Optimal Power Flow with Discontinous Fuel Cost Functions Using Decomposed GA Coordinated with Shunt FACTS

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Abstract – This paper presents efficient parallel genetic algorithm (EPGA) based decomposed network for optimal power flow with various kinds of objective functions such as those including prohibited zones, multiple fuels, and multiple areas. Two coordinated sub problems are proposed: the first sub problem is an active power dispatch (APD) based parallel GA; a global database generated containing the best partitioned network: the second subproblem is an optimal setting of control variables such as generators voltages, tap position of tap changing transformers, and the dynamic reactive power of SVC Controllers installed at a critical buses. The proposed approach tested on IEEE 6-bus, IEEE 30-bus and to 15 generating units and compared with global optimization methods (GA, DE, FGA, PSO, MDE, ICA-PSO). The results show that the proposed approach can converge to the near solution and obtain a competitive solution with a reasonable time.

Keywords: Parallel Genetic Algorithm, Decomposed Network, System loadability, FACTS, SVC, Optimal power flow, Planning and control

1. Introduction

The optimal power flow (OPF) problem, which first introduced in 1960 by Carpentier, is an important and powerful tool for power system operation and control [1].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. A number of conventional mathematical programming methods have been proposed to solve the OPF problem. Many of these methods require objective function and constraints have linear relationship, which may lead to loss accuracy [2].

In the literature [3] many researches consider the input-output characteristics as quadratic functions to solve the economic dispatch (ED). However, real input-output characteristics of the source units display higher-order nonlinearities and discontinuities due to valve-point loading in fossil fuel burning plants [4], the prohibited operating zones which can be due to vibrations in a shaft bearing caused by a steam value or can be generated by faults in the machines themselves or the auxiliary equipments. The inclusion of valve-point loading effects makes the modelling of the fuel cost function of the generators more practical. This increases the non-linearity as well as number of local optima in the solution space. In recent years stochastic and heuristic optimizations techniques such as Genetic Algorithm (GA), Evolutionary programming (EP), Differential Evolution (DA), Power Swarm Optimization, and Ant Colony have emerged as efficient tools for global optimization and have been successfully used to overcome the non-convexity problems of the constrained ED [5].

The GA method has usually 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. The main disadvantage of GAs is the high CPU time execution and the qualities of the solution deteriorate with practical large-scale optimal power flow (OPF) problems [5]. To overcome premature convergence and speed up the search process, a simple approach based decomposed parallel genetic algorithm implemented with Matlab program to minimize the total non-smooth fuel cost function and also to maintain 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 proposed approach over other traditional optimization techniques and global optimization methods have been demonstrated through the results of the IEEE 6-bus, and IEEE 30-bus test system.

2. Optimal Power Flow Formulation

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

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

$$\text{Subject to:} \quad g(x,u)=0 \tag{2}$$

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

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$$x_{\min} \le x \le x_{\max} \quad (4)$$

$$u_{\min} \le u \le u_{\max} \quad (5)$$

where $f(x,u)$ is the objective function and, $h(x,u)$ are respectively the set of equality and inequality constraints. The vector of state and control variables are denoted by x and u respectively. In general, the state vector includes bus voltage angles δ, load bus voltage magnitudes V_L, slack bus real power generation $P_{g,\,slack}$ and generator reactive power Q_g.

$$x = \left[\delta, V_L, P_{g,slack}, Q_g\right]^T \quad (6)$$

The control variable vector consists of real power generation P_g, generator terminal voltage V_g, shunt capacitors/reactors B_{sh}, shunt dynamic compensators (SVC) B_{svc} and transformers tap ratio t.

$$u = \left[P_g, V_g, t, B_{sh}, B_{svc}\right]^T \quad (7)$$

For optimal active power dispatch, the objective function f is total generation cost as expressed follows:

$$Min \quad f = \sum_{i=1}^{N_g} \left(a_i + b_i P_{gi} + c_i P_{gi}^2\right) \quad (8)$$

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 real and reactive power balance equations, expressed as follows:

$$P_{gi} - P_{di} - \sum_{j=1}^{N} V_i V_j \left(g_{ij} \cos\delta_{ij} + b_{ij} \sin\delta_{ij}\right) = 0 \quad (9)$$

and;

$$Q_{gi} - Q_{di} - \sum_{j=1}^{N} V_i V_j \left(g_{ij} \sin\delta_{ij} - b_{ij} \cos\delta_{ij}\right) = 0 \quad (10)$$

Where P_{gi}, Q_{gi} are the active and the reactive power generation at bus i; P_{di}, Q_{di} are the real and the reactive power demands at bus i; V_i, V_j, the voltage magnitude at bus i, j, respectively; δ_{ij} is the admittance angle, g_{ij} and b_{ij} are the real and imaginary part of the admittance and N is the total number of buses.

