January 2012

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Recommended Citation

Tiwari, Aditya (2012) "Optimal Allocation of FACTS Devices by using multi-Objective Optimal Power Flow and Genetic Algorithms," *International Journal of Electronics Signals and Systems*: Vol. 1 : Iss. 3 , Article 13.

DOI: 10.47893/IJESS.2012.1041

Available at: <https://www.interscience.in/ijess/vol1/iss3/13>

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Optimal Allocation of FACTS Devices by using multi-Objective Optimal Power Flow and Genetic Algorithms

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Abstract: *The introduction of the flexible AC transmission system (FACTS) in the power system reduces the losses, reduces the cost of the generation, improves the stability and also improves the load capability of the system. Some application of the Flexible AC transmission system (FACTS) technologies to existing high voltage power system has proves the use of FACTS technology may be a cost effective option for power delivery system enhancement. Amongst various power electronic devices unified power flow controller (UPFC) may be considered to be a capable of regulating the power flow and minimizing the power loss simultaneously. Since for the cost effective application of the FACTS technology a proper selection of the number and the placement of these devices is required. The main aim of this paper is to propose the methodology based on the genetic algorithm, able to identify the optimal number and the location of the UPFC devices in an assigned power system network for maximizing system capabilities. In order to validate the usefulness of the approach suggested here is , a case study using a IEEE 30-bus power system is presented and discussed.*

Keywords: *FACTS, UPFC, transmission system, multi-objective, genetic algorithms*

1. INTRODUCTION

The electric power industry is changing to be more competitive all over the world. In the new scenario of liberalized electricity markets, the increasing of transmission capacity can have a strategic impact on competition among the power generators, discouraging the induction of transmission congestions by a firm. A possible solution is to reinforce the network by building a new transmission line system. Since the reinforcement of the transmission line network appears sometimes infeasible, especially in highly populated regions, and considering that with liberalization the changing of geographic generation-load pattern produces a mutation of the network topology, the installation of flexible devices appears to be the most feasible solution for controlling the power flow, delaying the construction of new transmission infrastructures. On the other hand the need for an increasing transfer capability of a power delivery system requires a change in the operating philosophy, passing from a preventive operating procedure to a corrective one to adequate the system performance, hence the use of flexible devices cannot be disregarded. Today, technologies, developed as a part of a Flexible AC Transmission System (FACTS), can be used to help the utilities and operators to move toward corrective methods, consisting in taking immediate action after a contingency occurs in the system, to adequate the system performance. FACTS devices, which permit to achieve many objectives in an electric power

system [1-3], can be used to reduce the flow on the overloaded lines and to increase the utilization of the alternative paths excess capacity. This allows increasing the transfer capability in existing transmission and distribution systems network under normal conditions, obtaining the possibility to load lines much closer to their thermal limits. However, due to the mutual and, sometimes, adverse interactions between FACTS devices, the problem of finding out which locations are the most effective and how many devices have to be installed on economic basis is a question of great significance. All this has addressed this study towards the adoption of evolutionary algorithms in the problem solving of changing, by inserting the FACTS devices in the lines, the power transfers over the system to reduce the loading on critical lines. In the present paper, a methodology, based on a Genetic Algorithm (GA), is used for finding out the optimal number and the location of a particular type of FACTS devices, known as unified power flow controllers (UPFC). The objective function of the implemented GA comprises the generation costs, a branch load function and the cost of installation and maintenance of the UPFC devices. In the followings, the main results of tests on a IEEE 30-bus system for the proposed GA are shown to demonstrate the effectiveness of the proposed method.

2. RELATED WORK

Several methods have been proposed for finding optimal locations or optimal number of FACTS devices in vertically integrated power systems but little attention, however, has been devoted to unbundled power systems [4-18].

