OPF with Environmental Constraints with Multi Shunt Dynamic Controllers using Decomposed Parallel GA: Application to the Algerian Network

B. Mahdad†, T. Bouktir* and K. Srairi**

Abstract – Due to the rapid increase of electricity demand, consideration of environmental constraints in optimal power flow (OPF) problems is increasingly important. In Algeria, up to 90% of electricity is produced by thermal generators (vapor, gas). In order to keep the emission of gaseous pollutants like sulfur dioxide (SO2) and Nitrogen (NO2) under the admissible ecological limits, many conventional and global optimization methods have been proposed to study the trade-off relation between fuel cost and emissions. This paper presents an efficient decomposed Parallel GA to solve the multi-objective environmental/economic dispatch problem. At the decomposed stage the length of the original chromosome is reduced successively and adapted to the topology of the new partition. Two subproblems are proposed: the first subproblem is related to the active power planning to minimize the total fuel cost, and the second subproblem is a reactive power planning design based in practical rules to make fine corrections to the voltage deviation and reactive power violation using a specified number of shunt dynamic compensators named Static Var Compensators (SVC). To validate the robustness of the proposed approach, the algorithm proposed was tested on the Algerian 59-bus network test and compared with conventional methods and with global optimization methods (GA, FGA, and ACO). The results show that the approach proposed can converge to the near solution and obtain a competitive solution at a critical situation and within a reasonable time.

Keywords: Environmental economic dispatch, Dynamic control, Parallel Genetic Algorithm, multi-objective, System loadability, FACTS, SVC, Optimal power flow, System security, Planning and control

1. Introduction

In recent years and with the growth in electricity demand, environmental considerations have become one of the major management concerns. And due to pressing public demand for clean air, integrating pollution control into the standard Optimal Power Flow (OPF) has become a vital concern for organizations and governments worldwide, and has forced utilities to modify their operational strategies to reduce the pollution and atmospheric emissions of their thermal power plants [1-5].

The main objective of an OPF strategy is to determine the optimal operating state of a power system by optimizing a particular objective while satisfying certain specified physical and operating constraints. In its most general formulation, the OPF is a nonlinear, nonconvex, large-scale, static optimization problem with both continuous and discrete control variables. It becomes even more complex when flexible AC transmission systems (FACTS) devices are taken into consideration as control variables [1-4].

The global optimization techniques known as genetic algorithms (GA), simulated annealing (SA), tabu search (TS) and evolutionary programming (EP), which are the forms of probabilistic heuristic algorithms, have been successfully used to overcome the nonconvexity problems of the constrained ED [5]. The GA method usually has better efficiency because the GA has parallel search techniques. Due to its high potential for global optimization, GA has received great attention in solving optimal power flow (OPF) problems. Fig. 1 shows the decomposed parallel genetic approach combined with FACTS devices to enhance the optimal power flow (OPF) under severe loading conditions.

The literature on the application of the global optimization in the OPF problem is vast and [6] represents the major contributions in this area. In [7] the authors present an enhanced genetic algorithm (EGA) for the solution of the OPF problem with both continuous and discrete control variables. The continuous control variables modeled are unit active power outputs and generator bus voltage magnitudes, while the discrete ones are transformer tap settings and switchable shunt devices. With the aid of the problem specific operators proposed, the efficiency and the accuracy of the solution are enhanced.

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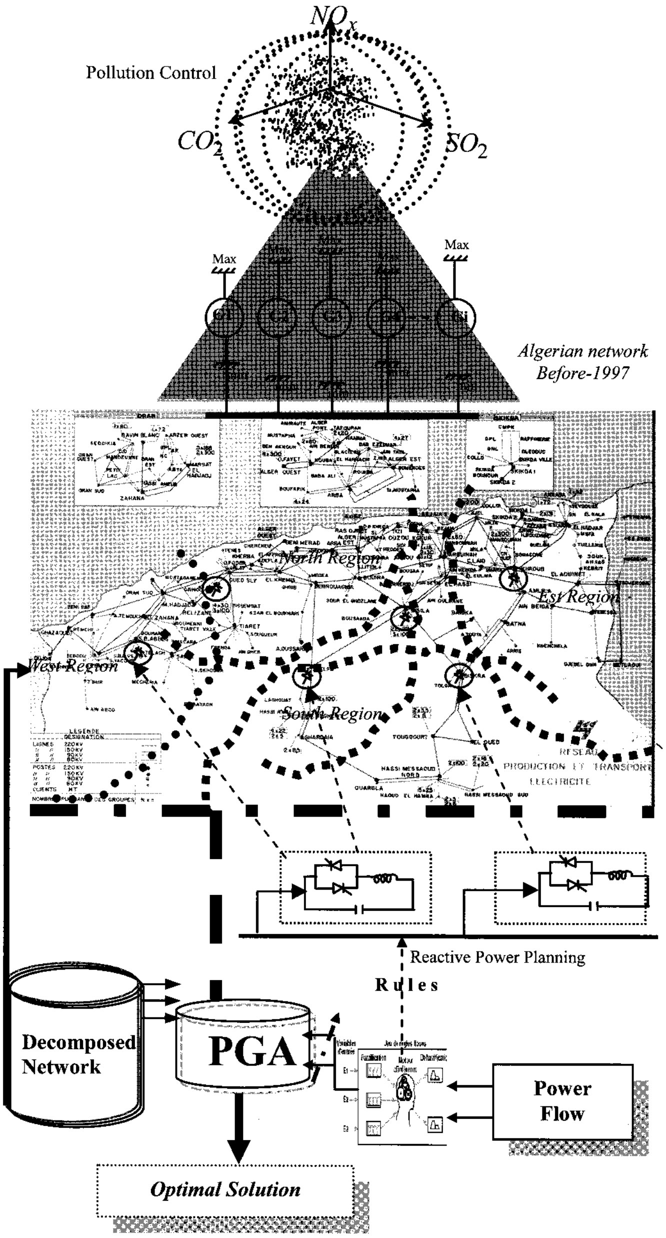

Fig. 1. Efficient decomposed parallel GA approach proposed coordinated with FACTS for the Environmental/economic dispatch

In [8], the authors have proposed the use of an ant colony search algorithm to solve the economic power dispatch with pollution control. To accelerate the processes of ant colony optimization (ACO), the controllable variables are decomposed to active constraints that directly affect the cost function included in the ACO process and the passive constraints which are updated using conventional power flow.