The inequality constraints $h(x,u)$ reflect the security limits, expressed as follows:

- Upper and lower limits on the active power generations:

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \quad (11)$$

- Upper and lower limits on the reactive power generations:

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max}. \quad (12)$$

- Upper and lower bounds on the tap ratio (t).

$$t_{ij}^{\min} \le t_{ij} \le t_{ij}^{\max} \quad (13)$$

- Upper and lower bounds on the shifting (α) of variable transformers:

$$\alpha_{ij}^{\min} \le \alpha_{ij} \le \alpha_{ij}^{\max} \quad (14)$$

- Upper limit on the active power flow (P_{ij}) of line i-j.

$$\left|P_{ij}\right| \le P_{ij}^{\max} \quad (15)$$

- Upper and lower bounds in the bus voltage magnitude:

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (16)$$

- Upper and lower bounds in the Shunt FACTS parameters

$$X^{\min} \le X_{FACTS} \le X^{\max} \quad (17)$$

2.1 Non-smooth cost function with Prohibited operation zones

The prohibited operating zones in the input-output performance curve for a typical thermal unit can be due to robustness in the shaft bearings caused by the operation of steam values or to faults in the machines themselves or in the associated auxiliary, equipment such as boilers; feed pumps etc. [3]-[4]. In practice when adjusting the operation output of a unit one must avoid the operation in the prohibited zones. Thus the input-output performance curve for a typical thermal unit can be represented as shown in Fig. 1.

$$P_i \in \begin{cases} P_i^{\min} \le P_i \le P_{i,1}^{1} \\ P_{i,k-1}^{u} \le P_i \le P_{i,k}^{1}, \quad k = 2, \ldots\ldots, z_i \\ P_{i,z_i}^{u} \le P_i \le P_i^{\max} \end{cases} \quad (18)$$

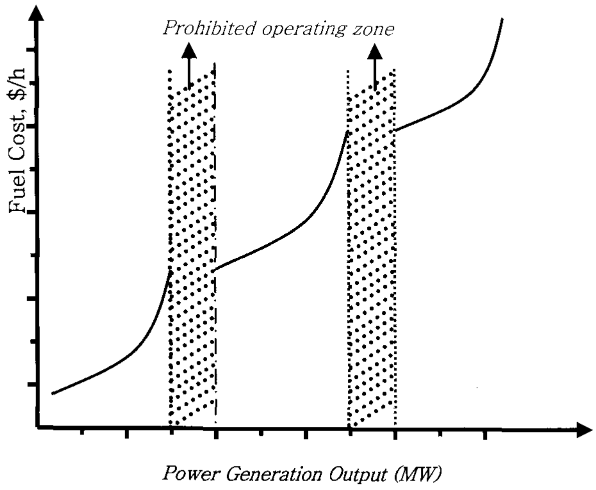

Fig. 1. Input-Output curve with prohibited operating zones

z_i is the number of prohibited zones of unit i;

k is the index of prohibited zones of a unit i;

$P_{i,k}^{l/u}$ is the lower/upper bounds of the kth prohibited zone of unit i;

2.2 Non-smooth cost function with Valve-point loading effects

The valve-point loading is taken in consideration by dding a sine component to the cost of the generating units. Typically, the fuel cost function of the generating units with valve-point loadings is represented as follows [3]:

$$f = \sum_{i=1}^{N_g} \left(a_i + b_i P_{gi} + c_i P_{gi}^2\right) + \left| d_i \sin\left(e_i \left(P_i^{\min} - P_i\right)\right)\right| \quad (19)$$