In [4, 5] the optimal power flow with FACTS devices is formulated using different objective functions. In other works methodologies for optimal FACTS allocation and control system design problem are applied to improve the dynamic performance of the system and to estimate the impact of FACTS devices on the power system stability [6-8]. In [9] a method is presented to decide the optimal number of thyristor controlled phase shifters and their location in order to minimize line real power losses and to augment the stability of a power system. In the work, which doesn't make reference to an open market power, the minimization of power losses is based on the phase shifter distribution factor and the selection of the number and location of phase shifters is based on the analysis of the influence of each device on the real line power loss. Yet, in the proposed approach it is assumed that once specific costs of devices are given the algorithm determines the advantage of adding the devices but the relationship between the costs of installing and maintaining devices and the reduction in losses costs are not examined.

In [10] to identify the size and location of the FACTS devices, continuation power flow technique is used. The paper proposes an analytical method for determining the location and amount of series compensation to increase the steady state power transfer capability in a vertical integrated power system. In [11] a genetic algorithm has been used to determine the best location of a given set of phase shifters based on the return of investment of the devices and on the cost of production. In this work the authors stated that the behaviours of phase shifters devices which can block the flow on a weak line in order to protect it or balance the flows between parallel paths in a corridor in order to increase its load ability. Yet, the problem of the selection of the best number of phase shifters is not taken under consideration by the authors, but studies for 1, 2 and 3 phase shifters are compared. In [12, 13] the optimal locations of the FACTS devices are obtained by solving the economic dispatch problem plus the cost of these devices making the assumption that all the lines, initially, have these devices. In [12] the algorithm to allocate the strategic locations for the compensation devices is a two-level hierarchical approach based on the decomposition-coordination method. At the first level, a decision on a trial value of compensation is made. At the second level, given the trial value from the first level, the optimal power flow problems are solved. The feedback from the second level to the first level is used to form a sensitivity factor, which indicates the variation of the generation cost with respect to the variations in the FACTS devices compensation. The proposed approach stated that the compensation of series capacitors or static phase shifters may reduce the total cost of operating and may avoid the problem of load curtailment. Gerbex et al. [14] have used a genetic algorithm to seek the optimal location of multi-type FACTS devices in a power system. Optimizations have been performed on three parameters: the locations of the devices, their types, and their values. The system load ability was employed as a measure of power system performance. Yet, in [14] costs of installing and maintaining devices are not taken into consideration and the number of devices to install is assigned before optimization. In [15] the optimal placement of a prefixed amount of FACTS devices is developed in an electricity market having pool and contractual dispatches by a two-step procedure. First, by using a sensitivity-based approach the few locations of FACTS devices is decided and then the optimal dispatch problem is solved to select the optimal location and parameter settings. In [18] a parallel tabular search based method, for determining the optimal allocation of UPFC devices is used and discuss.

The method allows to minimize the active power losses and to maximize the power transfer capacity of a network by considering the incremental load rate and the active power losses as performance indexes for the allocation of a given number of UPFC devices. In [19] the optimal location of UPFC devices is determined by using a pragmatic approach based on the augmented Lagrange multiplier method. The method proposed in [19] is based on an objective function considering investment cost of the devices and real power losses. Recently, the authors of this paper have proposed in [20] the adoption of evolutionary computation for simultaneous identification of the optimal number and placement of thyristor-controlled phase shifting transformers devices. In the paper, for identifying the number and location of devices, generation costs, transmission losses, line overload and the costs of installation and maintenance of the devices are considered.

The review of works resulting from the literature survey reveals that the optimal FACTS solution problem is one of main points for the enhancement of transmission systems, and it has received great attention by power systems' researchers. At the same time the literature evidences that the problem of the simultaneous identification of the optimal number and location of the FACTS devices in an open market scenario is quite new.

3. MATHEMATICAL MODEL OF UPFC.

The UPFC device consist of the two voltage source converter as shown in the fig 1 one connected in shunt and other connected in the series. The series converter provides the main function of the UPFC by injecting the AC voltage with the controllable magnitude and phase angle in series with the transmission line via a series connected coupling transformer. The basic function of the shunt converter instead is to supply or it will absorb the real power demanded by the series converter at the common DC link. It can also generate or absorb controllable reactive power and provide independent shunt Reactive power compensation for the line.