The authors in [9] proposed a combined GA-Fuzzy based approach for solving the optimal power flow (OPF). The GA parameters, e.g. crossover and mutation probabilities, are governed by fuzzy rule base. The authors in [10] proposed a method based on an efficient successive linear programming technique for optimal power flow (OPF) with environmental constraint. The algorithm was tested on the Algerian 59-bus power system.

This paper proposes a simple approach based on a decomposed parallel genetic algorithm implemented with Matlab program to minimize the total fuel cost of generation and environmental pollution caused by fossil based thermal generating units and also maintaining an acceptable system performance in terms of limits on generator reactive power outputs, bus voltages, dynamic shunt compensators (SVC, STATCOM) parameters and overload in transmission lines. The advantages of the approach proposed over other traditional optimization techniques and global optimization methods have been demonstrated through the results of the Algerian 59-bus test system.

2. Optimal Power Flow Formulation

The active power planning problem is considered as a general minimization problem with constraints, and can be written in the following form:

$$\text{Min}\, f(x,u) \tag{1}$$

$$\text{S.t}\quad g(x,u)=0 \tag{2}$$

$$h(x,u)\leq 0 \tag{3}$$

$$x=\left[\delta \quad V_L\right]^T \tag{4}$$

$$u=\left[P_G \quad V_G \quad t \quad B_{svc}\right]^T \tag{5}$$

$f(x,u)$ is the objective function, $g(x,u)$ and $h(x,u)$ are respectively the set of equality and inequality constraints. x is the state variables and u is the vector of control variables. The control variables are generator active and reactive power outputs, bus voltages, shunt capacitors/reactors and transformer tap settings. The state variables are voltage and angle of load buses. For optimal active power dispatch, the objective function f is the total generation cost expressed as follows:

$$\text{Min}\quad f=\sum_{i=1}^{N_g}\left(a_i+b_iP_{gi}+c_iP_{gi}^2\right) \tag{6}$$

Where N_g is the number of thermal units, P_{gi} is the active power generation at unit i and a_i, b_i and c_i are the cost coefficients of the i^{th} generator.

The equality constraints $g(x)$ are the power flow equations.

The inequality constraints $h(x)$ reflect the limits on physical devices in the power system as well as the limits created to ensure system security.

2.1 Emission Objective Function

An alternative dispatch strategy to satisfy the environmental requirement is to minimize operation cost under environmental requirement. Emission control can be included in conventional economic dispatch by adding the environmental cost to the normal dispatch. The objective function that minimizes the total emissions can be expressed as the sum of all three pollutants (NO_x, CO_2, SO_2) resulting from generator real power [9].

In this study, NO_x emission is taken as the index from the viewpoint of environment conservation. The amount of NO_x emission is given as a function of generator output (in Ton/hr), that is the sum of quadratic and exponential functions [10].

$$f_e = \sum_{i=1}^{ng} 10^{-2} \times \left(\alpha_i + \beta_i P_{gi} + \gamma_i P_{gi}^2 + \omega_i \exp\left(\mu_i P_{gi}\right)\right) \text{ Ton/h} \tag{7}$$

where α_i, β_i, γ_i, ω_i and μ_i are the parameters estimated on the basis of unit emissions test results.

The pollution control can be obtained by assigning a cost factor to the pollution level expressed as:

$$f_{ce} = \omega . f_e \qquad \text{\$/h} \tag{8}$$

where ω is the emission control cost factor in $/ton.

Fuel cost and emission are conflicting objectives and cannot be minimized simultaneously. However, solutions may be obtained in which fuel cost and emissions are combined in a single function with a different weighting factor. This objective function is described by:

$$\textit{Minimize} \qquad F_T = \alpha f + (1-\alpha) f_{ce} \tag{9}$$

where α is a weighting factor that satisfies $0 \le \alpha \le 1$.

In this model, when weighting factor $\alpha = 1$, the objective function becomes a classical economic dispatch, when weighting factor $\alpha = 0$, the problem becomes a pure minimization of the pollution control level.

3. Reactive Power Dispatch

The solution of the reactive power dispatch problem involves the optimization of the nonlinear objective function with nonlinear constraints. In general, the objectives considered are the real power loss in the transmission network and voltage deviations at the load buses.

3.1 Power Loss

The objective function here is to minimize the active power loss (P_{loss}) in the transmission system. It is given as:

$$P_{loss} = \sum_{k=1}^{Nl} g_k \left[\left(t_k V_i\right)^2 + V_j^2 - 2 t_k V_i V_j \cos\delta_{ij} \right] \tag{10}$$

where N_l is the number of transmission lines; g_k is the conductance of branch k between buses i and j; t_k the tap ration of transformer k; V_i is the voltage magnitude at bus i; δ_{ij} the voltage angle difference between buses i and j.

