Embedding FACTS into the grid for optimizing its operation

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Abstract--This paper is aimed toward the optimal location of FACTS devices with the purpose of improving the operation of an electric power system. To achieve it, measures are used based in voltages, losses of active power and generation costs. Once located the device, it is possible to use optimization methods like the genetic algorithms to optimize its performance based on combinations of such measures. Through voltage and costs indices, results are presented in a testing net that exhibit the applicability of the technique.

Key Words— Electronic equipment, FACTS devices, Genetic algorithms, Optimization methods.

1. Introduction

The energy markets evolution, the weakness of the transmission net due to financial difficulties, the environmental restrictions and costs for rights of way that don't make viable the construction of new lines, they have given place to power systems operating under conditions of lines highly loaded while other corridors are much less loaded, with high operative restrictions on steady and dynamic state, with obligatory generation of more expensive resources that other available ones for security purposes.
This has a high economic cost on the operation, which is reflected in operative costs that affect on the user, and also in an inadequate use of the infrastructure, taking it to a quick waste and additional maintenance, that finally impacts the society and the viability of the participant companies.
In this highly restrictive operation of the Electric Power Systems (EPS), difficulties arise that the literature has also approached with a wide variety of techniques to deal with them. Methodologies are proposed for each problem of the network's expansion or operation. Many of those ones address a single problem and are difficult to embed, given non explicit information, and in many cases they give qualitative information only, not quantitative one that allows a quick, agile and effective taking of decisions.
This paper is organized as follows. An introduction to sensitivities is presented in paragraph II. Three measures to allocate FACTS devices are presented. Finally results are exhibited on a testing net composed of 10-generators, showing the applicability of the technique.

2. Problem definition

This paper analyses the optimal allocation of four FACTS devices: HVDC-VSC, UPFC, STATCOM and SSSC. Each of these devices allow to control one or more electrical quantities (bus voltage magnitude, line active and reactive power).
In order to the original power flow balance can be reproduced easily when the device is embedded, just one parameter for each device is assumed to be free, while the other(s) one(s) is (are) fixed. This can be done by adjusting the corresponding value of the free parameters. Table I shows the variables of each FACTS and their type, where |V| stands for the voltage magnitude and θ for the phase angle of the Voltage Sourced Converter (VSC).

TABLE I. FACTS' VARIABLES AND THEIR TYPE

	Independent (free)	**Dependent**
SSSC	$\|V_S\|$	θ_S
STATCOM	$\|V_V\|$	θ_V
UPFC	$\|V_S\|$, θ_S and $\|V_V\|$	θ_V
HVDC-VSC	$\|V_{V1}\|$, θ_{V1} and $\|V_{V2}\|$	θ_{V2}

A. Sensitivities

Let us assume the problem

$$h(X,U)=k \qquad (1)$$
$$\begin{cases} f(X,U)=0 \\ X_{\min} \le X \le X_{\max} \end{cases}$$

where function $h(.)$ is elected as an index, being a vector or a scalar function (bus voltage magnitudes, active losses, and/or generating costs), and $f(.)$ denotes the set of power flow equations. X is the state vector (bus voltage magnitudes, phase angles, and FACTS' dependent variables) ranging within the interval $[X_{min}, X_{max}]$, and U is the FACTS' free parameters vector.

By Taylor's series expansion around the equilibrium point (X^0, U^0), and neglecting high order terms, eqn. (1) becomes

$$\Delta h = \left[\frac{\partial h}{\partial X}\right]\Delta X + \left[\frac{\partial h}{\partial U}\right]\Delta U \tag{2}$$

$$0 = \left[\frac{\partial f}{\partial X}\right]\Delta X + \left[\frac{\partial f}{\partial U}\right]\Delta U \tag{3}$$

In this proposition it is required to evaluate the sensitivities respect to the FACTS' parameters. $[\partial f/\partial X]$ is the Jacobian matrix just after the power flow calculation has converged; $[\partial f/\partial U]$ is sparse and easily constructed because of the number of FACTS in the grid is relatively small; $[\partial h/\partial X]$ is the index' derivative with respect to the state vector. Since function h is not related explicitly with the FACTS' parameters, most of the elements of $[\partial h/\partial U]$ are zero. From eqn. (3) can be written

$$\Delta X = \left[\frac{\partial X}{\partial U}\right]\Delta U \tag{4}$$

where

$$\left[\frac{\partial X}{\partial U}\right] = -\left[\frac{\partial f}{\partial X}\right]^{-1}\left[\frac{\partial f}{\partial U}\right] \tag{5}$$

Substituting ΔX into eqn. (2) results

$$\Delta h = \left\{\left[\frac{\partial h}{\partial U}\right] + \left[\frac{\partial h}{\partial X}\right]\left[\frac{\partial f}{\partial X}\right]^{-1}\left[\frac{\partial f}{\partial U}\right]\right\}\Delta U = S\Delta U \tag{6}$$

where S is named the sensitivity matrix of h with respect to U [1].