Figure 1 scheme of the UPFC device

After all, the UPFC can supply real power in addition to the reactive power. This means no restriction exists on the relative phase of the injected voltage with respect to the line current.

As far as the model of the UPFC is concerned the equivalent circuit and the relative phase diagram are shown in the figure 2 and 3 [16],

Figure 2 Equivalent circuit diagram of the UPFC device

Figure 3 Phasor diagram of the equivalent circuit diagram of a UPFC device

Using network analysis the corresponding injection model of the device can be derived as depicted in the figure 4, [16]

Figure 4 injection model of the UPFC device

The expression for the P_{si}, Q_{si}, P_{sj} and Q_{sj} are as follows-

$$P_{si} = r \frac{1}{X_s} V_i V_j \sin(\theta_{ij} + \gamma) \quad (1)$$

$$Q_{si} = r \frac{1}{X_s} V_i^2 \cos(\gamma) \quad (2)$$

$$P_{sj} = -r \frac{1}{X_s} V_i V_j \sin(\theta_{ij} + \gamma) \quad (3)$$

$$Q_{sj} = -r \frac{1}{X_s} V_i V_j \cos(\theta_{ij} + \gamma) \quad (4)$$

Where $r = |\bar{V}_s|/|\bar{V}_i|$ is variable from 0 to r_{max} and $\gamma = \angle \bar{V}_s$ as shown in the **figure 3** is controllable from 0 to 2π also assuming loss less circuit $P_{si} - P_{sj} = 0$ and UPFC doesn't generate or absorb the active power

4. MULTI-OBJECTIVE OPTIMAL POWER FLOW

A multi-objective optimal power flow (MO-OPF) problem minimizes simultaneously a number “ n ” of objective functions on X , a set of feasible solutions, and that may be formulated as follows [21]:

$$\begin{aligned} & \text{Minimize } F(x) \\ & \text{Subject to } x \in X = \{x \mid \begin{matrix} h(x)=0 \\ g(x) \leq 0 \end{matrix} \} \end{aligned} \quad (5)$$

Where the vector x consist of the set of the controllable quantities and dependent variables. The controllable quantities can be assumed to be include generating unit outputs, company transactions, facts controlled variables, generator bus voltage magnitudes. The vector $F(x)$ of the objective function can include multiple objectives associated.

As well known, in the open market environment, assumed to be structured as a pool and bilateral transaction, several subjects must interact: producers, buyers, dispatchers, and eligible customers. As a consequence of the market structure, pool and bilateral/multilateral transactions coexist. In such an environment the independent system operator (ISO) objective consists in supplying at least cost and without any security violations all pool demand and in delivering all bilateral and multilateral transactions in full [15,17], maximizing the social welfare:

$$\max_{P_{pi}, D_{pk}} \sum_{k=1}^{Ne} B_k(D_{pk}) - \sum_{i=1}^{Ng} C_i(P_{pi}) \quad (6)$$

Assuming that the generation pattern and the UPFC devices alleviate the congestion completely [15,17], the normal dispatch problem (6) can be written as:

$$\min_{P_{pi}} = \min_{P_{pi}} \sum_{i=1}^{Ng} C_i(P_{pi}) - \sum_{k=1}^{Ne} B_k(D_{pk}) \quad (7)$$

Subject to:

$$\tilde{L}(P_p, D_p, P_t Q, V, \theta, X_{ps}) = 0 \quad (8)$$

$$\tilde{G}(P_p, D_p, P_t Q, V, \theta, X_{ps}) \leq 0 \quad (9)$$

where 1 F is assumed as the first objective function and it is representative of the social welfare. Moreover the ISO, while maximizing the social welfare, aims to increase the loadability limit of the system, avoiding situations in which the transmission lines are overloaded. In order to prevent congestions in expectation of future loads increments, in the proposed MO-OPF the branch overloading function, F_2 is considered as an objective function to be minimized jointly with F_1 . The function F_2 is defined as:

$$F_2 = \left(\prod_{i=1}^{N_{line}} l_i \right)^{-1} \quad (10)$$

$$l_i = \begin{cases} 1 & B_{li} < B_{li}^{nom} \\ \exp [\lambda_{li} (B_{li}^{nom} - B_{li})] & B_{li} \geq B_{li}^{nom} \end{cases} \quad (11)$$

where l_i is related to the loading of the i th branch, “ il ” is a coefficient used to adjust the slope of the exponential. $Nom Bli$ is the nominal loading value for the i th branch, expressed in percentage terms of the maximum loading limit of the i th line, which is the constraint imposed in the optimal power dispatch. Bli is the branch loading expressed in percentage terms of the maximum loading limit of the i th line. The function F_1 is computed by calculating for every line of the network the term l_i , and then multiplying all the lines terms. Each term is equal to 1 while the branch loading is less than the correspondent branch nominal loading value $nom Bli$, than it decreases exponentially with the current [14]. In the proposed MO-OPF two objectives functions F_1 and F_2 , having different characteristics and in trade-off relations, must be minimized. Solving a multi-objective problem means to find a non-inferior solution, for that any further improvement in one objective would result in a degradation in another objective.

The characteristics of the specific optimization problem suggest the use of the goal programming method [3,22,23], which pursuits the satisfaction of objectives rather than their optimization, as solving methodology. In this paper, the goal attainment method of Gembicki [24] is used for computing non-inferior solutions. With such a method, as it can be easily proved, the best-compromise solution, if it exists, is a Pareto optimal solution for the problem. Moreover the method doesn't suffer of any convexity limitations, and the parameters that it uses have a convenient intuitive meaning. The goal attainment method involves expressing a set of design goals, $f^* = \{f_1^*, f_2^* \dots f_m^*\}$, which is associated with a set of objective functions, $f(x) = \{f_1(x), f_2(x) \dots f_m(x)\}$. The degree to which these goals are met is adjusted using a vector of weighting coefficients, $w = \{w_1, w_2, \dots, w_m\}$, and the optimization problem is expressed using the following formulation:

$$\min_{\zeta \in R, x \in \Omega} \zeta \quad \text{Such that } f_i(x) - w_i \zeta \leq f_i^* \quad i = 1, \dots, m \quad (12)$$

In the previous formulation the scalar ζ & is a measure of how far away a solution point is from the goals, the weighting vector, w , enables the designer to choose the relative tradeoffs between the objectives. By varying the weighs, the set of non-inferior solutions (Pareto optimal) for a problem is generated [25, 26]. In the present study the trade-off analysis and the decision-making problem for the “best” compromised solution are made by applying Bellman and Zadeh's maximizing decision [27]. The essence of the maximizing decision lies in taking the minimum value of the performance indices, and finding the maximum value of such minimum performance indices to represent the best option for the

decision. Moreover, due to the imprecise nature of the decision maker's judgement, it is assumed that the decision maker has fuzzy goals for each of the objective functions. The fuzzy goals are quantified by defining their corresponding membership functions. These functions represent the degree of membership in certain fuzzy sets using values from 0 to 1. The membership value 0 indicates incompatibility with the sets, while 1 means full compatibility. Taking account of the minimum and maximum values of each objective function together with the rate of increase of membership satisfaction, the decision maker has to determine the membership function $\mu(f_i)$ is a subjective manner.

In the present research it is assumed that $\mu(f_i)$ is a strictly monotonic decreasing and continuous function defined as

$$\mu(f_i) = \begin{cases} 1 & f_i \leq f_i^{\min} \\ \frac{f_i^{\max} - f_i}{f_i^{\max} - f_i^{\min}} & f_i^{\min} \leq f_i \leq f_i^{\max} \\ 0 & f_i \geq f_i^{\max} \end{cases} \quad (13)$$