3.2 Voltage Deviation

One of the important indices of power system security is the bus voltage magnitude. The voltage magnitude deviation from the desired value at each load bus must be as small as possible. The deviation of voltage is given as follows:

$$\Delta V = \sum_{k=1}^{N_{PQ}} \left| V_k - V_k^{des} \right| \tag{11}$$

where N_{PQ} is the number of load buses and V_k^{des} is the desired or target value of the voltage magnitude at load bus k.

4. Shunt facts modeling

4.1 Static VAR Compensator (SVC)

The steady-state model proposed in [11] is used here to incorporate the SVC on power flow problems. This model is based on representing the controller as a variable impedance, as depicted in Fig. 2.

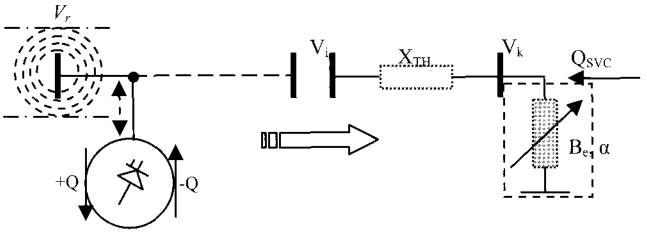

Fig. 2. SVC steady-state circuit representation

$$V = V_{ref} + X_{sl} I \tag{12}$$

X_{sl} is in the range of 0.02 to 0.05 p.u. with respect to the SVC base. The slope is needed to avoid hitting limits. At the voltage limits the SVC is transformed into a fixed reactance. The total equivalent impedance Xe of SVC may be represented by:

$$X_e = X_C \frac{\pi / k_X}{\sin 2\alpha - 2\alpha + \pi(2 - 1/k_X)} \tag{13}$$

where $k_X = x_C / x_L$

5. Strategy of the Efficient Parallel GA for OPF

5.1 Principle of the Approach Proposed

Parallel execution of various SGAs is called PGA (Parallel Genetic Algorithm). Parallel Genetic Algorithms (PGAs) have been developed to reduce the large execution times that are associated with simple genetic algorithms for finding near-optimal solutions in large search spaces. They have also been used to solve larger problems and to find better solutions.

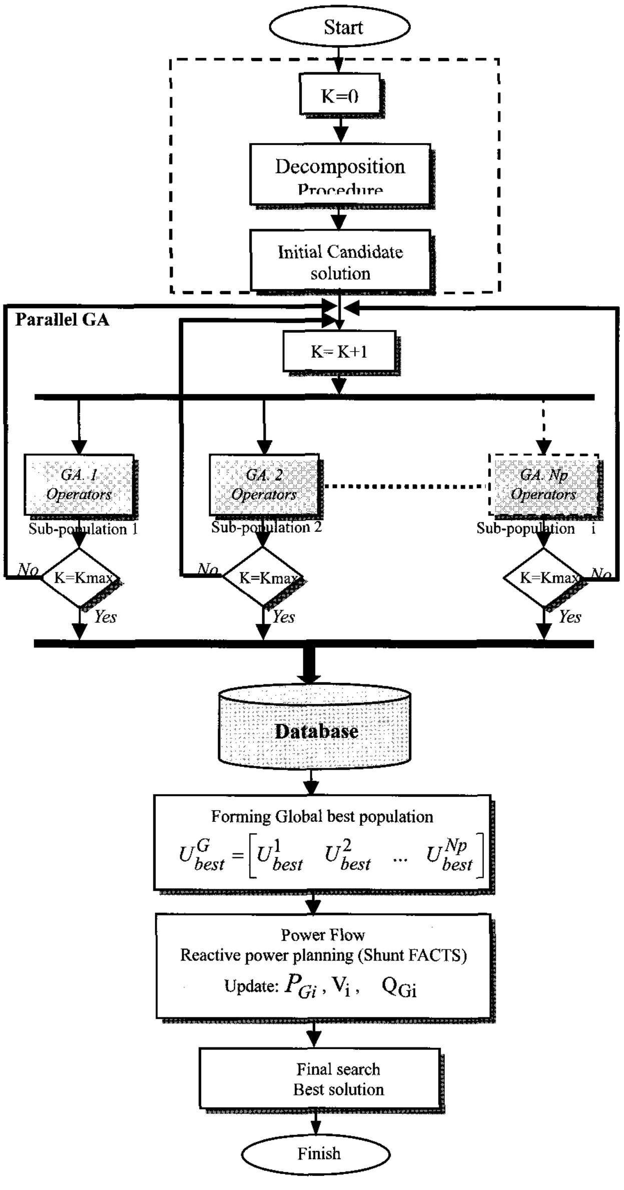

Fig. 3. Flowchart of the proposed DPGA approach-based OPF

The proposed algorithm decomposes the solution of such a modified OPF problem into two linked subproblems. The first subproblem is an active power generation planning solved by the proposed efficient genetic algorithm, and the second subproblem is a reactive power planning [14-15] to make fine adjustments on the optimum values obtained from the EPGA. This will provide updated voltages, angles and point out generators having exceeded reactive limits.

5.2 Decomposition Mechanism

Problem decomposition is an important task for large-scale OPF problems, which needs answers to the following two technical questions:

- How many efficient partitions are needed?
- Where to practice and generate the efficient inter-independent sub-systems?

The decomposition procedure decomposes a problem into several interacting subproblems that can be solved with reduced sub-populations, and coordinates the solution processes of these subproblems to achieve the solution of the whole problem.

