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Optimal cost and allocation for UPFC using HRGAPSO to improve power system security and loadability

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Abstract
With the electricity market deregulation, the number of unplanned power exchanges increases. Some lines located on particular paths may become overload. It is advisable for the transmission system operator to have another way of controlling power flows in order to permit a more efficient and secure use of transmission lines. The FACTS devices (Flexible AC Transmission Systems) could be a mean to carry out this function. In this paper, unified power flow controller (UPFC) is located in order to maximize the system loadability and index security. The optimization problem is solved using a new evolutionary learning algorithm based on a hybrid of real genetic algorithm (RGA) and particle swarm optimization (PSO) called HRGAPSO. The Newton-Raphson load flow algorithm is modified to consider the insertion of the UPFC devices in the network. Simulations results validate the efficiency of this approach to improvement in security, reduction in losses of power system, minimizing the installation cost of UPFC and increasing power transfer capability of the existing power transmission lines. The optimization results was performed on 14-bus test system and implemented using MATLAB.

Keywords: Power system security; System loadability; Real power loses; UPFC; Optimization; Optimal allocation; PSO; RGA; HRGAPSO.

1. Introduction
In recent years, with the development of electric power systems, transmission systems are becoming increasingly stressed and more difficult to operate. The fast development of solid-state has made flexible AC transmission system (FACTS) devices a promising concept for future power systems. FACTS controllers are based on power electronic devices. They are capable to control various electrical parameters of transmission systems. The UPFC is the universal and the most versatile FACTS devices, which consists of series and parallel connected converters. It can provide simultaneous and independent control of voltage magnitude and active and reactive power flow.
This paper presents an approach to find optimum location of a UPFC in a power system, with minimum transmission losses and cost of generation. The system loadability and index security are applied as a measure of power system performance. For solving complex real-world problems of optimization, in contrast to traditional computation systems, evolutionary computation [1] provides a more robust and efficient approach.
GA is a global evolutionary search technique that can result a feasible as well as optimal solution. To increase the speed and the exactitude of the process of research, the ordinary (binary) GA can be modified using real codes as real-GA (RGA), in which decoding is not needed to be done [2]. RGA is

very efficient at exploring the entire search space, but it is relatively poor in finding the precise local optimal solution in the region where the algorithm converges.

Particle swarm optimization (PSO) is an exciting new methodology in evolutionary computation that is somewhat similar to a genetic algorithm in that the system is initialized with a population of random solutions. Unlike other algorithms however, each potential solution (called a particle) is also assigned a randomized velocity and then flown through the problem hyperspace. Particle swarm optimization has been found to be extremely effective in solving a wide range of engineering problems. It is very simple to implement and solves problems very quickly. PSO is able to accomplish the same goal as RGA optimization in a new and faster way[3].

When PSO and RGA both work with a population of solutions, combining the searching abilities of both methods seems to be a good approach. RGA and PSO are strong combined for solving this problem of optimization. In order to overcome the drawbacks of particle swarm optimization and standard genetic algorithm, some improved mechanisms based on non-linear ranking selection, crossover and mutation are adapted in the genetic algorithm, and dynamical parameters are adapted in PSO. During each iteration, the population is divided into three parts, which are evolved with the elitist strategy, PSO strategy and the RGA strategy respectively. Therefore, this kind of technique can make balance between acceleration convergence and averting precocity as well as stagnation.

In the literature, many power flow algorithms are proposed. The majority of these methods are based on Newton-Raphson algorithm because of its quadratic convergence properties [4-5]. An existing Newton-Raphson load flow algorithm is modified to include FACTS devices is presented in [5]. In this paper, this algorithm is extended in order to include the UPFC devices into the power system. Load flow equations represent the equality constraints. The inequality constraints are the operating limits of the UPFC and the security limits.

The remaining sections of this paper are organized as follows: Section 2 presents the model of power system with UPFC device. Section 3 briefly explains the problem formulation. Section 4 describes the implementations of RGA and PSO in the proposed HRGAPSO algorithm. The numerical examples are then presented in section 5 and conclusion is made in section 6

2. Implemented power system model

2.1 Power flow in line transmission

Power flow through the transmission line i-j namely *Pij* and *Qij* are depended on line reactance *Xij*, bus voltage magnitudes *Vi, Vj*, and phase angle between sending and receiving buses *δi-δj* [6].These are expressed by:

$$P_{ij} = -Pji = \frac{ViVj}{Xij}\sin(\delta_i - \delta_j) \tag{1}$$

$$Qij = (\frac{1}{Xij} - \frac{Bik0}{2})V_i^2 - \frac{ViVj}{Xij}\cos(\delta_i - \delta_j) \tag{2}$$

$$Qji = (\frac{1}{Xij} - \frac{Bik0}{2})V_j^2 - \frac{ViVj}{Xij}\cos(\delta_i - \delta_j) \tag{3}$$

From the Figure 1 it can be conclude the following remarks:

-Changing the phase shift acts primarily on the reactive power.

-The variation of the reactance of the line acts simultaneously on the active and reactive power.

-Control of the voltage changes the flow units for the calculation of reactive power.

2.2 Mathematical model of power systems with UPFC devices

The objective of this section is to give a power flow model for a power system with a UPFC device. Modified Newton-Raphson algorithm as described in [5] is used to solve the power flow equations.