Where $f_i^{\min}$ and $f_i^{\max}$ are the minimum and maximum values of i th objective function in which the solution is expected. The value of the membership function indicates, how much (in scale from 0 to 1) a solution is satisfying the f_i objective. To search for the optimal weight pattern in the non-inferior domain an evolutionary optimization technique, proposed in [28] and already used by the authors [3], is used. Such optimization technique starts defining a hypercube of weight combination around an initial search point, w_i^c of the hypercube $i = 2, 3, \dots, L$, where L is the number of objectives. Then 2^{L-1} weight combinations at the edges of the hypercube are generated as given below:

$$w_i^j = w_i^c + \Gamma_i^j; i = 2, 3, \dots, L; j = 1, 2, \dots, 2^{L-1} \quad (14)$$

$$w_1^j = 1 - \sum_{i=2}^L w_i^j; j = 1, 2, \dots, 2^{L-1} \quad (15)$$

Where Γ is the distance of the corners of the hypercube from the point around which hypercube is generated. The membership functions for each objective $\mu(f_i)^k |_{i=1,2,3,\dots,L}$ and the intersection of the membership function $\mu_k^{\min} = \min\{\mu(f_i)^k |_{i=1,2,3,\dots,L}\}$ are then computed for each weight combination. The decision regarding the 'best' solution is made by the selection of *minimax* of membership function as defined below:

$$\mu^0 = \max\{\mu_k^{\min} | k = 1, 2, \dots, 2^{L-1} + 1\} \quad (16)$$

Where L is the number of objectives 2^{L-1} is the number of the corner points of an $L-1$ dimensional hypercube. Then to continue the iterative process, another hypercube is formed around the combination $w_i^{c^0}$ having maximum satisfied membership function μ^0 as compared to the previous one and the procedure is repeated until the solution criteria for 'best' compromised solution is met.

5. GENETIC ALGORITHM FOR THE IDENTIFICATION OF THE OPTIMAL NUMBER AND THE LOCATION OF THE UPFC DEVICE

In this section the problem of identifying simultaneously the amount and the placement of UPFC devices is formulated assuming the system in normal state and using an objective function intended to social welfare maximization, branch overloading minimization and considering the capital and installation costs of the devices. A GA is used for selecting of the optimal number and of the location of the UPFC devices to be settled on an electric system in order to minimize an objective function, while the control parameters of the devices are calculated

in a procedure, nested in the GA, which solves the MO-OPF. In the implemented GA, having assumed the system in normal state, the objective function to be minimized is:

$$\sum_{B=IP,P,I,OP} (F_1 \cdot F_2 \cdot nh_B) + C'_U \quad (17)$$

Where F_1 and F_2 are computed in correspondence of four different bands - instantaneous peak (IP), peak (P), intermediate (I), off peak (OP) - of the assumed load duration curve depicted in fig. 5 and multiplied by the total number of hours, nh_B , of the corresponding band. As far as the cost of UPFC device is concerned, assuming to disregard any relations between the cost and the control parameters of the UPFC, and considering the UPFC cost associated only to the operating voltage and current ratings of the circuit [11], the cost function of each device can be expressed as a positive constant value, which takes into the account the capital and investment cost of the device.

$$C'_U = \beta C_U \quad (18)$$

Where C_U the total cost of the UPFC device is installed in the system and can be expressed as follows-

$$C_U = \sum_{i=1}^{n_u} C_i \quad (19)$$

While β is the capital recovery factor expressed as follows:

$$\beta = \frac{\zeta(1 + \zeta)^{ny}}{(1 + \zeta)^{ny} - 1} \quad (20)$$

Figure 5 Load Duration Curve

UPFC devices in the assigned network. For a given individual, say a bit string s , $s(j)=1$ means that the line j is equipped with a UPFC device, while $s(k)=0$ means that the line k is not equipped with a UPFC device. This representation of individuals is able to consider both the number and the location of devices in a very simple manner. Then for each individual of the initial population the objective fitness function and the UPFC control parameters are evaluated by solving the nested MO-OPF previously described. At each generation, a new set of better individuals is created by selecting individuals according to their fitness, the selection mechanism used in the GA is the normalized geometric ranking scheme. After the new population is selected, each genetic operator is applied a discrete number of times to selected individuals within the new population such that the total number of children created by all of the operators equals the number of individuals within the old population.