5.3 Justification for using Efficient Parallel Continuous GA

a. Standard Genetic Algorithm

GA is a global search technique based on the mechanics of natural selection and genetics. It is a general-purpose optimization algorithm that is distinguished from conventional optimization techniques by the use of concepts of population genetics to guide the optimization search. Instead of a point-to-point search, GA searches from population-to-population. The advantages of GA over traditional techniques are [7]:

i) It needs only rough information of the objective function and places no restriction such as differentiability and convexity on the objective function.

ii) The method works with a set of solutions from one generation to the next, and not a single solution, thus making it less likely to converge on local minima.

iii) The solutions developed are randomly based on the probability rate of the genetic operators such as mutation and crossover; the initial solutions thus would not dictate the search direction of GA.

b. Continuous GA Applied to the OPF Problem

The binary GA has its precision limited by the binary representation of variables; using floating point numbers instead easily allows representation to the machine precision. This continuous GA also has the advantage of requiring less storage than the binary GA because a single floating-point number represents the variable instead of N_{bits} integers. The continuous GA is inherently faster than the binary GA, because the chromosomes do not have to be decoded prior to the evaluation of the cost function [9]. Fig. 4 shows the chromosome structure within the approach proposed.

A. Algorithm of the Approach Proposed

1. Initialization based in Decomposition Procedure

The main idea of the proposed approach is to optimize the active power demand for each partitioned network to minimize the total fuel cost. An initial candidate solution is generated for the global N population size.

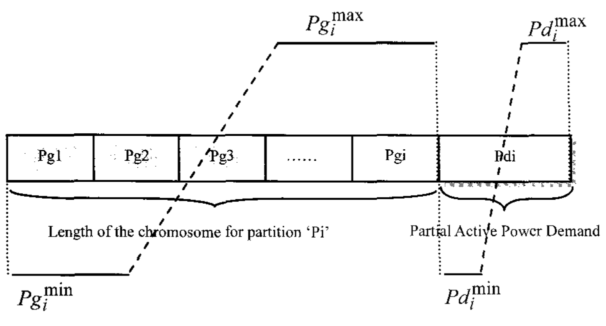

Fig. 4. Chromosome structure

1-For each decomposition level estimate the initial active power demand:

For NP=2 Do

$$Pd1 = \sum_{i=1}^{M1} P_{Gi} \tag{14}$$

$$Pd2 = \sum_{i=1}^{M2} P_{Gi} = PD - Pd1 \tag{15}$$

Where NP is the number of partition

$Pd1$: the active power demand for the first initial partition.

$Pd2$: the active power demand for the second initial partition.

PD : the total active power demand for the original network.

The following equilibrium equation should be verified for each decomposed level:

For level 1:

$$Pd1 + Pd2 = PD + Ploss \tag{16}$$

2-Fitness Evaluation based Load Flow

For all sub-systems generated, perform a load flow calculation to evaluate the proposed fitness function. A candidate solution formed by all sub-systems is better if its fitness is higher.

$$f_i = 1/\left(F_{\cos t} + \omega_l F_{li} + \omega_V F_{Vi}\right) \tag{17}$$

$$F_{Vi} = \sum_{j=1}^{NPQ} \left(\left|V_{PQij} - V_{PQij}^{\lim}\right|\right) \Big/ \left(\left|V_{PQij}^{\max} - V_{PQij}^{\min}\right|\right) \tag{18}$$

where f_i is fitness function for sub-systems decomposed at level i.

F_{li} denotes the per unit power loss generated by sub-systems at level i; $F_{\cos t}$ denotes the total cost of the active power planning related to the decomposition level i; F_{Vi} denotes the sum of the normalized violations of voltages related to the sub-systems at level i.

3-Consequently under this concept, the final value of active power demand should satisfy the following equations.

2. Final Search Mechanism

- All the sub-systems are collected to form the original network, global database generated based on the best results Ubest (parti) found from all sub-populations.
- The final solution Ubest (Global) is found after reactive power planning procedure to adjust the reactive power generation limits, and voltage deviation, the final optimal cost is modified to compensate the reactive constraints violations.

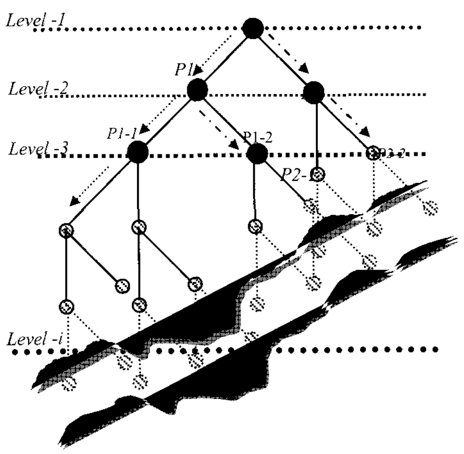

Fig. 5. Sample of network in tree decomposition

Fig. 5 shows an example of tree network decomposition; Fig. 6 illustrates the mechanism of search partitioning.