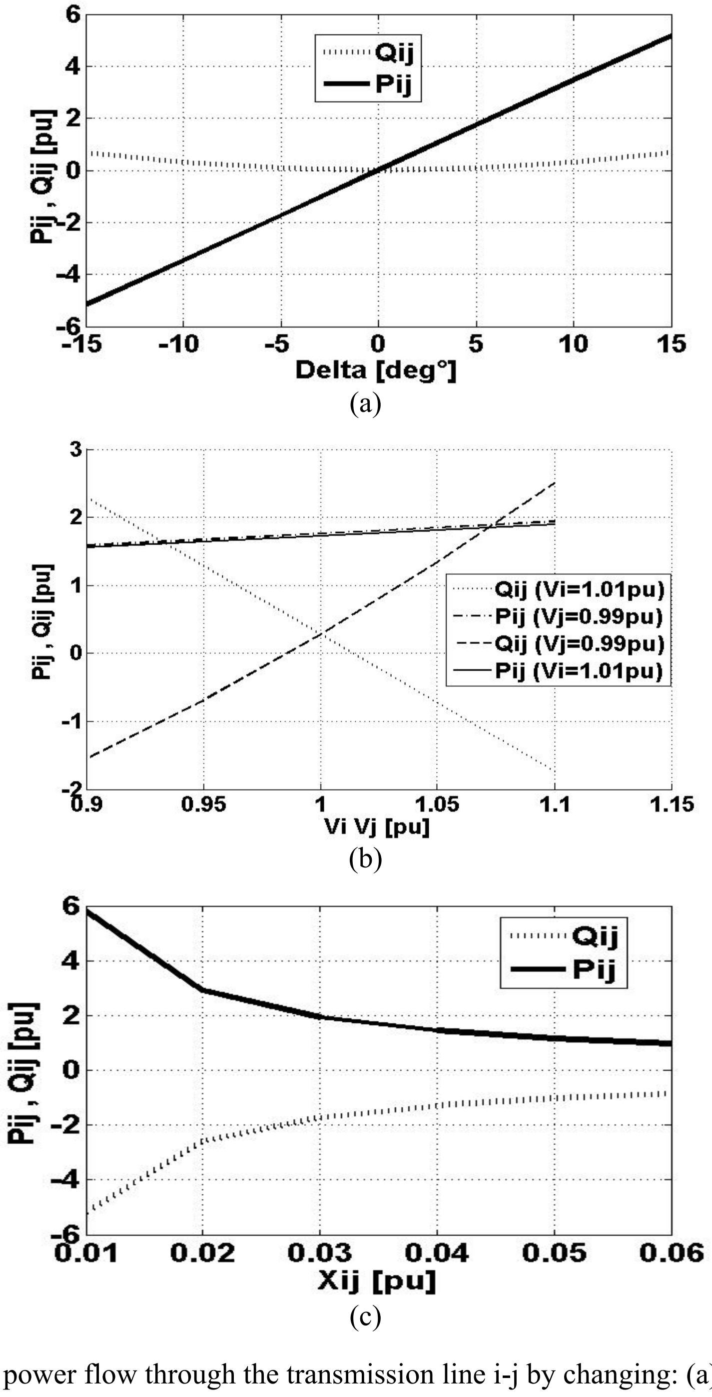

Figure 1. Control of power flow through the transmission line i-j by changing: (a) Phase angle between the sending and receiving end voltages $\delta_i - \delta_j$; (b) Voltage magnitude V_i, V_j ; (c) Impedance *Xij*

2.2.1 Power flow analysis without UPFC

Consider a power system with N buses. For each bus *i*, the injected real and reactive powers can be described as:

$$P_i = \sum_{j=1}^{N} V_i V_j Y_{ij} \cos\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{4}$$

$$Q_i = \sum_{j=1}^{N} V_i V_j Y_{ij} \sin\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{5}$$

where V_i and δ_i are respectively modulus and argument of the complex voltage at bus *i*, Y_{ij} and θ_{ij} are respectively modulus and argument of the ij-*th* element of the nodal admittance matrix Y.

The power flow equations are solved using the Newton-Raphson method where the nonlinear system is represented by the linearized Jacobian equation given by the following equation :

$$\begin{bmatrix} J^1 & J^2 \\ J^3 & J^4 \end{bmatrix} \begin{bmatrix} \Delta\alpha \\ \Delta V \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (6)$$

The ij-th elements of the sub-jacobian matrices J^1, J^2, J^3 and J^4 are respectively

$$J^1(i,j) = \frac{\partial P_i}{\partial \delta_j}, \quad J^2(i,j) = \frac{\partial P_i}{\partial V_j}, \quad J^3(i,j) = \frac{\partial Q_i}{\partial \delta_j} \text{ and } J^4(i,j) = \frac{\partial Q_i}{\partial V_j}$$

2.2.2 Power flow analysis with UPFC

Basically, the UPFC is composed of series and shunt voltage source inverters. These two inverters share a common DC-link storage capacitor [7]. They are connected to the power system through two coupling transformers. The series inverter injects a controllable AC voltage system in series with the transmission line to control the real and reactive power flows. The shunt inverter supplies or absorbs the real power demand (negative or positive value) by the series inverter at the DC-link. Also, it can provide independent shunt reactive compensation and generate or absorb controllable reactive power [7-8].
The schematic diagram of UPFC is shown in Figure2.

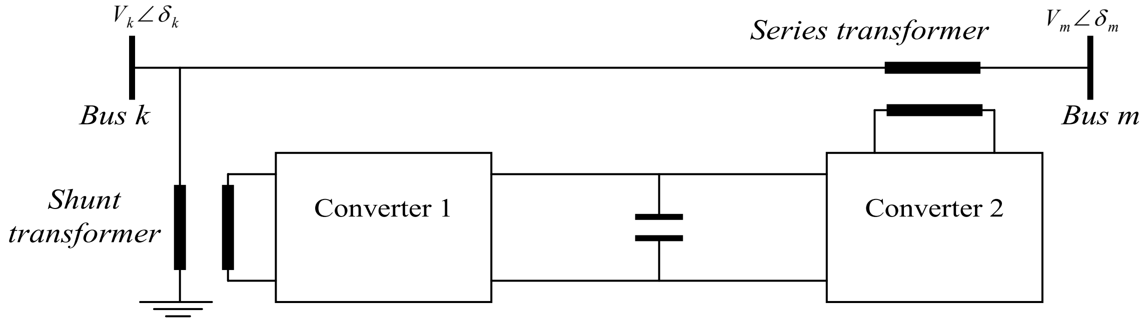

Figure 2. Simplified diagram of UPFC

The series voltage source is modelled as an ideal series voltage Es in series with impedance. The shunt voltage source inverter is equivalent to an adjustable voltage source E_p in series with impedance. E_s and E_p are controllable in magnitude and phase. Figure 3 represents the equivalent circuit of UPFC installed between buses *k* and *m*.
Y_s is the admittance of the line *k-m* including the series component of the UPFC. Y_p is the admittance of the parallel component.
The injected real and reactive powers for all buses of the system with UPFC remain same as those of the system without UPFC except for buses k and m, where they have the following expressions [10] :