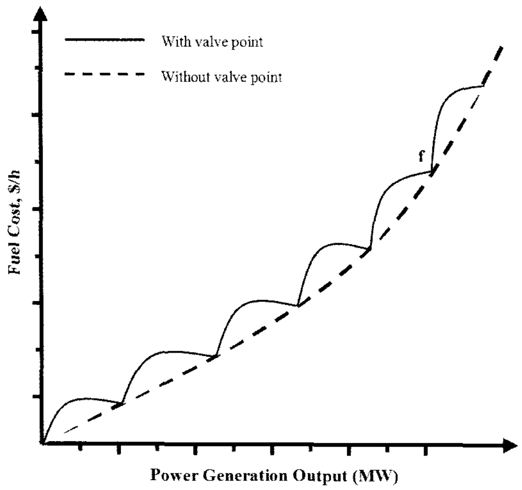

Fig. 2. Input-Output curve under valve-point loading

d_i and e_i are the cost coefficients of the unit with valve-point effects.The input-output performance curve for a typical thermal unit can be represented as shown in Fig 2.

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 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:

$$P_{loss} = \sum_{k=1}^{N_l} g_k \left[(t_k V_i)^2 + V_j^2 - 2 t_k V_i V_j \cos \delta_{ij}\right] \quad (20)$$

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:

$$\Delta V = \sum_{k=1}^{N_{PQ}} \left| V_k - V_k^{des} \right| \quad (21)$$

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 [9] 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 3.

The steady-state control law for the SVC is the typical current-voltage characteristic, illustrated in Fig. 4.

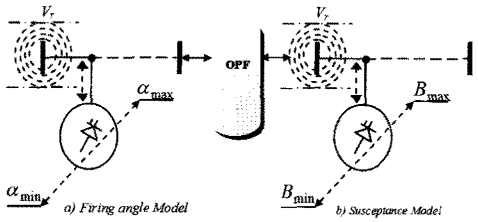

Fig. 3. SVC steady-state circuit representation

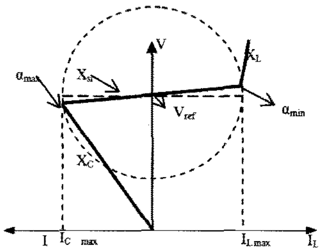

Fig. 4. Typical steady state V-I Characteristics of SVC

5. Strategy of the Proposed Approach

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 [6]-[7].

The proposed algorithm decomposes the solution of such a modified OPF problem into two linked sub problems. The first sub problem is an active power generation planning solved by the proposed Efficient Genetic Algorithm, and the second sub problem is a reactive power planning [5] 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. Fig. 5 shows the principle of the parallel GA optimization approach for EPD.

5.1 Decomposition Mechanism

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

1- How many efficient partitions needed?

2- Where to practice and generate the efficient inter-independent sub-systems?

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

Fig. 6 shows the chromosome structure within the proposed approach. Fig. 7 presents the mechanism of search partitioning.