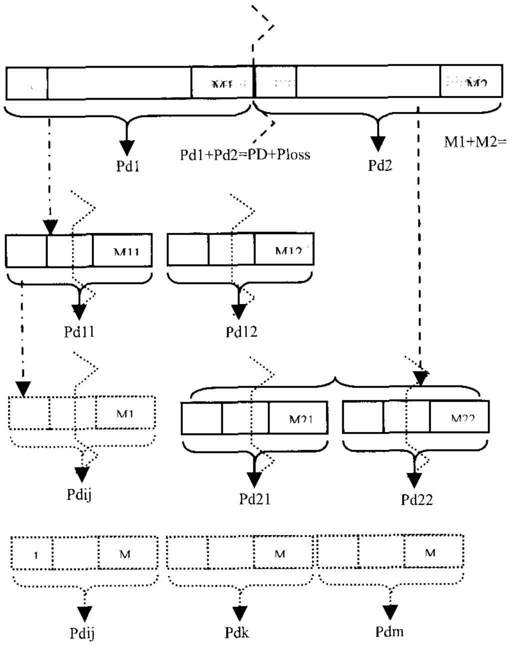

Fig. 6. Mechanism of search partitioning

6. Application Study

6.1 Active Power Dispatch without SVC Compensators

The proposed algorithm is developed in the Matlab programming language using version 6.5. The approach proposed has been tested on a part of the Algerian network. It consists of 59 buses, 83 branches (lines and transformers) and 10 generators. Table 1 shows the technical and economic parameters of the 10 generators, with the knowledge that the generator of bus N°=13 is not in service. Table 2 shows the generator's emission coefficients. The generator's data and cost coefficients are taken from [8]-[10]. For the voltage constraint the lower and upper limits are 0.9 p.u and 1.1 p.u, respectively. The GA population size is taken equal 30, the maximum number of generation is 100, and crossover and mutation are applied with initial probability 0.9 and 0.01 respectively. For the purpose of verifying the efficiency of the proposed approach, we made a comparison of our algorithm with other competing OPF algorithms. In [9] they presented a fuzzy controlled genetic algorithm. In [8] they presented a standard GA, in [8], the authors presented an ACO algorithm, and then in [10], they proposed a fast successive linear programming algorithm. Fig. 7 shows the topology of the Algerian network test with 59-bus.

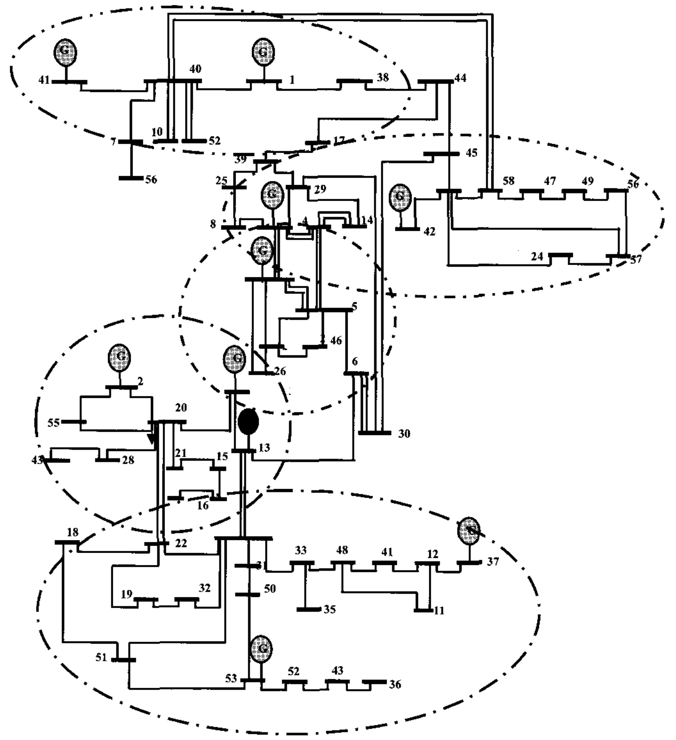

Fig. 7. Topology of the Algerian production and transmission network before 1997

Table 1. Technical Admissible parameters of Generators and the Fuel Cost Coefficients

Bus Number	Pmin [MW]	Pmax [MW]	Qmin [Mvar]	Qmax [Mvar]	a [\$/hr]	b [\$/MWhr]	c [\$/MW²hr]
1	8	72	-10	15	0	1.50	0.0085
2	10	70	-35	45	0	2.50	0.0170
3	30	510	-35	55	0	1.50	0.0085
4	20	400	-60	90	0	1.50	0.0085
13	15	150	-35	48	0	2.50	0.0170
27	10	100	-20	35	0	2.50	0.0170
37	10	100	-20	35	0	2.00	0.0030
41	15	140	-35	45	0	2.00	0.0030
42	18	175	-35	55	0	2.00	0.0030
53	30	450	-100	160	0	1.50	0.0085

To demonstrate the effectiveness and the robustness of the approach proposed, three cases have been considered with and without consideration of SVC Controllers installation:

Case 1: Minimum total operating cost (α =1).
Case 2: Minimum total emission (α =0).
Case 3: Minimum total operating cost and emission (α =0.5).

Table 2. Generator Emission Coefficients

N° Bus	Generator	α	βx1e-2	γx1e-4	ω	μx1e-2
1	1	4.091	−5.554	6.490	2.00e-04	2.857
2	2	2.543	−6.047	5.638	5.00e-04	3.333
3	3	4.258	−5.094	4.586	1.00e-06	8.000
4	4	5.326	−3.550	3.380	2.00e-03	2.000
13	5	4.258	−5.094	4.586	1.00e-06	8.000
27	6	6.131	−5.555	5.151	1.00e-05	6.667
37	7	4.091	−5.554	6.490	2.00e-04	2.857
41	8	2.543	−6.047	5.638	5.00e-04	3.333
42	9	4.258	−5.094	4.586	1.00e-06	8.000
53	10	5.326	−3.550	3.380	2.00e-03	2.000