$$P_k = P_{km} + \sum_{j=1}^{N} V_k V_j Y_{kj} \cos\left(\delta_k - \delta_j - \theta_{kj}\right) \quad (7)$$

$$Q_k = Q_{km} + \sum_{j=1}^{N} V_k V_j Y_{kj} \sin\left(\delta_k - \delta_j - \theta_{kj}\right) \quad (8)$$

$$P_m = P_{mk} + \sum_{j=1}^{N} V_m V_j Y_{mj} \cos\left(\delta_m - \delta_j - \theta_{mj}\right) \quad (9)$$

$$Q_m = Q_{mk} + \sum_{j=1}^{N} V_m V_j Y_{mj} \sin\left(\delta_m - \delta_j - \theta_{mj}\right) \quad (10)$$

where:

$$P_{km} = V_k^2 Y_p \cos\theta_p + V_k^2 Y_s \cos\theta_s - V_k E_p Y_p \cos\left(\delta_k - \delta_p - \theta_p\right) + V_k E_s Y_s \cos(\delta_k - \delta_s - \theta_s) \\ - V_m V_k Y_s \cos(\delta_k - \delta_m - \theta_s) \tag{11}$$

$$Q_{km} = -V_k^2 Y_p \sin\theta_p - V_k^2 Y_s \sin\theta_s - V_k E_p Y_p \sin\left(\delta_k - \delta_p - \theta_p\right) + V_k E_s Y_s \sin(\delta_k - \delta_s - \theta_s) \\ - V_m V_k Y_s \sin(\delta_k - \delta_m - \theta_s) \tag{12}$$

$$P_{mk} = -V_m^2 Y_s \cos\theta_s - V_m E_s Y_s \cos(\delta_m - \delta_s - \theta_s) - V_m V_k Y_s \cos(\delta_m - \delta_k - \theta_s) \tag{13}$$

$$Q_{mk} = -V_m^2 Y_s \sin\theta_s - V_m E_s Y_s \sin(\delta_m - \delta_s - \theta_s) - V_m V_k Y_s \sin(\delta_m - \delta_k - \theta_s) \tag{14}$$

where E_p and δ_p are magnitude and phase of the shunt voltage source, E_s and δ_s are magnitude and phase of the series voltage source.

Finally, the modified power flow equations can be solved with the Newton-Raphson method by using equation (15).

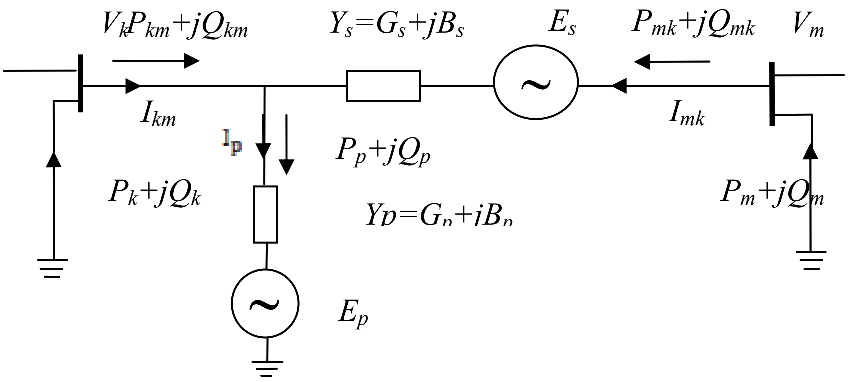

Figure 3. Equivalent circuit of UPFC

$$\begin{array}{c} \\ P_k \\ P_m \\ P_{Eps} \\ P_{km} \\ Q_k \\ Q_m \end{array}
\begin{array}{c} \begin{array}{ccccccc} \alpha_k & \alpha_m & E_p & V_m & \alpha_p & \alpha_s & E_s \end{array} \\
\begin{bmatrix}
\frac{\partial P_k}{\partial \alpha_k} & \frac{\partial P_k}{\partial \alpha_m} & \frac{\partial P_k}{\partial E_p} & \frac{\partial P_k}{\partial V_m} & \frac{\partial P_k}{\partial \alpha_p} & \frac{\partial P_k}{\partial \alpha_s} & \frac{\partial P_k}{\partial E_s} \\
\frac{\partial P_m}{\partial \alpha_k} & \frac{\partial P_m}{\partial \alpha_m} & \frac{\partial P_m}{\partial E_p} & \frac{\partial P_m}{\partial V_m} & \frac{\partial P_{mk}}{\partial \alpha_p} & \frac{\partial P_m}{\partial \alpha_s} & \frac{\partial P_m}{\partial E_s} \\
\frac{\partial P_{Eps}}{\partial \alpha_k} & \frac{\partial P_{Eps}}{\partial \alpha_m} & \frac{\partial P_{Eps}}{\partial E_p} & \frac{\partial P_{Eps}}{\partial V_m} & \frac{\partial P_{Eps}}{\partial \alpha_p} & \frac{\partial P_{Eps}}{\partial \alpha_s} & \frac{\partial P_{Eps}}{\partial E_s} \\
\frac{\partial P_{km}}{\partial \alpha_k} & \frac{\partial P_{km}}{\partial \alpha_m} & \frac{\partial P_{km}}{\partial E_p} & \frac{\partial P_{km}}{\partial V_m} & \frac{\partial P_{km}}{\partial \alpha_p} & \frac{\partial P_{km}}{\partial \alpha_s} & \frac{\partial P_{km}}{\partial E_s} \\
\frac{\partial Q_k}{\partial \alpha_k} & \frac{\partial Q_k}{\partial \alpha_m} & \frac{\partial Q_k}{\partial E_p} & \frac{\partial Q_k}{\partial V_m} & \frac{\partial Q_k}{\partial \alpha_p} & \frac{\partial Q_k}{\partial \alpha_s} & \frac{\partial Q_k}{\partial E_s} \\
\frac{\partial Q_m}{\partial \alpha_k} & \frac{\partial Q_m}{\partial \alpha_m} & \frac{\partial Q_m}{\partial E_p} & \frac{\partial Q_m}{\partial V_m} & \frac{\partial Q_m}{\partial \alpha_p} & \frac{\partial Q_m}{\partial \alpha_s} & \frac{\partial Q_m}{\partial E_s}
\end{bmatrix} \end{array}
\begin{bmatrix} \Delta_\alpha \\ \Delta_{\alpha p} \\ \Delta_{\alpha_s} \\ \Delta_{E_p} \\ \Delta V \end{bmatrix}
=
\begin{bmatrix} \Delta P \\ \Delta P_{Eps} \\ \Delta P_{km} \\ \Delta Q \end{bmatrix} \tag{15}$$