B. Measures

Different sensitivities can be easily evaluated by eqn. (6). For instance, this paper is focused on the calculation of voltage profile, active losses, and generating costs by sensitivities.

Voltage Profile. In this case the function h of eqn. (1) depends upon bus voltage magnitudes of the PQ-nodes (voltages of PV-buses are constants). When an increment in the same direction for all voltages of PQ-buses comes about in response to an incremental movement of the FACTS' free parameters, the transmission line where it is embedded can be chosen as an appropriate candidate. The voltage function has the following structure

$$h_V = V = [|V_i|\,|V_{i+1}|\cdots|V_{nPQ}|]^T,\ i = 1, 2, \cdots, nPQ\ buses \tag{7}$$

and the proposed index is,

$$Jv = e^{\sum_i h_V(i)} = \prod_{i=1}^{nPQ} e^{\Delta V(i)}$$

Power System Losses. The total active losses can be expressed by the nonlinear relation

$$h_{Ploss} = P_{loss} = \sum_{line(k,m)} (V_k + V_m)^2 g_{km} - 2V_k V_m g_{km}\cos(\delta_k - \delta_m) \quad \ldots(8)$$

the index is defined as:

$J_{Ploss} = \Delta h_{ploss}$

where V_k and V_m are the bus voltage magnitudes at the line's ends; δ_k and δ_m are their corresponding angle phases; g_{km} is the real part of the series line admittance. In this case, the location where the FACTS device produces the largest decrement over the system's losses will be elected. It is assumed that the pre-specified generators' active power are kept constant.

Generating Costs. The total generating costs are closely related to the power system's losses. The costs of each generating unit depends on the power injected into the system. The active power of a generating node can be expressed as

$$P_G = \sum_{i=1}^{nbuses} \left(V_k^2 g_{ki} - V_k V_i (g_{ki}\cos(\delta_k - \delta_i) + b_{ki}\sin(\delta_k - \delta_i))\right) + P_{k,load} \quad \ldots(9)$$

where V_k is the regulated voltage magnitude and V_i is the i-th bus voltage magnitude of the nodes connected to the generating unit; δ_k and δ_i are the corresponding phase angles; $g_{ki} + jb_{ki}$ is the line's series admittance; $P_{k,Load}$ is the k-th active load power. Thus, if a typical quadratic cost function is utilized the total generating cost becomes

$$h_{Cg} = C_G = \sum_{k=1}^{ngen} (\alpha_{2k} P_{G,k}^2 + \alpha_{1k} P_{G,k} + \alpha_{0k}) \tag{10}$$

the proposed index is

$J_{CG} = \Delta h_{CG}$

The corresponding location where the FACTS exhibits the largest cost reduction will be elected.

C. Example

In the following, the evaluations of the indices aforementioned are calculated through sensitivities for a 3-machines, 9-buses power system [2]. All sensitivities are evaluated for a FACTS located at line 6-5 with its shunt branch on bus 6 (case of the STATCOM and the UPFC). To evaluate the effect of the devices, each one is included into the base case. To avoid a bias when the device is embedded, the base case must be reproduced through the use of the device's free parameter. Fig. 1 shows an example of the insertion of one device preserving the solution of the base case.

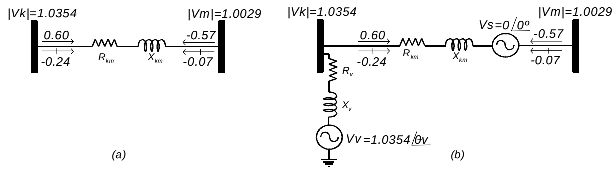

Fig. 1 (a) Base case and (b) UPFC parameters calculation to preserve the base case.

The SSSC and the STATCOM present one control variable; in this paper the voltage magnitude of the equivalent source is elected. The sensitivity matrix for the HVDC and the UPFC have three variables, and then multiple combinations can be explored for the ΔU vector, eqn. (6). In such case, there are eight possible combinations (each variable can take two possible values: $\Delta U_k = \pm 10^{-3}$). After evaluating all of these possible directions the index' largest variation is chosen.