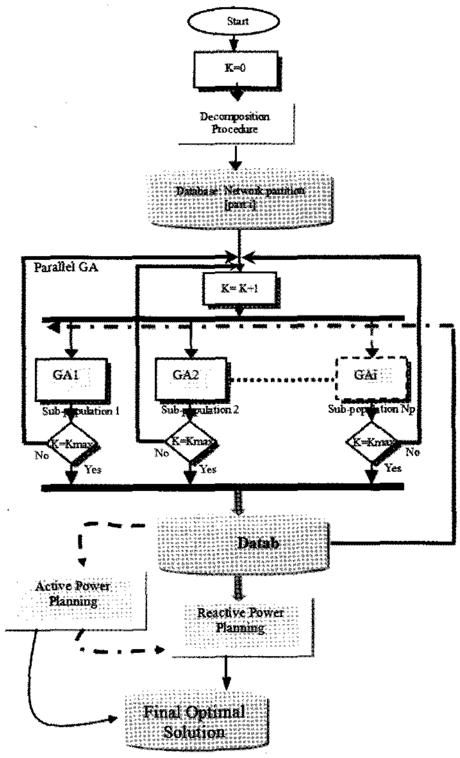

Fig. 5. Procedure of parallel GA optimization approach for EPD

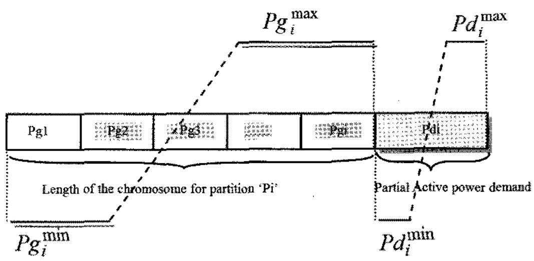

Fig. 6. Chromosome structure

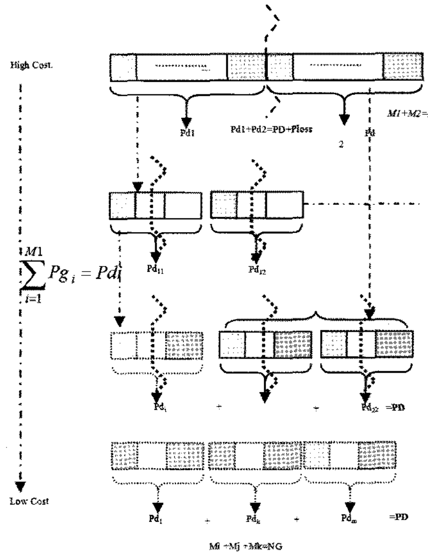

Fig. 7. Mechanism of search partitioning

5.2 Algorithm of the Proposed Approach

5.2.1 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 generated for the 'N' population size.

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

For NP=2 Do

$$Pd1 = \sum_{i=1}^{M1} P_{Gi} \quad (22)$$

$$Pd2 = \sum_{i=1}^{M2} P_{Gi} = PD - Pd1 \quad (23)$$

where NP the number of partitions;
$Pd1$: 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:
At each level 1:

$$Pd1 + Pd2 = PD + Ploss \quad (24)$$

- 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.

$$f_i = 1/\left(F_{\cos t} + \omega_l F_{li} + \omega_V F_{Vi}\right) \quad (25)$$

$$F_{Vi} = \sum_{j=1}^{NPQ} \left(\left|V_{PQij} - V_{PQij}^{\lim}\right|\right) / \left(\left|V_{PQij}^{\max} - V_{PQij}^{\min}\right|\right) \quad (26)$$

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.

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

$$\sum_{i=1}^{N_g} (Pg_i) = \sum_{i=1}^{part_i} (Pd_i) + ploss \quad (27)$$

$$Pg_i^{\min} \le Pg_i \le Pg_i^{\max} \quad (28)$$

5.2.2 Final Search Mechanism

- All the sub-systems are collected to form the original network, global data base generated based on the best results U_{best}^{Parti} of partition 'i' found from all sub-populations.
- The final solution U_{best}^{Global} is found out after reactive power planning procedure to adjust the reactive power generation limits, and voltage deviations, the final optimal cost is modified to compensate the reactive constraints violations. Fig. 7 shows an example of tree network decomposition used to search the global database.

6. Application Study

The proposed algorithm is developed in the Matlab programming language using 6.5 version. The proposed approach has been tested on a three test system; the 6-bus test system, IEEE 30-bus, and to 15 generating units. Three different types of generator cost curves are considered. These are: A quadratic model, a piecewise quadratic model and a quadratic model with sine component. For all application test considered in this paper, the desired precision is $\varepsilon = 10^{-5}$.

6.1 Case study 1: Six-bus test system

The first test system is the standard 6-bus, it consists of 4 generating units, 7 transmission lines and 4 taps-changing transformers, for the voltage constraint the lower and upper limits are 0.95 p.u and 1.05 p.u., respectively for generation buses, and 0.9 to 1.1 p.u for load buses. The GA population size is taken between 10 and 30 based on the size of the decomposed network; the maximum number of generation is 100. Line loadings are 100 MVA for all lines;

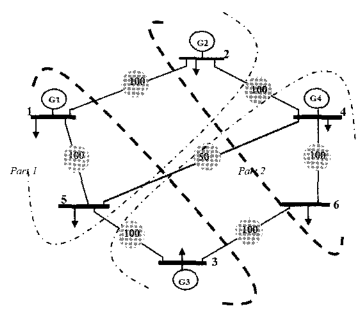

Fig. 8. Topology o the IEEE 6-bus network test

expect line (4-5) whose limit is 50 MVA as shown in Fig 8. The minimum and maximum limits on control variables are taken from [8].

The total cost of the test system obtained with the proposed approach is **7871.7** ($/h) and the power loss is **6.86** (MW) which are better than the others methods reported in the literature. All results obtained by the proposed approach do not violate the physical generation capacity constraints. The security constraints are satisfied for voltage magnitudes **(0.9<V<1.1 p.u)** and line flows ($P_{ij} < P_{ij\,max}$). Table 1, 2 show the results for active power and reactive power generation, voltage and phase angle profile, the details of the comparative study are given in Table 3. It is important to note that the proposed approach has considerably a faster convergence compared to the methods reported in the literature.