2.2.3 UPFC devices cost function

Using Simens AG database [9], cost function for UPFC is developed as follows:

$$C_{UPFC} = 0.0003s^2 - 0.2691s + 188.22 \ \ (US\$/KVar) \tag{16}$$

where s is the operating range of the UPFC devices in MVAR, $s = |Q_2 - Q_1|$

Q1 - MVAR flow through the branch before placing UPFC device.

Q2 - MVAR flow through the branch after placing UPFC device.

and C_{UPFC} is in US$/KVar. The cost function is shown in Figure 4.

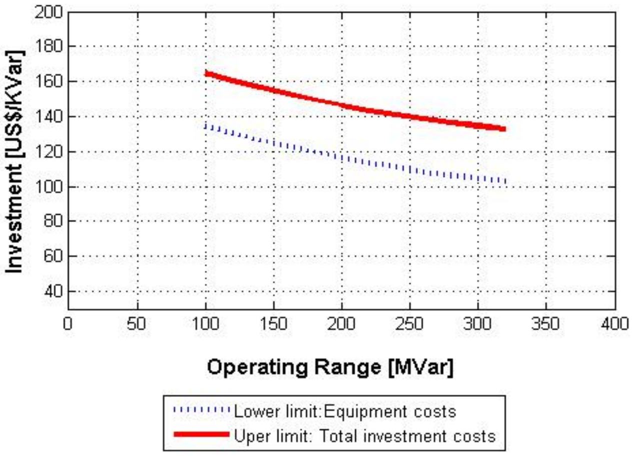

Figure 4. Cost Function of the UPFC device

3. Problem formulation

3.1 Optimal placement of UPFC device

The essential idea of the proposed UPFC device, UPFC placement approaches is to determine a line overloaded where the voltages at there extremities were out of acceptable limits, this line is considered as the best location for UPFC device. Once the location of UPFC device is determined, the economic load dispatch, security index and powers system losses can be obtained by solving the optimization problem using RGA, PSO and HRGAPSO approaches.

3.2 Maximum loadability limit (MLL)

The maximum lodability limit of power system is expressed as follow [10].

$$J_L = MLL = \sum_{j=1}^{n_G} P_j - P_L \tag{17}$$

where P_j is the real power generated by the unit j and P_L is the transmission loss.

3.3 Security index

The security index for contingency analysis of power system is expressed as follows [11]:

$$J_v = \sum_i w_i \left| V_i - V_{ref,i} \right|^2 \tag{18}$$

$$J_p = \sum_j w_j \left(\frac{S_j}{S_{j,\max}} \right)^2 \tag{19}$$

where V_i , w_i are voltage amplitude and associated weighting factor for i^th bus respectively, S_j , w_j are apparent power and associated weighting factor for j^th line respectively, $V_{ref.i}$ is nominal voltage magnitude which is assumed to be 1pu for all load buses (PQ buses) and to be equal to specified value for generation buses (PV buses) and $S_{j.\max}$ is apparent power nominal rate of j^th line or transformer.

3.4 Objective function of optimization
The aim of optimization is to perform the best utilization of the existing transmission lines. UPFC is located in order to enhance power system security and to maximize the system loadability. Fitness function is expressed as below:

$$\text{Fitness } J = a_1.J_p + a_2.J_v + a_3.(M - J_L) \tag{20}$$

A large constant positive constant M is selected to convert the MLL into a maximum one.
The coefficient a_1 to a_3 are optimized by trial and error to 0.237 , 0.315 and 0.448 respectively.

3.5 Problem constraints
3.5.1 Equality constraints
These constraints represent typical load flow equations as follows:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N} V_j \left[G_{ij}\, cos\left(\alpha_i - \alpha_j\right) + B_{ij}\, sin\left(\alpha_i - \alpha_j\right)\right] = 0 \tag{21}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{N} V_j \left[G_{ij}\, sin\left(\alpha_i - \alpha_j\right) - B_{ij}\, cos\left(\alpha_i - \alpha_j\right)\right] = 0 \tag{22}$$

where P_{Gi} and Q_{Gi} : generator real and reactive power at *i-th* bus, respectively; P_{Di} and Q_{Di} : load real and reactive power at *i-th* bus, respectively; G_{ij} and B_{ij} : transfer conductance and susceptance between buses *i* and *j*, respectively.