Voltage profile. As an example, Fig. 2 depicts the increments on bus voltages when variations on FACTS' parameters are allowed; only PQ-nodes are exhibited. Variation of the equivalent voltage of the SSSC produces the smallest effect on the system voltage profile. The HVDC-VSC produces the largest one due to the injection of reactive power on each shunt branch which is independently controlled. Results obtained with the STATCOM are comparable with those obtained for the UPFC and the HVDC-VSC, while the expected investment cost is lower.

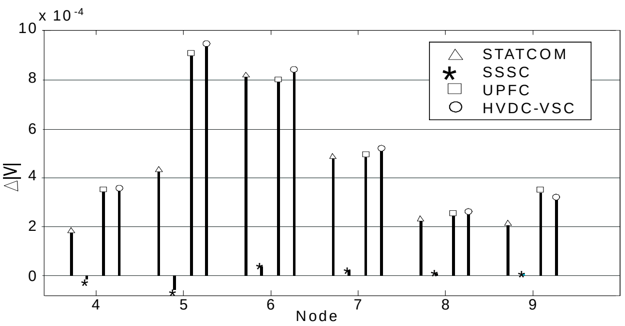

Fig. 2 Bus voltage magnitude sensitivities' respect to FACTS' parameters variations

Similar results can be encountered employing the remaining measures.

3. FACTS device allocation

The 10-machine, 39-buses New England equivalent system is used to test the proposed procedure. The one-line diagram is shown in Fig. 3. A set of 14 candidates transmission lines is previously chosen for the sensitivity analysis looking for embedding into them a FACTS device. They are elected because of being not joined close to a generator. These ones are remarking on Fig. 3. The total load of the system is about 7043 MW [3]. All the tap transformers are assumed at 1.0 p.u. and remain constant through all the calculations. The cost functions for the generating units are taken from reference [4].

A. Voltage sensitivities

The bus voltage magnitude's sensitivities Δh_V for each device, represented by the index J_V in eqn. (11), are exhibited in Fig. 4. Such indices represent the impact of the device on the voltages of the PQ-nodes and are evaluated for the candidate's location. Voltage sensitivities are evaluated on all the candidate lines (buses for the STATCOM device). The objective function includes the sensitivities of all PQ-buses and has the following structure

$$h=\left[|V_1|\ |V_2|\ \dots\ |V_{nPQ}|\right]^T, \qquad J_V=\prod_{i=1}^{nPQ} e^{\Delta h(i)}=\prod_{i=1}^{nPQ} e^{\Delta|V_i|} \qquad \dots(11)$$

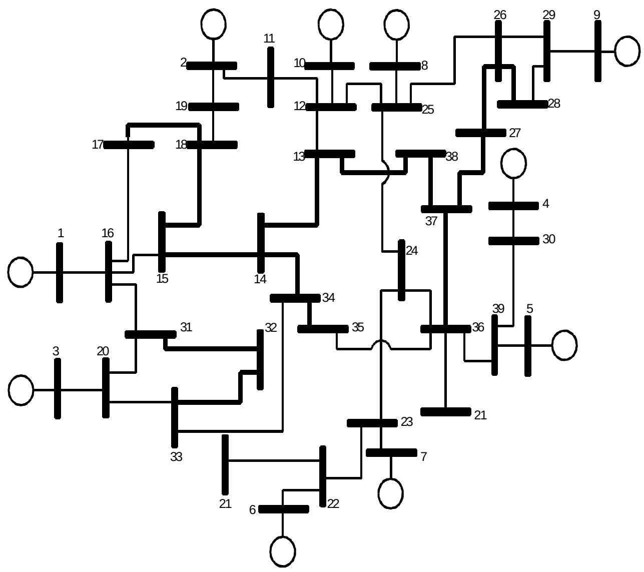

Fig. 3 New England equivalent test system

A positive increment in Δh will produce a value larger than one, while a negative one will produce values smaller than the unity. The maximum J_V indicates the place and the type of device to install in order to affecting voltages in a positive way.

The SSSC has an insignificant value. An STATCOM placed on buses 14,15 or 37 produces an index equal to 1.0053, while a UPFC inserted into line 33-34 (the first bus referenced on the *line* nomenclature corresponds to the bus where the voltage is regulated) produces an index of 1.0077. The maximum indices for the HVDC-VSC result on line 15-14 (J_V =1.0097) and on line 33-34 (J_V =1.0080). The locations with the highest indices for the cases of the STATCOM, the UPFC and the HVDC-VSC are similar. The elected FACTS is the HVDC-VSC placed on line 15-14, when solely the voltage profile is analyzed.