Table 3. Simulation Results for Three Cases without SVC Compensators

	Case 1: α =1	**Case 2: α =0**	**Case 3: α =0.5**
P_{gi} (MW)	Minimum Cost	Minimum emission	Minimum Cost and emission
P_{g1}	41.272	30.665	36.862
P_{g2}	37.319	70.00	53.170
P_{g3}	133.83	109.40	119.06
P_{g4}	142.32	79.80	138.32
P_{g5}	**0.00**	**0.00**	**0.000**
P_{g6}	24.80	80.58	22.860
P_{g7}	39.70	34.86	39.800
P_{g8}	39.54	70.04	59.900
P_{g9}	119.78	100.62	109.52
P_{g10}	123.46	128.02	122.92
Cost (\$/h)	**1769.70**	**1854.9**	**1765.8**
Emission (ton/h)	**0.5307**	**0.4213**	**0.4723**
Power loss (MW)	**18.314**	**19.8853**	**18.312**

Table 3 shows simulation results obtained by the approach proposed for the three cases (α =1, α =0, α =0.5), with the SVC controllers not taken in consideration. The comparison of the results obtained by the application of the decomposed parallel GA proposed with those found by global optimization (GA, FGA, and ACO) and the conventional method (FSLP) are reported in Tables 4 and 5. The proposed approach gives more important results compared to all cases. For example, in the case corresponding to the minimum total operating cost (α =1), the fuel cost is 1769.70 $/h, and the power loss is 17.921 MW which is better compared with the results found by global and conventional methods. It is important to note that all results obtained by the approach proposed do not violate physical generation capacity constraints. The security constraints are satisfied for voltage magnitudes (0.9<V<1.1 p.u) and line flows. Table 6 shows clearly the simulation results for voltage phase profile and reactive power generation for three cases.

Table 4. Comparison of the Results Obtained with Conventional and Global Methods: Case: 1 Minimum Cost

Generators N°	FGA [9]	GA [8]	ACO [8]	FSLP [10]	Our Approach
P_{g1} (MW)	11.193	70.573	64.01	46.579	41.272
P_{g2} (MW)	24.000	56.57	22.75	37.431	37.319
P_{g3} (MW)	101.70	89.27	82.37	134.230	133.83
P_{g4} (MW)	84.160	78.22	46.21	137.730	142.32
P_{g5} (MW)	**0.000**	**0.00**	**0.00**	**0.000**	**0.00**
P_{g6} (MW)	35.22	57.93	47.05	23.029	24.80
P_{g7} (MW)	56.80	39.55	65.56	35.238	39.70
P_{g8} (MW)	121.38	46.40	39.55	39.972	39.54
P_{g9} (MW)	165.520	63.58	154.23	117.890	119.78
P_{g10} (MW)	117.32	211.58	202.36	131.650	123.46
PD(MW)	684.10	684.10	684.10	684.10	684.1
Ploss(MW)	33.1930	29.580	39.980	19.65	**17.921**
Cost[$/hr]	1768.50	1937.10	1815.7	1775.856	**1769.70**

Table 5. Comparison of the Results Obtained with Conventional method

	FSLP[10]			*Our Approach*		
	Case1	Case 2	Case 3	Case1	Case 2	Case 3
P_{gi} (MW)	$\alpha=1$	$\alpha=0$	$\alpha=0.5$	$\alpha=1$	$\alpha=0$	$\alpha=0.5$
P_{g1}	46.579	28.558	37.464	41.272	30.5995	36.8311
P_{g2}	37.431	70.000	52.675	37.319	70.00	53.170
P_{g3}	134.230	114.200	116.080	133.83	109.40	119.06
P_{g4}	137.730	77.056	141.490	142.32	79.80	138.32
P_{g5}	**0.000**	**0.000**	**0.000**	**0.00**	**0.00**	**0.000**
P_{g6}	23.029	87.575	28.286	24.80	80.58	22.860
P_{g7}	35.238	32.278	34.565	39.70	34.86	39.800
P_{g8}	39.972	63.176	56.644	39.54	70.04	59.900
P_{g9}	117.890	95.645	101.800	119.78	100.62	109.52
P_{g10}	131.650	135.540	133.920	123.46	128.02	122.92
Cost ($/h)	1775.856	1889.805	1786.000	**1769.70**	**1854.8**	**1765.7**
Emission (ton/h)	0.5328	0.4329	0.4746	**0.5307**	**0.4213**	**0.4723**
Power loss (MW)	19.65	19.93	18.83	**17.921**	**19.8195**	**18.2811**

Table 6. Simulation Results for Voltage Phase Profile and Reactive Power Generation - Three Cases: without SVC Compensators

	Case 1: $\alpha=1$		**Case 2:** $\alpha=0$		**Case 3:** $\alpha=0.5$	
Bus	Phase (degre)	Qg (Mvar)	Phase (degre)	Qg (Mvar)	Phase (degre)	Qg (Mvar)
1	0.00	3.8300	0.00	7.391	0.00	5.56
2	3.2215	38.768	5.1849	33.588	2.3129	35.992
3	8.283	26.209	7.6622	27.654	6.0354	26.66
4	-8.975	57.312	-10.3037	80745	-11.2228	58.807
13	-0.74002	-29.947	-1.1833	-28.596	-2.6164	-29.131
27	-9.0873	28.74	-10.2907	7.46	-11.3271	29.099
37	-2.315	17.605	-9.3887	22.036	-3.9299	17.524
41	-3.9747	26.823	-1.1206	18.383	-2.4137	21.32
42	-0.08364	43.906	-1.2318	47.509	-1.4423	46.126
53	2.8753	26.002	3.0538	23.802	1.1658	25.824

6.2 Reactive Power Dispatch with SVC Compensators

In this second study dynamic shunt compensation is taken into consideration. The control variables selected for reactive power dispatch (RPD) are: the generator voltages, tap ratio of tap changing transformers and reactive power of the SVC compensators installed at specified buses.