3.5.2 Inequality constraints
These constraints represent are:

3.5.2.1 Security constraints
These include the constraints of voltage at load buses V_L , the thermal limits of line transmission and the generator capacity are given respectively as follows:

$$V_{Li}^{\min} \le V_{Li} \le V_{Li}^{\max}, i = 1,,...,N_L \tag{23}$$

$$S_j \le S_{j.\max}, \text{j=1,....Nb} \tag{24}$$

$$P_{j\min} \le P_j \le P_{j\max} \text{ for j=1,.....,} N_G \tag{25}$$

where $P_{j\min}$ and $P_{j\max}$ are the minimum and maximum real power output of generating unit j.

3.5.2.2 Parameters UPFC constraints

$$E_{p\min} \le E_p \le E_{p\max} \tag{26}$$

$$E_{s\min} \le E_s \le E_{s\max} \tag{27}$$

$$\delta_{p\min} \le \delta_p \le \delta_{p\max} \tag{28}$$

$$\delta_{s\min} \le \delta_s \le \delta_{s\max} \tag{29}$$

4. Hybrid of RGA and PSO (HRGAPSO)
The proposed HRGAPSO combines RGA with PSO to form a hybrid algorithm ,in order to improve the search ability of the algorithm. In this section, real GA and PSO are introduced first, followed by a detailed introduction of HRGAPSO.

4.1 Real genetic algorithm (RGA)

Heuristic methods are able to solve complex optimization problem, and to give a good solution of a certain problem, but they are do not assure to reach global optimum.GA is a global evolutionary search technique that can result a feasible as well as optimal solution. To increase the speed and the exactitude of the process of research, the ordinary (binary) GA can be modified using real codes as real-GA (RGA), in which decoding is not needed to be done [2]. The major issues of RGA can be addressed in crossover as well as mutation and selection stages. In the following those stages are explained in details [12-14]. Figure 5 illustrates the flow chart of the proposed RGA technique in this study.

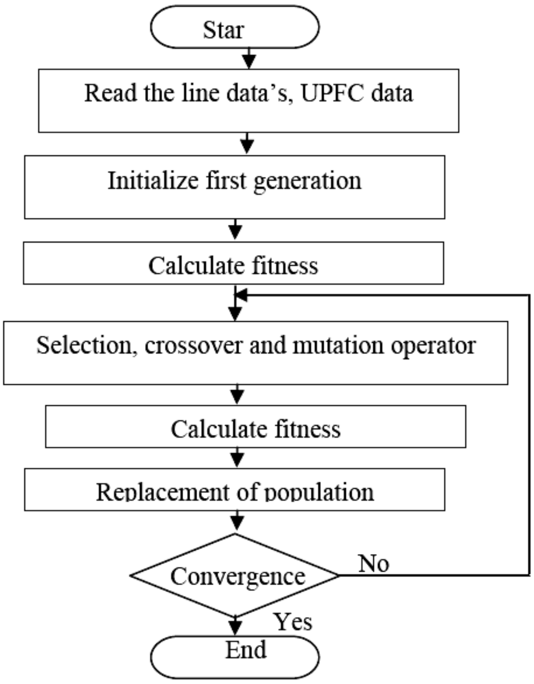

Figure 5. Real genetic algorithm flow diagram

4.2 Particle swarm optimization (PSO)algorithm

PSO is initialized with a group of random particles and the searches for optima by updating generation. Each particle represents a potential solution and has a position represented by $\vec{x}_i$. A swarm of particles moves through the problem space, with the moving velocity of each particle represented by a position vector $\vec{v}_i$. In every iteration each particle is updated by following two best values [15]. The first one is the best solution $\vec{p}_i$, which is associated with the best fitness it has achieved so far. Another best value that is the best position among all the particles obtained so far in the population is kept track of as $\vec{p}_g$. At each time step τ, by using the individual best position $\vec{p}_i(\tau)$ and global best position $\vec{p}_g(\tau)$, a new velocity for particle i is updated by:

$$\vec{v}_i(\tau+1) = \omega * \vec{v}_i(\tau) + c_1 * rand_1 * (\vec{p}_i(\tau) - \vec{x}_i(\tau)) + c_2 * rand_2 * (\vec{p}_g(\tau) - \vec{x}_i(\tau)) \quad (30)$$

where c_1 and c_2 are acceleration constants and $rand_1$ and $rand_2$ are uniformly distributed random numbers in [0, 1]. The term $\vec{v}_i$ is limited to its bounds. If the velocity violates this limit, it is set to its proper limit.

w is the inertia weight factor and in general, it is set according to the following equation:

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{T} . \tau \quad (31)$$

where $w_{\max}$ and $w_{\min}$ is maximum and minimum value of the weighting factor respectively. T is the maximum number of iterations and τ is the current iteration number.

Based on the updated velocities, each particle changes its position according to the following:

$$\vec{x}_i(\tau+1) = \vec{x}_i(\tau) + h(\tau) * \vec{v}_i(\tau+1) \tag{32}$$

where

$$h(\tau) = h_{\max} - \frac{(h_{\max} - h_0).\tau}{T} \tag{33}$$

where $h_{\max}$ and h_0 are positive constants.

According to (30) and (32), the computation of PSO is easy and adds only a slight computation load when it is incorporated into RGA. So, the flexibility of PSO to control the balance between local and global exploration of the problem space helps to overcome premature convergence of elite strategy in genetic algorithm, and enhances searching ability. The global best individual can be achieved by the RGA or by PSO, also it can avoid the premature convergence in PSO.

4.3 Hybrid of RGA and PSO (HRGAPSO)

The sequential steps of this algorithm (HRGAPSO) are given in Figure 6, which consists chiefly of genetic algorithm, combined with PSO to maintaining the integration of RGA and PSO for the entire run [15]. Briefly, the flow of key operations are illustrated in Figure 7.