Figure 6 Flowchart of the implemented optimization strategy

In particular the genetic operators employed are simple crossover operator which randomly selects a cut point dividing each parent into two segments and the binary mutation that changes each of the bits of the parent based on the probability of mutation. The iteration process continues until the stop criterion is reached, in the present application the algorithm stops when an assigned maximum number of generations is reached.

6. Case Study

To establish the availability of the proposed method, simulations were conducted by using an in-house computer program, implemented in Matlab environment, which inherits some features of the methodological approach used in the Power Simulation Package Matpower [29, 30]. Simulations were carried out on a IEEE 30-bus system. The power system considered comprises six generators, 41 lines and twenty loads. In the pool model production costs and benefit functions are assumed as quadratic functions of active power of pool loads and generators, as follows:

$$B_k(D_{pk}) = b_{0k} + b_{1k}D_{pk} + b_{2k}D_{pk}^2 \quad (21)$$

$$C_i(P_{pi}) = a_{0i} + a_{1i}P_{pi} + a_{2i}P_{pi}^2 \quad (22)$$

In table I the generator's economic characteristic coefficients are reported, while table II reports the customers' economic benefit coefficients. As can be observed from table II, the maximum power pool demand is 189.22 MW and all pool demand is supplied in this case. The load duration curve is that one reported in fig. 5 with the following values of the active power pool load:

$$\begin{cases} D_{IP} = \sum_k D_{pk}|_{B=PI} = 189.22 \text{ MW} \\ D_P = \sum_k D_{pk}|_{B=P} = 135.17 \text{ MW} \\ D_I = \sum_k D_{pk}|_{B=I} = 104.27 \text{ MW} \\ D_{OP} = \sum_k D_{pk}|_{B=OP} = 77.21 \text{ MW} \end{cases} \quad (22)$$

Table 1 Generator Characteristics

BUS	a_{2i} [\$/MWh ²]	a_{1i} [\$/MWh]	a_{0i} \$	P_{Gi}^{min} [MW]	P_{Gi}^{max} [MW]
1	0.072	30	0	0	118.92
2	0.072	30	0	0	118.92
22	0.0084	3.26	0	0	56
27	0.0084	3.26	0	0	56
23	0.027	3	0	0	30
13	0.071	30	0	0	118.92

Table 2 Customer Characteristics

BUS	b [\$/MWh ²]	b_{1i} [\$/MWh]	b_{0i} \$	P_{Gi}^{min} [MW]	P_{Gi}^{max} [MW]
2	-0.00535	302	2	0	21.72
3	-0.00891	130	2	0	2.5
4	-0.00745	130	2	0	7.7
7	-0.00745	130	2	0	22.9
8	-0.00536	302	2	0	30.0
10	-0.00891	130	2	0	5.9
12	-0.00745	130	2	0	11.3
14	-0.00745	130	2	0	6.4
15	-0.00536	130	2	0	8.5
16	-0.00891	302	2	0	3.7
17	-0.00536	302	2	0	9.0
18	-0.00891	130	2	0	3.3
19	-0.00745	130	2	0	9.7
20	-0.00745	130	2	0	2.5
21	-0.00536	130	2	0	17.7
23	-0.00891	130	2	0	3.5
24	-0.00745	130	2	0	8.9
26	-0.00745	130	2	0	3.7
29	-0.00536	302	2	0	2.5
30	-0.00891	130	2	0	10.7

For tuning the GA, a population size of 10 and a maximum number of 200 generation are set. The simulation experience tells that these values, for the power system under study, give the convergence of the algorithm to a satisfactory solution. Moreover, in this case study for the UPFC devices control variables it was assumed r variable in the range $[0; 0.09]$, and γ variables in the range $[0; 2\pi]$. The UPFC cost, C_i , is fixed at 100\$/KVA. For the capital recovery period, n_y , and the interest rate, ζ , is assumed the values of 10 years and 0.05, respectively. Regarding to the MO-OPF nested in the GA the goals used for the generation of the non-inferior

solutions are computed by solving the single objective problem for each single objective function and it is reasonably assumed that they coincide with the minimum values of the objectives used to determine the membership functions.