Table 1. Optimal power flow solution for IEEE 6-bus Test System without SVC Compensators

	Security Constraints		Generation		Load	
Bus	**Voltage**	**Angle**	**PG(MW)**	**QG(MVar)**	**MW**	**MVAr**
1	1.046	0.000	120.44	59.20	100	20
2	1.049	2.003	189.94	-3.03	100	20
3	1.012	-2.694	115.06	35.76	100	20
4	1.035	-0.210	181.42	47.11	100	20
5	1.005	-2.080	0.00	0.00	100	50
6	0.999	-3.590	0.00	0.00	100	10

Table 2. Line Power Flows solution for IEEE Six-bus test system without SVC Compensators

	Loading Factor λ=1.00 *Without SVC* PD=600 MW		
Line	Rating (MVA)	From Bus P(MW)	Q(MVAr)
1-2	100	-39.59	15.62
1-5	100	60.03	23.58
2-4	100	49.67	-6.57
3-5	100	-7.23	11.73
3-6	100	22.29	4.02
4-5	50	22.29	13.73
4-6	100	80.35	7.16
Total losses MW		**6.860**	

Table 3. Comparison of the Results Obtained with Conventional and Global Methods: Six-bus network test

Generators (MW)		Weber [10]	GA [11]	SA [12]	FGA [8]	Our Approach
P_{g1}	Part1	160.39	152.3252	131.80	140.865	120.44
P_{g2}		133.00	151.6563	190.98	188.025	189.94
P_{g3}	Part2	143.00	118.0913	109.15	100.244	115.06
P_{g4}		169.00	187.0893	178.24	180.205	181.42
Total PG		605.78	609.1621	610.17	609.3390	606.86
PD		600	600	600	600	600
Ploss(MW)		5.38	9.2088	8.83	9.33	**6.860**
Cost[$/hr]		8062.00	7987.1764	7987.1764	7905.9163	**7871.7**
Security constraints Violation		-	-	-	0	**0**
CPU time(s)		-	31	26	-	**~0.775**[a]

[a]. *time given after decomposition procedure convergence (two decomposed network).*

6.2 Case study2: IEEE 30-bus test system

The second test is the standard IEEE 30-bus, it consists of 6 generators production units, 41 transmission lines and 4 taps-changing transformers, 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 between 10 and 30 based on the size of the decomposed network, the maximum number of generation is 100, and crossover and mutation are applied with initial probability 0.9 and 0.01 respectively.

6.2.1 Case 1: Quadratic cost curve model

In this first case the fuel cost characteristics for all generating units are modeled by quadratic cost functions.
For the purpose of verifying the efficiency of the proposed approach, we made a comparison of our approach with others competing OPF algorithm. A non-linear programming method (NLP) [17], an evolutionary programming (EP) [13], a tabu search (TS) algorithm [15], an improved evolutionary algorithm (IEP) [18], and a GA-Fuzzy system approach [8]. The operating cost in our approach proposed is **801.0632** ($/h) and the power loss is **9.20** (MW) which are better than the others methods reported in the literature. Results depicted in Table 4 show clearly that the proposed approach gives better results. The convergence of the three decomposed network are shown in figures (9, 10, and 11).

Table 4. Comparison of the Results Obtained with Conventional and Global Methods: IEEE 30-bus network test: Case 1

Generators (MW)		NLP [17]	EP [13]	IEP [18]	TS [15]	FGA [8]	Our Approach
P_{g1}	Part1	176.26	173.848	176.2358	176.04	175.137	178.34
P_{g2}		48.84	49.998	49.0093	48.76	50.3530	47.14
P_{g5}	Part2	21.51	21.386	21.5023	21.56	21.4510	21.08
P_{g8}		22.15	22.630	21.8115	22.05	21.176	21.74
P_{g11}	Part3	12.14	12.928	12.3387	12.44	12.667	12.14
P_{g13}		12.00	12.000	12.0129	12.00	12.110	12.16
Total PG (MW)		292.90	292.79	292.9105	292.850	292.8940	292.60
PD (MW)		283.4	283.4	283.4	283.4	283.4	283.4
Ploss(MW)		/	/	/	/	**9.494**	**9.200**
Cost[$/hr]		802.40	802.62	802.465	802.29	802.0003	**801.0632**
Security constraints Violation		-	-	-	-	0	**0**
CPU time(s)		-	51.4	594.08	-	-	**~0.950**[a]