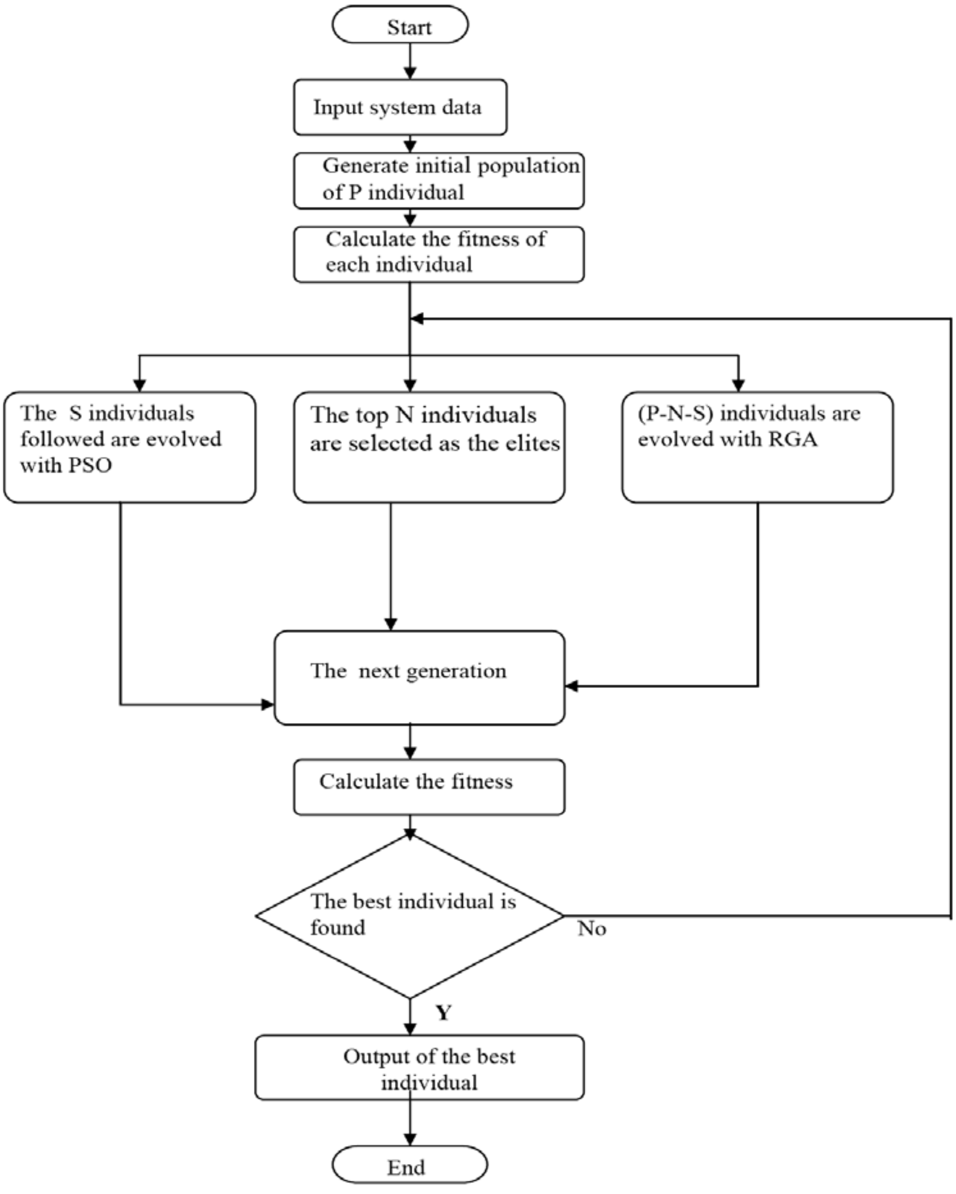

Figure 6. Flow chart of the proposed algorithm HRGAPSO

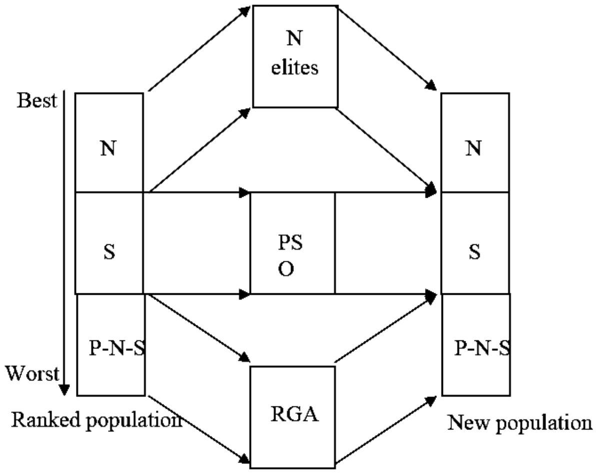

Figure 7. Flow of key operations in HRGAPSO

5. Numerical results

In order to verify the presented model of UPFC, the effectiveness of the approach proposed and illustrate the impacts of UPFC, we study two cases for a test system IEEE 14-bus. Data and results of system are based on 100 MVA and bus 1 is the bus of reference.

Case 1: results without UPFC, with line limits ignored.

Case 2: results with UPFC installed.

The test system data can be found in [16]. The thermal limit of complex power flow for lines (1) to (20), is given in Table 1. Table 2 gives the parameter values for RGA, PSO and HRGAPSO.

Table 1. Complex power line in IEEE-14 bus system

Line No	From Bus	To Bus	Line limit	Line No	From Bus	To Bus	Line limit	Line No	From Bus	To Bus	Line limit
1	1	2	1	8	10	11	1	15	9	14	1.2
2	1	5	0.6	9	12	13	1.5	16	7	8	1.2
3	2	3	1	10	13	14	0.4	17	7	9	0.8
4	2	4	1	11	6	11	1.2	18	4	7	1
5	2	5	0.6	12	6	12	1	19	4	9	0.5
6	3	4	1.2	13	6	13	0.8	20	5	6	0.5
7	4	5	0.4	14	9	10	1				

Table 2. Parameter values for RGA, PSO and HRGAPSO

Parameter	IEEE-14 bus		
	RGA	PSO	HRGAPSO
Population size	100	100	100
Generations	300	300	300
C1	-	2	2
C2	-	2	2
Wmax	-	0.9	0.9
Wmin	-	0.4	0.4
Probability of selection	0.1	-	0.1
Probability of crossover	0.8	-	0.8
Probability of mutation	0.02	-	0.02

Figure 8 represents a 14-bus test system that, applied to an optimal power flow with DC load flow model [5]. We also use the voltage profile and the transmitted power through the transmission line as the objective function for this test system to find optimal location of UPFC. There are two cases to be discussed. The results are shown in Figure 9 and Figure 10.