The results obtained from the GA evidenced that the optimal number of UPFC to be installed in the network is equal to 3 as shown in table III and fig. 7.

Table 3 Optimal Location of the FACTS Devices

Line
8-28
6-28
19-20

Figure 7 IEEE 30 bus system with UPFC device

The results, summarized in table IV and table V, reveal the feasibility of the proposed approach, achieving a substantial reduction of production costs and an improvement of the branch loading function F_2 . Comparing the total production costs, it is evidenced a cost reduction of about 1.860 M\$/year for the system equipped with UPFC devices, while the total costs of the UPFC devices installed is of 1.247 M\$/year, corresponding to a total capital investment of 9.610 M\$.

Table 4. Production costs [\$/hour]

Band	Network with UPFC	Network without UPFC
Instantaneous Peak	2195	3178
Peak	514	1133
Intermediate	379	385273
Off Peak	273	276

Table 5 Branch loading function F_2

Band	Network with UPFC	Network without UPFC
Instantaneous Peak	1.45	1.48
Peak	1.43	1.57

Intermediate	1.04	1.08
Off Peak	1.03	1.03

Obviously the reduced improvement of the branch loading is mainly due to the original choice to consider the capital and installation costs in the objective function (17) of the GA, furnishing, indirectly, an upper bound to the number of devices to be installed.

7. Conclusion

This paper has analyzed the contribute of FACTS technologies for an increased transmission utilization without impairing transmission reliability. The paper has presented an approach for identifying, simultaneously, the optimal number and location of UPFC devices to be installed in a new or restructured power transmission system. As discussed in the previous sections, in obtaining the goals generation costs, line overload and the costs of installation and maintenance of the UPFC devices are considered. This means that a new device is installed only if its placement is cost-effective. With the same approach the algorithm identifies where a new device is cost effective amongst several candidate locations. The simulation results presented, besides to highlight the benefits of applying FACTS technologies for increased power transfers, reveal the feasibility of the proposed approach, observing an increased loadability, and reduced costs of production.

8. Nomenclature

P_{si}, P_{sj} = real power flows at bus i and j , respectively, [MW];

Q_{si}, Q_{sj} = reactive power flows at bus i and j , respectively, [MVAR];

$V_i \angle \theta_i$ = complex voltage at bus i ;

$V_j \angle \theta_j$ = complex voltage at bus j ;

θ_{ij} = difference between θ_i and θ_j

X_{series} = reactance of the series transformer, [Ω];

N_e = number of pool load buses;

N_g = number of pool generator buses;

D_{pk} = active power of the pool load k , [MW];

B_k = bid price of the pool load k , [\$/];

P_{pi} = active power of the pool generator i , [MW];

C_i = bid price of the pool generator i , [\$/];

D_p = vector of pool power injection, [MW];

P_p = vector of pool power extractions, [MW];

P_t = vector of bilateral contracts;

Q = vector of reactive powers, [MVAR];

V = vector of voltages magnitudes, [V];

θ = vector of voltage angle, [deg];

$\bar{L}$ = contracted transaction relationship and the power balance equation;

$\bar{G}$ = inequality constraints consisting of the usual system operating constraints, such as bus voltage levels and line overloads and of the Magnitude of pool demands;

X_{ps} = vector of FACTS devices control parameter;

C_U^t = total cost and maintenance of the UPFC device [\$/year];

C_U = total cost of the UPFC device installed, [\$/];

c_i = positive constant value including the capital and installation costs of the i th device, [\$/];

β = capital recovery factor;

ζ = interest rate, [%];

ny = capital recovery plan, [year];

N_U = total number of UPFC installed;

N_{Line} = total number of lines;

B_{li}^{nom} = assigned nominal loading value for the i th branch;

B_{li} = branch loading for the i th branch.

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