[a]. *time given after decomposition procedure convergence (three decomposed network).*

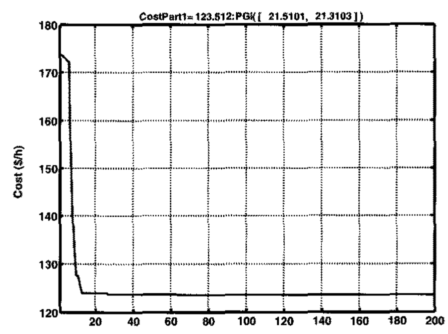

Fig. 9. Convergence of the first decomposed network: **(Part1-case1)**

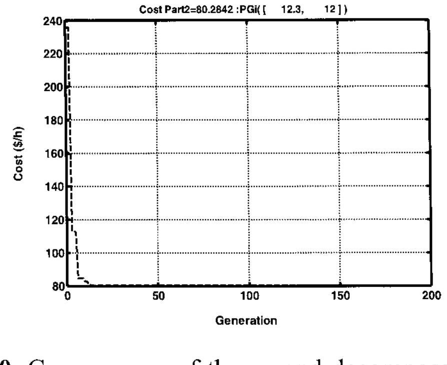

Fig. 10. Convergence of the second decomposed network: **(Part2-case1)**

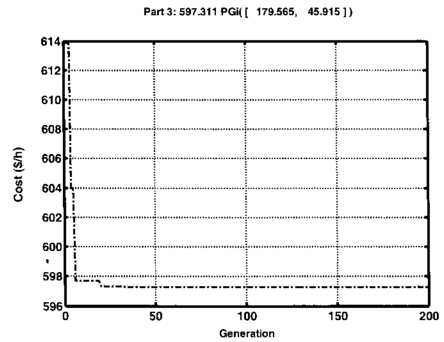

Fig. 11. Convergence of the third decomposed network: **(Part3-case1)**

6.2.2 Case 2: Piecewise quadratic cost curve model

For this second case study, the cost coefficient for the units represented by a piecewise quadratic function are taken from paper [8]. Table 5 presents a summary of the optimization results for the best OPF solution. It can be observed that the minimum cost obtained by the proposed algorithm is near the global optimum solution, the computational time is reduced compared to those given by IEP [18], EP [13], and PSO [13].

Table 5. Comparison of the Results Obtained with Conventional and Global Methods: IEEE 30-bus network test: Case 2

Generators (MW)		EP [13]	PSO[14]	IEP [18]	Our Approach
P_{g1}	Part1	140.00	140.00	139.9962	139.95
P_{g2}		55.00	55.00	54.9849	55.00
P_{g5}	Part2	24.165	24.15	23.2558	23.28
P_{g8}		35.00	35.00	34.2794	34.36
P_{g11}	Part3	18.773	18.51	17.5906	19.16
P_{g13}		17.531	17.79	20.7012	18.85
Total PG (MW)		290.469	290.45	290.8081	290.60
PD (MW)		283.4	283.4	283.4	283.4
Ploss (MW)		/	/	/	**7.204**
Cost[$/hr]		647.79	647.69	649.312	**648.4044**
Security constraints Violation		-	-	-	**0**
CPU time(s)		51.6	-	602.56	**~4.245**

[a]. time given after decomposition procedure convergence (three decomposed network).

6.2.3 Case 3: Quadratic cost curve model with sine component

To improve the robustness of the proposed approach a sinusoidal component is added to the cost curves of the generating units at bus 1 and bus 2 to reflect the valve-point effects [8] as indicated in equation (19).The cost coefficient for the units characterized by the valve-point effect are taken from paper [8]. The best solution found by the proposed algorithm were compared with the results reported using EP [13], TS [15], IPE [18], and MDE [19]. Results depicted in Table 6 show clearly that the proposed approach gives solution to the OPF with respect to the security constraints. The best fuel cost fond by EP [13], TS [15], and FGA [8] violates at least one of the security constraints. It is important to note that the proposed approach has considerably a faster convergence which confirms the ability of the proposed approach to find efficient OPF solutions with consideration of the effects of multiple valve-points.