B. Active losses' sensitivities

Sensitivity of total power system active losses respect to FACTS devices is depicted in Fig. 5 which shows the impact of the FACTS parameters on the power system losses. The best results are obtained for a small change on the equivalent source series magnitude of the SSSC embedded into the line 27-26. An STATCOM allocated on buses 14, 27, 34 and 37 exhibit similar results as those of the SSSC. The impact of the UPFC is larger, specially when is located on lines 34-35 and 33-34. The HVDC-VSC presents the largest impact on power system active losses; results for this one indicate that the best location for this device is on line 27-26.

C. Generation costs

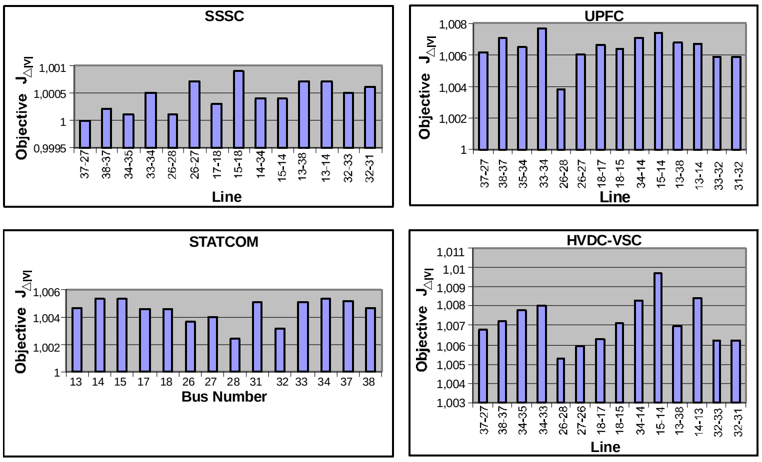

Fig. 4 Objective function based on voltages

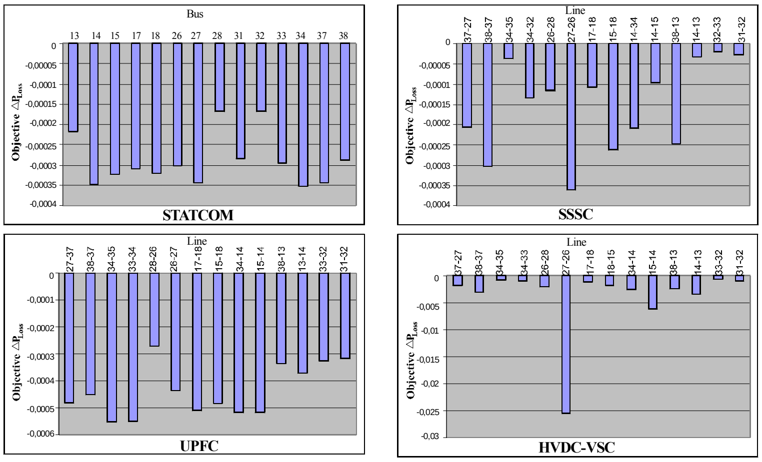

Fig. 5 Total power system losses' sensitivities respect to FACTS location

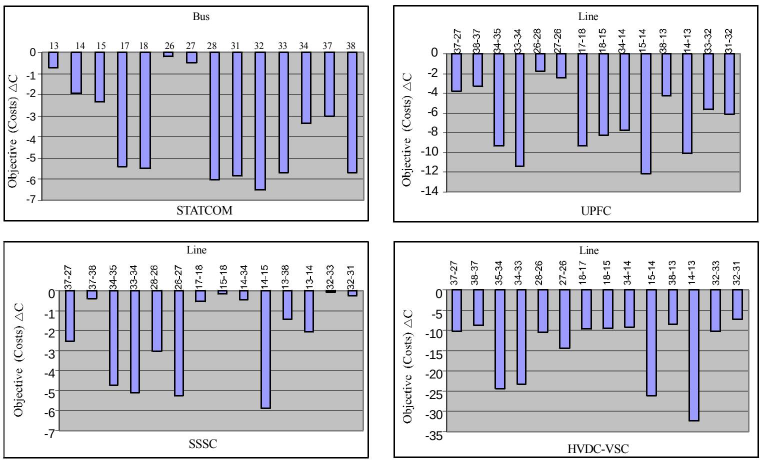

Fig. 6 Total generation costs' sensitivities respect to FACTS devices parameters

For the base case, the total generation costs are about \$176,324. The coefficients for the cost functions for each generating unit are shown on Table II [4]. Small changes on the STATCOM's VSC magnitude, produce a reduction of about \$ 6.4 when the device is placed on bus 32, Fig. 6. The SSSC into line 14-15 has its largest effect; this reduction is not larger than \$6. The UPFC evaluated into line 15-14 produces a reduction of about \$12. The reductions produced by the changes on the parameters of the HVDC-VSC are about \$33.

