installing *SVC* in the substation 13^{th} and 14^{th}, which numerical results are illustrated in Table 5. The *SVC* parameters selected are those belong to the best coordinated tuning solution obtained by the *GADP* algorithm.

Table 5. Voltage values in the IEEE14 system, with *SVC* installed in substations 13^{th} and 14^{th}.

Substation	*Base case* (p.u.)	*2^{nd} Scenario* (p.u.)	*3^{rd} Scenario* (p.u.)	*4^{th} Scenario* (p.u.)	*5^{th} Scenario* (p.u.)	*6^{th} Scenario* (p.u.)	*7^{th} Scenario* (p.u.)	*8^{th} Scenario* (p.u.)
4	1,0178	1,0100	1,0176	1,0188	1,0186	1,0114	1,0054	1,0013
5	1,0196	1,0115	1,0198	1,0204	1,0192	1,0156	1,0118	1,0070
7	1,0620	1,0587	1,0623	1,0657	1,0654	1,0593	1,0350	1,0293
9	1,0568	1,0539	1,0578	1,0646	1,0636	1,0545	1,0398	1,0334
10	1,0517	1,0493	1,0523	1,0254	1,0576	1,0498	1,0376	1,0285
11	1,0573	1,0560	1,0574	1,0435	1,0606	1,0563	1,0501	1,0347
12	1,0504	1,0504	1,0540	1,0536	1,0614	1,0504	1,0504	1,0384
13	1,0415	1,0415	1,0368	1,0369	1,0351	1,0415	1,0414	1,0379
14	1,0382	1,0380	1,0380	1,0385	1,0363	1,0380	1,0370	1,0364

Such as illustrated on Table 5, the most critical operating condition is the 5^{th} Scenario, where the voltage modules of the whole system are successfully corrected by installing the group of compensators, which parameters were adjusted by the *GADP* algorithm.

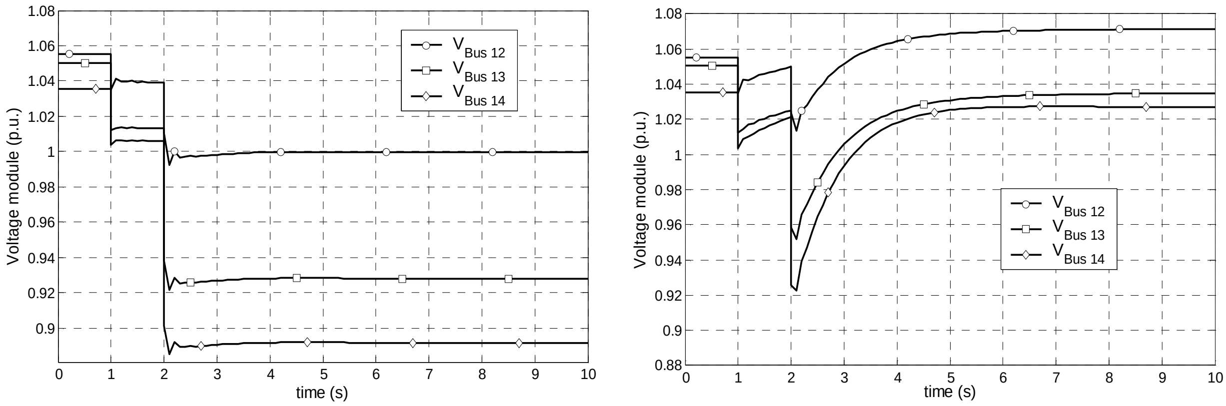
An optimal coordinated tuning of the compensators, at steady state, also determines a good dynamic performance on single contingencies. The most critical operating conditions, such as the 5^{th} and 8^{th} scenarios, were dynamically simulated in order to validate the referred hypothesis. For that reason, a standard dynamic model of the *AVR*, associated to each *SVC* [2], was used and it is described in Fig. 5.



Standard Values: K_r = 10 p.u.; T_r = 10 s.;

Figure 5. Dynamic model of the *SVC* voltage regulator.