Table 6. Comparison of the Results Obtained with Conventional and Global Methods: IEEE 30-bus network test: Case 3

Generators (MW)		EP [13]	TS[15]	IEP [18]	MDE [19]	Our Approach
P_{g1}	Part1	199.60	200.00	149.7331	197.426	199.24
P_{g2}		20.00	39.65	52.0571	52.037	49.94
P_{g5}	Part2	22.204	20.42	23.2008	15.000	13.40
P_{g8}		24.122	12.47	33.4150	10.000	10.42
P_{g11}	Part3	14.420	10.00	16.5523	10.001	10.36
P_{g13}		13.001	12.00	16.0875	12.000	12.02
Total PG (MW)		293.3470	294.54	291.0458	296.464	295.38
PD (MW)		283.4	283.4	283.4	283.4	283.4
Ploss(MW)		-	-	-	13.064	**11.977**
Cost[$/hr]		919.89	919.72	953.573	930.793	**928.9851**
Security constraints Violation		2	1	-	0	**0**
CPU time(s)		-	-	-	41.85	**~8.245**

[a]. time given after decomposition procedure convergence (three decomposed network).

6.3 Efficient Reactive Power Dispatch witht SVC Compensators

In this second step shunt compensation taken in 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. The minimum and maximum limits on control variables are shown in Fig. Table 7 gives details of the SVC Data.

Table 7. SVCs data

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

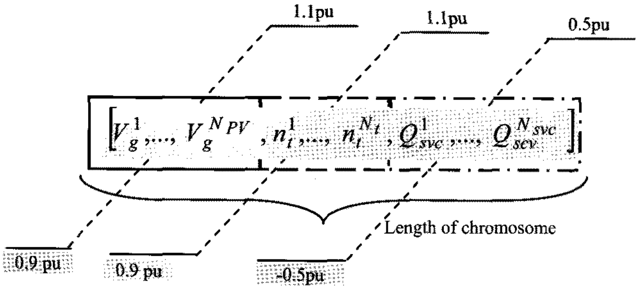

Fig. 12. Chromosome structure for reactive power dispatch

Table 8. Results of the Reactive power Dispatch of the Multi-SVC Installation: Three cases

N	Nsvc	Case 1 QSVC (Mvar)	Case 1 Qg (Mvar)	Case 2 QSVC (Mvar)	Case 2 Qg (Mvar)	Case 3 QSVC (Mvar)	Case 3 Qg (Mvar)
1	10	15.1747	-3.62	15.3125	5.01	15.4812	-7.95
2	12	7.8125	-3.58	7.8834	-11.39	7.9703	-0.90
5	15	2.9488	29.70	2.9756	28.36	3.0084	32.78
8	17	4.8461	37.19	4.8901	29.89	4.9440	41.56
11	21	6.0209	-2.15	6.0756	-2.43	6.1426	-2.22
13	23	3.7594	12.14	3.7935	11.28	3.8354	11.90
-	24	4.4839	-	4.5246	-	4.5745	-
-	29	2.4475	-	2.4698	-	2.4970	-
Pg1, slack MW		178.07		139.36		198.12	
Ploss MW		8.929		6.613		10.862	
Cost ($/hr)		800.1624		647.1674		929.5544	
Voltage limits		0.95<Vi<1.1		0.95<Vi<1.1		0.95<Vi<1.1	
P_{ij} (MW)		$< P_{ij}^{\max}$		$< P_{ij}^{\max}$		$< P_{ij}^{\max}$	

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. 12.

Table 8 shows results of dynamic reactive power compensators using SVC Controllers for the three cases, the active power loss reduced for the three cases, and the voltage profile enhanced compared to the base case.

6.4 Case Study 3: 15 Unit-System with Prohibited Zones

This case study consisted of 15 thermal units of generation with the effects of valve-point loading, the complexity and nonlinearity to the solution procedure is increased. The expected power demand to be met by the all fifteen generating units is 2650 MW without considering power loss. The detail parameters of the system can be retrieved from [24].

The final fuel costs obtained using the ICA-PSO [25], and the proposed approach for power demand of 2650 MW were summarized in Table 9, which shows that the minimum cost value obtained by the proposed approach is comparatively less compared to the ICA-PSO proposed in [25]. Table 10 shows a comparison of the proposed approach with others methods cited in [25] in terms of minimum generation cost, and average computational time. Clearly, the proposed approach has always better solutions than those of the others methods.