TABLE II. UNITS' GENERATION COEFFICIENTS

Unit No.	P_{min}	P_{max}	α_0	α_1	α_2
	MW	MW	(\$)	(\$/MWh)	(\$/MW^2 h)
1	100	1200	100	16.9	0.00048
2	100	1200	970	17.26	0.00031
3	100	1200	700	16.60	0.00200
4	100	1200	680	1650	0.00211
5	100	1200	450	19.70	0.00398
6	100	1200	370	22.26	0.00712
7	100	1200	480	27.74	0.00079
8	100	1200	660	25.92	0.00413
9	100	1200	665	27.27	0.00222
10	100	1200	670	27.79	0.000173

4. Example

In order to exemplify the applicability of the proposition, in this section a combination between variations on bus voltage magnitudes and generating cost are used as objective function in order to allocate FACTS devices into the grid. The reason of choosing it, neglecting active losses, is that a power system configuration in which the active losses are small does not implies necessarily the most economic operation of the system, eqn. (12). Voltages' terms are expected to be greater than one (always positive) and are used as weighting factors. Terms related to generating costs are expected to be less than zero. Since the term related to the voltages is close to one, the most important part of the J index is related to the generating costs' increments. The index J is evaluated from the results of the sensitivity analysis.

$$J = J_V J_{CG} = \left(\prod_{i=1}^{nPQ} e^{\Delta h(i)} \right) \left(\Delta C_G \right) \qquad (12)$$

The four devices on the 14 candidate lines (or buses) are evaluated by eqn. (12) to find out the best device. In this case, the HVDC-VSC located into line 14-13. The index J obtained for this element has a value of -33.65. A UPFC embedded into the same line results on an index equal to -12.17. The elected device then is an HVDC-VSC into line 14-13. Once the device has been allocated, the genetic algorithms are used in order of minimizing this index, tuning its parameters.

A Optimization of the FACTS' parameters

Once the location and type of device to install has been decided, a genetic algorithm is used to optimize its parameters together with a simple generating re-dispatch. The objective function has the following form:

$$fitness = J + W_1 \;\; ; \;\; W_1 = \begin{cases} 0 \; if \; \Sigma P_g \geq P_{load} \\ K \; if \; \Sigma P_g < P_{load} \end{cases} \qquad (13)$$
$$J = w_V J_{CG} = w_V \left(C_G^{FACTS} - C_G^{base} \right)$$

where w_V is similar to that proposed in reference [5]

$$w_V = \prod_{i=1}^{nPQ} e^{\left(2|1\text{-VL}_i| - 0.05 \right)} \qquad (14)$$

where VL is the voltage magnitude of each PQ-bus. This term is used as a weighting factor and the way it penalizes the fitness function is shown in Fig. 7.

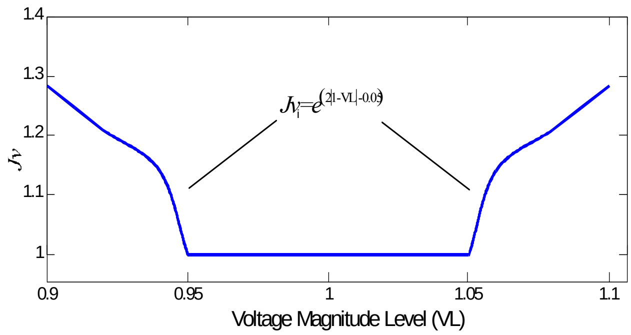

Fig. 7 Voltage penalty function, J_V.

For the HVDC embedded, each individual in the genetic algorithm has the following structure

$$x_i = \left[P_{G1} \;\; P_{G2} \;\; \cdots \;\; P_{Gn_G - 1} \;\; P_{Gn_G} \;\; |V_{V1}| \;\; P_{DC}^{FLOW} \;\; |V_{V2}| \right]^T \qquad (15)$$

where P_{Gi} is the i-th active power generation; V_{V1}, V_{V2} and P_{DC} are the variables related to the HVDC, so that the value of the power flow on the dc line is predefined.