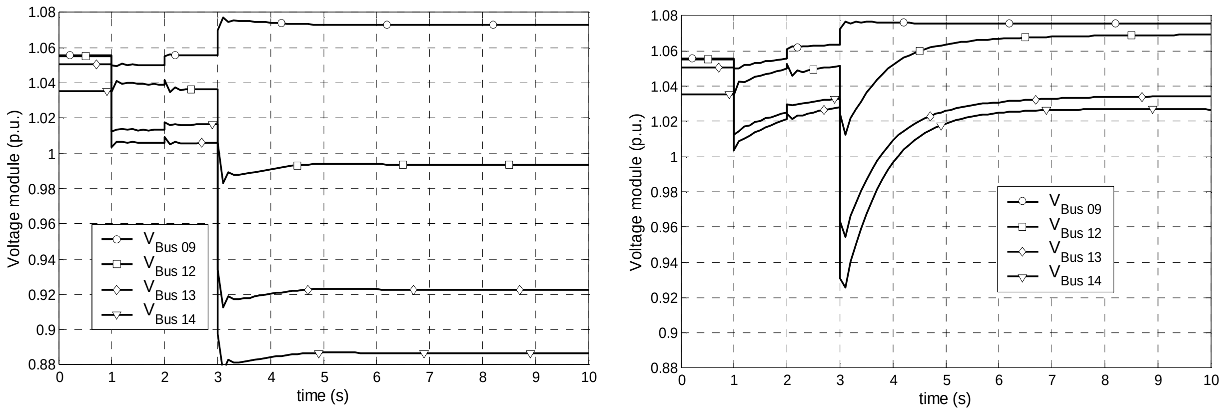
In Fig. 5, the variables: V_{REF}, Q_{min} and Q_{max} correspond to the adjusted parameters, at steady state. The dynamic model, associated to each *SVC*, generates the necessary reactive power to be injected to the *PES* for correcting and regulating the voltage level of the whole system for any disturbance. The 5th scenario is the most critical operating condition and is simulated dynamically using the software *PSAT*, and numerical results are shown in Fig. 6; where, *TL* 6 – 13 and *TL* 9 – 14 are disconnected at 1 and 2 s, respectively, after starting the time simulation. In Fig. 6 (a) the simulation was made without any *SVC* installed in the system test; but the dynamic results considering the compensators adjusted and installed in substations 13th and 14th are shown in Fig. 6 (b).



(a) Simulation without any *SVC*.

(b) Simulation with the *SVC* group adjusted.

Figure 6. Time simulation of the 5th Operating Condition.



(a) Simulation without any *SVC*.

(b) Simulation with the *SVC* group adjusted.

Figure 7. Time simulation of Three Transmission Lines disconnection.

The disconnection of three transmission lines was simulated in order to validate the dynamic performance of the group of compensators, adjusted by applying the proposed multi-objective coordinated tuning algorithm. Then, the *TL* 6 – 13, *TL* 9 – 10 and *TL* 9 – 14 are disconnected at 1, 2 and 3 s, respectively, after starting the time simulation, and the numerical results are shown in Fig. 7.

The simulation was made, firstly, without any compensator installed in the system, illustrating in Fig. 7 (a) the voltage drops, because insufficient reactive compensation. Then, in Fig. 7 (b), the response curve of each voltage module was simulated considering the compensator group adjusted by the proposed methodology. The numerical results, such as shown in Table 5 and dynamic simulations illustrated in Fig. 6 and Fig. 7, indicate the optimal performance of the *SVC* devices. The group of adjusted compensators maintains a good voltage level in the whole *PES*, in steady state, and, shows a good dynamic performance on single contingencies.

5 Conclusions

The two proposed coordinated tuning procedures are able to adjust several static compensator devices, considering several operating conditions, simultaneously. Both methodologies are based on the *MOGA*, the *GAWS* and the *GAPD*, and modify the *Fitness* calculation. In the *GAWS* algorithm, the *Fitness* is calculated with the weighted sum of the considered objective functions, and is obtained a unique optimal solution at the end of the execution. However, in the *GAPD* algorithm, the *Pareto Dominance* rules are applied in order to obtain a group of optimal solutions. The *GAPD* algorithm owns greater search capacity than the *GAWS* search procedure, according to the numerical results, despite of spending more computational time. The set of compensators, adjusted at steady state, also presents a good dynamic performance in single contingences, like transmission line disconnection.

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