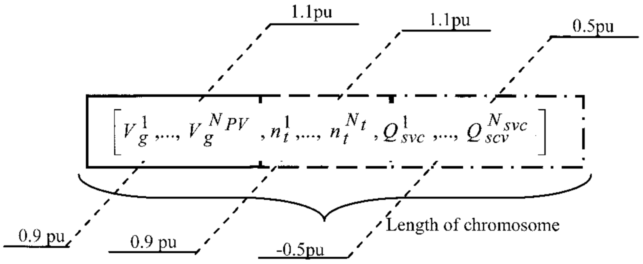

Fig. 8. Chromosome structure for reactive power dispatch

where N_t is the number of tap positions in a tap changing transformer and N_{svc} the number of dynamic shunt compensator available at each bus. The security limits for each control variable are indicated in Fig. 8.

A. Optimal Placement of Shunt FACTS

Before the insertion of SVC devices, the system was pushed to its collapsing point by increasing both the active and reactive loads discretely using continuation load flow [5]. In this test system, according to results obtained from the continuation load flow, buses 7, 14, 17, 35, 36 , 39, 44, 47, 56 are the best location points for installation and coordination between SVC Compensators and the network. Table 7 gives details of the SVC Data.

Table 7. SVC DATA

	B_{min} (p.u)	B_{max} (p.u)	B_{init} (p.u)
Susceptance SVC Model	-0.5	0.5	0.025

Table 8. Simulation Results for Three Cases: Voltage Phase Profile and Reactive Power Generation with SVC Compensators

	Case 1: *α =1*		**Case 2:** *α =0*		**Case 3:** *α =0.5*	
Bus	Phase (degre)	Qg (Mvar)	Phase (degre)	Qg (Mvar)	Phase (degre)	Qg (Mvar)
1	0.00	3.830	0.00	7.549	0.00	5.605
2	3.3935	38.768	5.4169	33.409	2.4987	35.743
3	8.4549	26.209	7.8935	27.563	6.2215	26.53
4	-8.7439	57.312	-10.0176	80.745	-10.9732	58.807
13	-0.56592	29.947	-0.95314	-33.633	-2.4279	-34.909
27	-8.8563	28.74	-10.0046	-1.302	-11.0776	20.296
37	-1.2011	17.605	-8.2914	20.804	-2.8015	16.004
41	-3.7423	26.823	-0.87981	10.485	-2.1861	13.675
42	-0.01542	43.906	-1.1279	36.247	-1.3704	35.07
53	3.0526	26.002	3.2913	21.401	1.3572	22.465
Ploss MW	**16.925**		**18.731**		**17.275**	

Table 9. Results of the Reactive power Dispatch of the Multi-SVC Installation: Case 1: α=1, Minimum Cost

Bus	**QSVC(p.u)**	**V(p.u) with SVC**	**Fixed Shunt Capacitors**	**V(p.u) without SVC**
7	0.01103	0.9865		0.96157
14	0.11911	0.9630		**0.93498**
17	0.05554	0.9764		0.94881
35	0.06796	0.9820		0.95694
39	-0.01399	0.9764		0.95566
44	-0.05579	0.9764		0.98030
47	0.08487	0.9864		**0.93798**
56	0.08487	0.9968		0.96289
13			-0.40652	
27			0.3900	
36			0.1197	
48			0.0963	
Pg1, slack MW	**40.276**			
Ploss MW	**16.925**			
Cost ($/hr)	**1767.5**			
Voltage limits	**0.95<Vi<1.1**			

Table 8 shows results for voltage angle profile and reactive power generation with SVC Compensators for the three cases (**α =1, α =0, α =0.5**), the active power loss reduced for the three cases compared to base case without reactive power dispatch. Tables 9, 10, and 11 show details of the control variables (Q_{svc}) reactive power of the multi SVC exchanged with the network before and after optimization for the three cases (minimum cost α =1, minimum emission α =0, and minimum cost and emission α =0.5). The minimum and maximum limits of load bus voltage are 0.9 and 1.1 p.u. From the base case corresponding to the first case (α =1) without SVC compensators, fuel cost is reduced to 1767.5 ($/h) and power loss reduced also to 16.925 MW. It is important to note that all results for power generation obtained by the approach proposed do not violate physical generation capacity constraints. The security constraints are satisfied for voltage magnitudes ($0.95<V<1.1$p.u) and line flows ($|P_{ij}| \le P_{ij}^{\max}$). Fig. 9 shows the voltage magnitude improvement using SVC Compensators installed at critical buses. Table 10 shows the results of the best cost and average CPU time for the four best decomposed networks. Fig. 10 shows clearly the convergence of the approach proposed for the first partition at α =1. These results confirm clearly the ability of the proposed approach to find accurate and efficient OPF solution with consideration of Shunts FACTS Compensators.