As aforementioned, the initial operating cost for the base case is about \$176,324. After 150 generations (with a constant population of 20 individuals), the best values for the HVDC-VSC parameters become V_{V1} =1.05 p.u., θ_{V1} =-0.2730 rads, and V_{V2} =1.05 p.u., with a dc power flow equal to 0.1969. The cost is reduced to \$167,532 and the voltage profile has been improved as can be verified in Fig. 8.

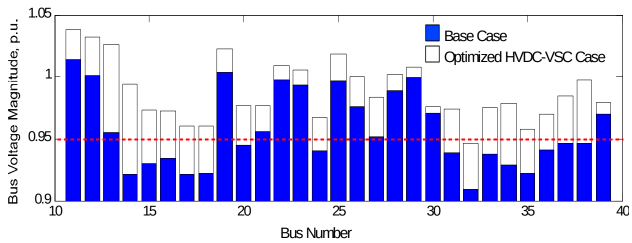

Fig. 8 Voltage profile improvement

B. Optimal allocation of a second device

The high costs of installing some FACTS device suggest a satisfactory long term planning. During such period of time, the electrical network can experience changes in its structure (power demand, generation, transmission system re-configuration, etc.), thus a planning taking into account these changes should produce more accurate results. In this paper, as an academic assumption, the authors consider no changes neither on the network topology nor on load demand, and the FACTS allocation is carried out sequentially instead as proposed in reference [5].

The new base case has a total generation cost of $167,532, so that its reduction is expected. The sensitivity analysis includes variations on such devices, the existing one and the candidate. The starting values for the installed HVDC-VSC are those optimized previously. The starting values for the second candidate's device are elected in order of preserving the solution of the new base case. The best indices and locations for each type of FACTS are shown on Table III. It can be seen that there are only four buses involved on the best locations (34, 33 18 and 15). The indices for the SSSC, the STATCOM and the UPFC are similar in magnitude, although the best index is obtained for a new HVDC-VSC. In this paper economical restrictions related to the FACTS investment cost were not dealt with, but their inclusion could help to give a best weight to the indices. For instance, the merely technical indices of the STATCOM and the UPFC are similar, but the investment costs related to the later are expected to be higher than those of the former.

As a second objective, the optimal parameters for both HVDC-VSC are now simultaneously obtained, besides a generating re-dispatch in order to minimize eqn. (13). After 150 generations of the GA's taking 20 individuals on each one, the best values are those exhibited in Table IV. Table V shows the corresponding active power for each unit (on a 100 MVA base).

After the installation of this new device, the generating cost is reduced to $164,446 and the bus voltage of bus 32, originally lower than 0.95 p.u., has been improved. All the PQ-bus voltages are within the interval $0.95 \le VL_i \le 1.05$.

TABLE III. BEST LOCATIONS FOR EACH FACTS IN COMBINATION WITH THE HVDC-VSC$_{14\text{-}13}$

	Line-Bus	*J* Index
SSSC	34-33	-39,27
STATCOM	18	-39,8
UPFC	18-15	-42,76
HVDC-VSC	34-33	-72,13

TABLE IV. SIMULTANEOUSLY OPTIMIZED VALUES FOR BOTH HVDC-VSC

HVDC-VSC (14-13)	$\lvert V_{V1} \rvert$	**1.0367**
	$\lvert V_{V2} \rvert$	**1.05**
	θ_{V1}	**-0.3604**
HVDC-VSC (34-33)	$\lvert V_{V1} \rvert$	**0.99**
	$\lvert V_{V2} \rvert$	**1.033**
	θ_{V1}	**-0.3043**

TABLE V. ASSIGNED ACTIVE POWER TO EACH UNIT

Unit	1	2	3	4	5	6	7	8	9	10
P_G	-	414	571	942	785	557	928	800	500	557

5. Conclusions

In this paper diverse steady state measures are used to locate devices FACTS in an electric power system. The analysis of the location is carried out through first order sensitivities. It is possible to introduce more than one device in a sequential way; that is, one by one. The influences of such devices on steady state variables (voltage levels, transmission losses, and generating costs) are very remarkable. The benefit for each type of FACTS can be associated with its particularities and properties. Once located, genetic algorithms are used to optimize their performance to improve the operation of the net. An example on a testing grid exhibits satisfactory results so that it is possible to enlarge the application to nets of great size.

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