Table 9. Results of the Minimum Cost and Power Generation Compared with ICA-PSO for 15-Generation Units with Prohibited Zones: PD=2650 MW

Generators (MW)		ICA-PSO [25]	Our Approach
P_{g1}	Part1	455.00	455.0000
P_{g2}		420.00	455.0000
P_{g3}		130.00	130.0000
P_{g4}	Part2	130.00	130.0000
P_{g5}		260.00	255.1557
P_{g6}		430.00	460.0000
P_{g7}	Part3	465.00	465.0000
P_{g8}		60.00	60.0000
P_{g9}		25.00	25.0000
P_{g10}	Part4	62.60	25.0000
P_{g11}		80.00	80.0000
P_{g12}		77.40	54.8443
P_{g13}	Part5	25.00	25.0000
P_{g14}		15.00	15.0000
P_{g15}		15.00	15.0000
Total Output (MW)		2650.00	2650.00
Cost ($/h)		**32480.91**	**32472.0**
Ploss (MW)		0	0

Table 10. Comparison of EPGA with other Global Optimization Methods

Methods	*Minimum Cost($/h)*	*Average CPU time (s)*
ICA-PSO [25]	*32480.91*	*27.3760*
DSGE [25]	*32545.00*	-
IGAMU [25]	*32506.33*	-
ESO [25]	*32507.67*	-
Our Approach	***32472.00***	***2.7660***[a]

[a]. *time given after decomposition procedure convergence (five decomposed network).*

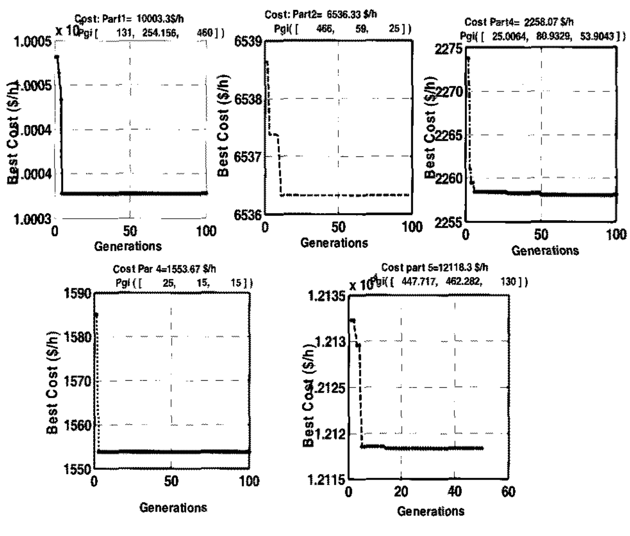

Fig. 13. Convergence of the five decomposed electrical network for 15 generating units

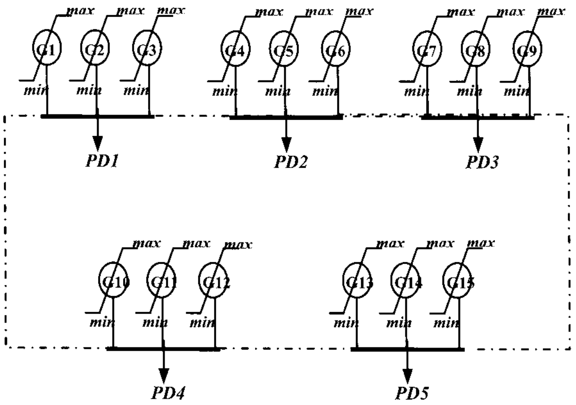

Fig. 14. The five decomposed electrical network for 15 generating units

7. Conclusion

Application of an efficient decomposed parallel GA to enhance the OPF solution with consideration of three different kinds of fuel cost function in the presence of multi Shunt FACTS devices is demonstrated in this paper. Two linked sub problems proposed: 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, a global database generated containing the best technical sub-systems. In the second stage a reactive power dispatch proposed to enhance the solution of the optimal power flow.

The performance of the proposed approach was tested on the 6-bus test case, IEEE 30-bus test system, and to the 15 generating units, the simulation results of the proposed algorithm compared with conventional method and with recent global optimization methods. It is observed that the proposed approach is capable of finding the near global solutions of non-linear, non-smooth, and non-differentiable objective functions and obtain a competitive solution at a reduced time.

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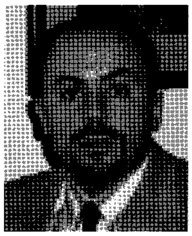

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