The voltage profile of the system with and without UPFC devices are shown in Figure 9. As shown in the figure, the voltage at bus 4 and bus 14 were out of acceptable limits (<0.9 pu) and improved significantly with the UPFC devices installed.

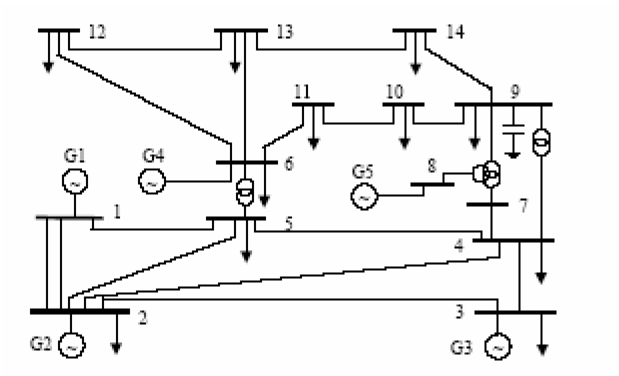

Figure 8. IEEE-14 bus test system

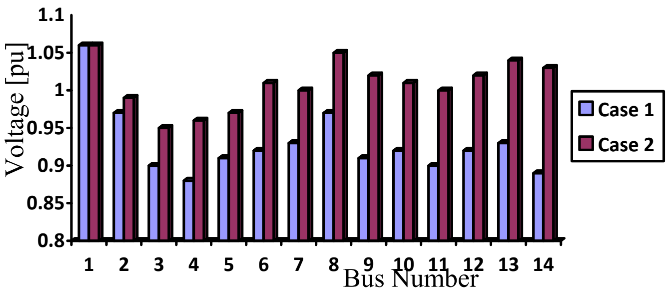

Figure 9.Voltage profile after and before employing UPFC

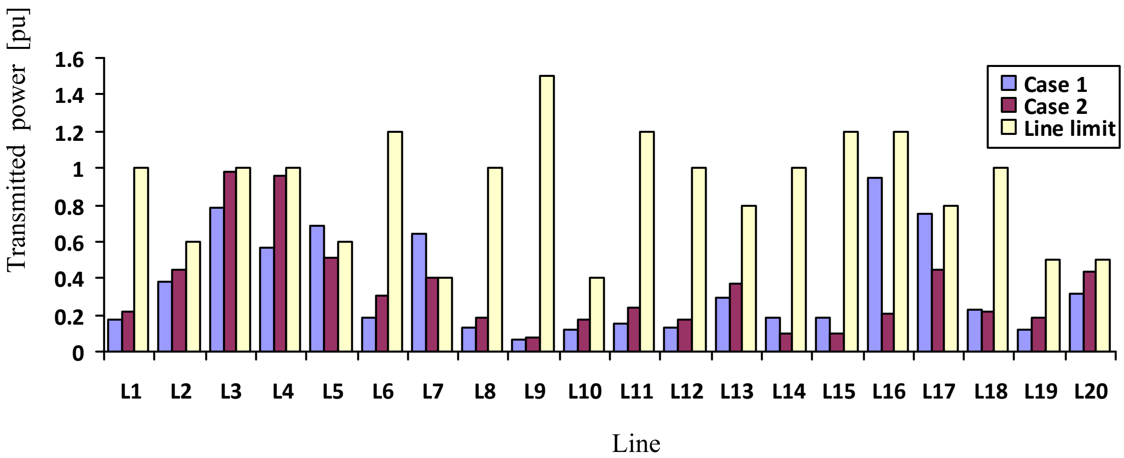

Figure 10 .Transmitted power after and before employing UPFC

As can be observed in the Figure 10, when line limits are relaxed, the results of case 1 are the results of the traditional economic dispatch. For this case, line 2-5 (L5) and line 4-5 (L7) would carry more than limits. After installing an UPFC in line 4-5 near bus 4 (V4=0.88<0.9pu), the results of simulation carried out have proved that the presence of an UPFC device in the transmission system can increase system loadability and may help in reaching a more balanced distribution of line flow. The line flows tend to distribute by approaching the thermal limits.

The performance index evolution of different methods without and with UPFC is shown in Figure 11 and Figure 12 respectively. Results are presented in Table 3 and Table 4 respectively.

The results show the difference of the convergence speed between several representative approaches, and reveal that HRGAPSO appeared to be the best amongst the three in two cases in term of convergence rate, CPU Time, and probability of attaining better solutions to improvement in security, reduction in losses of power system, minimizing the installation cost of UPFC and increasing power transfer capability of the existing power transmission lines.