Table 10. Results of the Reactive power Dispatch of the Multi-SVC Installation: Case 2: α=0, Minimum Emission

Bus	**QSVC(p.u)**	**V(p.u) with SVC**	**Fixed Shunt Capacitors**	**V(p.u) Without SVC**
7	0.01702	0.9865		0.95607
14	0.11962	0.9630		**0.93472**
17	0.05562	0.9764		0.94801
35	0.04814	0.9820		0.96422
39	-0.01386	0.9764		0.95497
44	-0.05308	0.9764		0.97927
47	0.09464	0.9864		**0.93167**
56	0.06845	0.9864		0.95744
13			-0.40652	
27			0.3900	
36			0.1197	
48			0.0963	
Pg1, slack (MW)	**0.29511**			
Ploss (MW)	**0.18731**			
Cost ($/hr)	**1852.6**			
Voltage limits	**0.95<Vi<1.1**			

Table 11. Results of the Reactive power Dispatch of the Multi-SVC Installation: Case 3: α=0.5, Minimum Cost and Emission

Bus	QSVC(p.u)	V(p.u) with SVC	Fixed Shunt Capacitors	V(p.u) without SVC
7	0.01521	0.9865		0.95755
14	0.11941	0.9630		**0.9347**
17	0.05584	0.9764		0.94743
35	0.06833	0.9820		0.95681
39	-0.01406	0.9764		0.95456
44	-0.04962	0.9764		0.9784
47	0.09201	0.9864		**0.93331**
56	0.06659	0.9968		0.95878
13			-0.40652	
27			0.3900	
36			0.1197	
48			0.0963	
Pg1, slack (MW)	**35.825**			
Ploss (MW)	**0.17275**			
Cost ($/hr)	**1763.6**			
Voltage limits	**0.95<Vi<1.1**			

Table 12. Results of the best cost and average CPU time for the best four decomposed Network

Partition	Pgi	Best Cost $/hr	Worst Cost $/hr	Average CPU time (s)
Part 1	[Pg1, Pg2]	187.4522	187.6080	0.230
Part 2	[Pg3, Pg4]	737.6220	737.9309	0.230
Part 3	[Pg6, Pg7]	171.7722	171.9310	0.230
Part 4	[Pg8, Pg9, Pg10]	662.3062	662.6031	0.260

Table 13. Results of the best of active power generation for the four decomposed Network: without reactive power Dispatch

Active Power Generation Pgi (MW)				
Partition	Test 1	Test 2	Test 3	Test 4
Part 1	**44.820** 33.600	**44.780** 33.640	**44.740** 33.680	**44.80** 33.60
Part 2	136.70 139.26	136.94 139.06	139.06 139.94	141.280 134.720
Part 3	15.040 49.280	14.540 49.760	14.60 49.70	14.620 49.680
Part 4	49.9200 129.580 103.240	49.780 129.28 103.68	49.560 128.440 104.760	49.900 129.140 103.720
$\sum Pg_i$	701.44	701.46	704.48	701.46
Power Flow without SVC Compensators				
Pg-slack (MW)	**48.266**	**48.183**	**44.757**	**48.625**
$\sum Pg_i$	704.8860	704.8630	704.4970	705.2850
Cost ($/h	**1742.2**	**1742.6**	**1747.2**	**1743.7**
Ploss (MW)	20.766	20.763	20.397	21.185
Voltage Limits	**0.9<Vi<1.1**	**0.9<Vi<1.1**	**0.9<Vi<1.1**	**0.9<Vi<1.1**

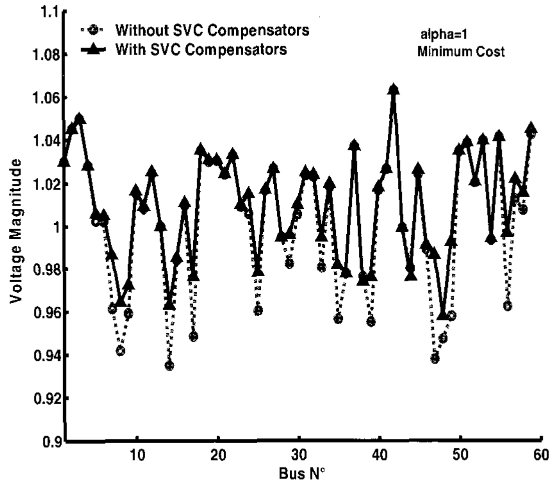

Fig. 9. Voltage Magnitude improvement using SVC Compensators: case α =1; Minimum Cost

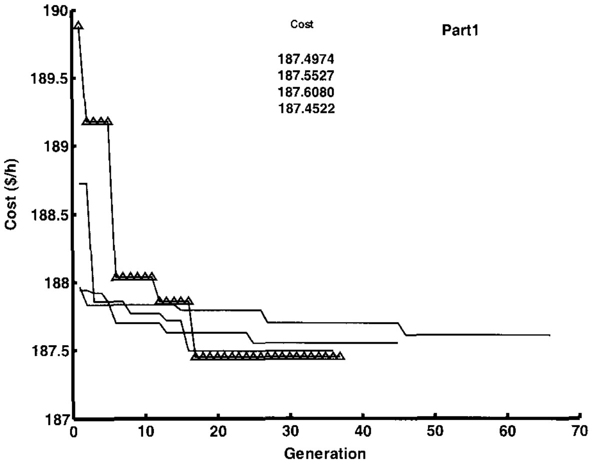

Fig. 10. Convergence of the approach proposed for the first partition: case α =1: Minimum Cost

7. Conclusion

A decomposed parallel GA approach to solve the optimal power flow (OPF) with consideration of environmental constraints and multi dynamic shunt Compensators (SVC) is presented. The main objective of the proposed approach is to improve the performance of the standard GA in terms of reduction time execution for an online application to large-scale power systems. In the first stage, the original network was decomposed in multi sub-systems and the problem transformed to optimize the active power demand associated to each partitioned network, and a global database generated containing the best technical sub-systems. In the second stage, two linked subproblems, namely active power dispatch and reactive power planning, were proposed to enhance the solution of the optimal power flow. The performance of the proposed approach was tested on the Algerian 59-bus test case, the proposed algorithm compared with conventional method and with recent evolutionary algorithms. It was found that the proposed approach can converge at the near solution and obtain a competitive solution at a reduced time.

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