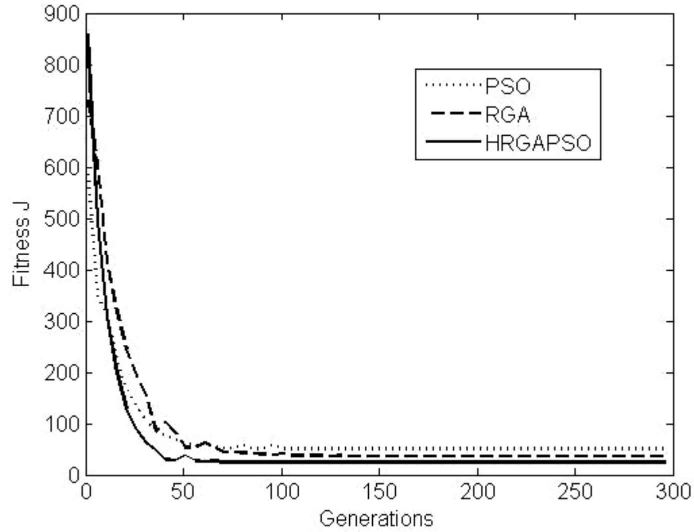

Figure 11. Performance index evolution of different approaches for case 1

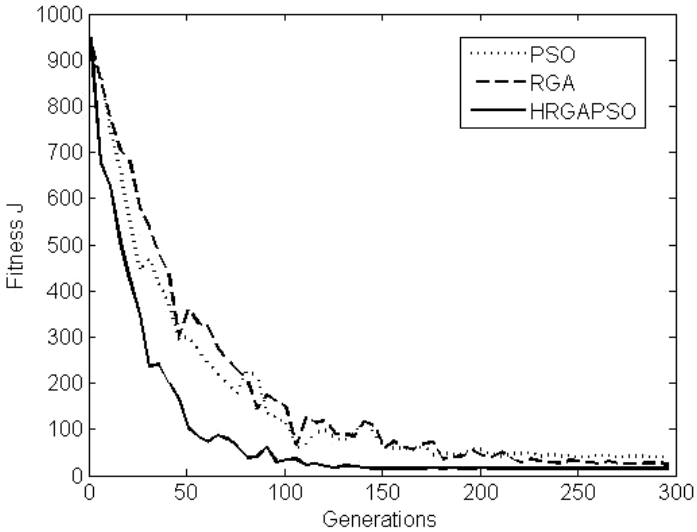

Figure 12. Performance index evolution of different approaches for case 2

Table 3. Simulation results of different approaches without UPFC

Approache	J_p	J_v	J_L
PSO	1.83	12.65	427.1
RGA	1.71	12.1	431.4
HRGAPSO	1.69	11.9	433.7

Table 4. Simulation results of different approaches with UPFC

Approache	J_p	J_v	J_L
PSO	1.63	8.55	469.3
RGA	1.59	7.85	473.6
HRGAPSO	1.56	6.15	476.1

Table 5. System active losses after and before UPFC employing

Algorithm	Active losses(MW) Case 1	Active losses (MW) Case 2
PSO	80.31	28.82
RGA	79.47	27.88
HRGAPSO	75.12	21.93

UPFC capital cost (installing and equipment) equals to 13.7 millions$ [17]. The reduced cost of losses that is returned by using UPFC is given in Table 6.

Table 6. Impact of UPFC installing for different approaches

Algorithm	Reduction losses (MW)	Cost of losses (million$)	Economic (million$)
PSO	51.49	80.68	66.98
RGA	51.59	80.84	67.14
HRGAPSO	53.19	83.34	69.64

As can be seen from Table 5 and Table 6, when the UPFC is installed, the comparison with RGA and PSO, demonstrate the superiority of HRGAPSO in higher load economic dispatch accuracy and reduction of system active losses (Table 7).

Table 7. Parameters of UPFC in IEEE-14 bus system

Control parameters of UPFC	Series source		Shunt source	
	E_s (pu)	δ_s (deg)	E_p (pu)	δ_p (deg)
PSO	0.041	-59.147	0.971	-11.474
RGA	-0.068	-38.217	0.945	-8.731
HRGAPSO	0.047	-56.522	0.996	-12.081

6. Conclusion

This paper presents a new algorithm for optimally locating the UPFC in electrical power system. In order to take advantage of the peculiarities of RGA and PSO, the proposed algorithm integrates the main features of them into the optimization process. Simulation of IEEE-14 bus test system for tow cases with and without FACTS shows that the placement of UPFC devices to improvement in security, reduction in losses of power system, minimizing the installation cost of UPFC and increasing power transfer capability of the existing power transmission lines. This proposed HRGAPSO methodology is also effective for the optimal locating of the UPFC in the electrical power system.

Appendix

Table A1. Line data

Line	R (Ω)	X(Ω)	Line	R (Ω)	X(Ω)
10-11	8.205	19.207	4-5	1.335	4.211
12-13	22.092	19.988	6-11	9.498	19.89
13-14	17.093	34.802	6-12	12.291	25.581
1-2	1.938	5.917	6-13	6.615	13.027
1-5	5.403	22.304	7-8	0	17.615
2-3	4.699	19.797	7-9	0	11.001
2-4	5.811	17.632	9-10	3.181	8.45
2-5	5.695	17.388	9-14	12.711	27.038
3-4	6.701	17.103			

Table A2.Transformer data

Transformer	Shc Volt. %	u, Magnitude HV-Side (pu)	u, Magnitude LV-Side (pu)
Trf 4-9	20.912	0.9079347	0.9030717
Trf 5-6	55.618	0.9195941	0.9354145
Trf 4-7	25.202	0.9079347	0.9267493

Table A3. Load data

Load	Active power MW	Reactive power Mvar	Power Factor
Ld 10	14.157	9.123	0.841
Ld 11	5.505	2.831	0.889
Ld 12	9.595	2.517	0.967
Ld 13	21.235	9.123	0.918
Ld 14	23.438	7.865	0.948
Ld 2	34.134	19.977	0.863
Ld 3	148.177	29.887	0.980
Ld 4	75.189	-6.135	0.997
Ld 5	11.955	2.517	0.978
Ld 6	17.618	11.797	0.831
Ld 9	46.403	26.112	0.871

Table A4. Generation data

Gi	N° Bus	$P_{gi}^{\min}$ (pu)	$P_{gi}^{\max}$ (pu)	$Q_{gi}^{\min}$ (pu)	$Q_{gi}^{\max}$ (pu)
G1	1	0.3	2	-0.5	0.5
G2	2	0.2	2.7	-0.8	1
G3	3	0.2	2	-0.8	0.8
G4	6	0.4	2	-0.7	0.7
G5	8	0.2	2.5	-0.8	0.8

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