Unit Commitment and Economic Load Dispatch using Self Adaptive Differential Evolution

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Abstract: - Unit Commitment (UC) and Economic load dispatch (ELD) are significant research applications in power systems that optimize the total production cost of the predicted load demand. The UC problem determines a turn-on and turn-off schedule for a given combination of generating units, thus satisfying a set of dynamic operational constraints. ELD optimizes the operation cost for all scheduled generating units with respect to the load demands of customers. The first phase in this project is to economically schedule the distribution of generating units using Genetic Algorithm (GA) and the second phase is to determine optimal load distribution for the scheduled units using Self Adaptive Differential Evolution (SADE) algorithm. GA is applied to select and choose the combination of generating units that commit and de-commit during each hour. These pre-committed schedules are optimized by SADE thus producing a global optimum solution with feasible and effective solution quality, minimal cost and time and higher precision. The effectiveness of the proposed techniques is investigated on two test systems consisting of six and ten generating units and the experiments are carried out using MATLAB R2008b software. Experimental results prove that the proposed method is capable of yielding higher quality solution including mathematical simplicity, fast convergence, diversity maintenance, robustness and scalability for the complex UC-ELD problem.

Keywords : - Unit Commitment, Economic load dispatch, Genetic Algorithm, Self Adaptive Differential Evolution, computational time, IEEE 30 bus system.

1. Introduction

The Unit Commitment (UC) and Economic Load Dispatch (ELD) [1] are well known problems in the power industry and have the potential to save millions of dollars per year in fuel and related costs. This problem is a complex decision-making process and it is difficult to develop any rigorous mathematical optimization methods capable of solving the UC-ELD problem for any real-size system. Also, multiple constraints should be imposed which must not be violated while finding the optimal or near-optimal solution. Hence, classical methods like Newton's method [2], gradient search method [3], and Lagrangian Relaxation [4, 5] are not preferred for solving practical UC-ELD problems.

Nature and Bio-inspired techniques are successful nowadays due to their inherent capability of processing a population of potential solution simultaneously, which allows them to perform an extensive search space thus arriving at an optimal solution. Modern heuristic methods like Evolutionary Programming [6], Tabu search [7], Simulated Annealing [8] and Fuzzy Logic [9] are successful in locating the optimal solution for the ELD problem, but they are usually slow in convergence and require heavy computational cost. Also, these methods may get trapped to a local optimum, which is the problem of premature convergence.

In this paper, GA-SADE algorithm is applied to solve the Unit Commitment and Economic Load Dispatch problems. The UC problem determines a turn-on and turn-off schedule for a given combination of generating units, thus satisfying a set of dynamic operational constraints using GA. ELD optimizes the operation cost for all scheduled generating units with respect to the load demands of customers using SADE. The proposed algorithm is evaluated in terms of total fuel cost, execution time, mean cost, robustness and algorithmic efficiency. The significance of this approach is to obtain a least cost solution for the UC-ELD problem.

The paper is organized as follows: Section 2 details a brief literature survey of ELD and UC problems using Differential Evolution algorithms. The mathematical formulation of the UC and ELD problems along with the constraints are given in Section 3. The implementation of GA and SADE for solving the problem under consideration is delineated in Section 4. Experimental results for two test systems are tabulated and enlightened in Section 5. Section 6 draws the concluding remarks and future expansions of this work.

2. Literature Survey

Differential Evolution (DE) is a heuristic optimization technique proposed by Storn and Price [10] to reveal consistent and reliable performance in non-linear and multimodal environment. They have proved to be efficient for constrained optimization problems [11]. In [12], the authors proposed the classical DE for solving ELD problems with specialized constraint handling mechanisms. Khamsawang et. Al.,[13] proposed the original DE for ELD with regenerated population technique and tuning of parameters. Wang et. Al., [14] used the concept of the 1/5 success rule of evolutionary strategies in the original Hybrid DE (HDE) to accelerate the search for the global optimum in ELD problems. The need for fixed and random scale factors in HDE was overcome by the work of Chiou et. Al., [15], in which a variable scaling factor was added to HDE thus improving the search for the global solution for ELD problems.

Mariani et. Al., [16] proposed a hybrid technique that combined the differential evolution algorithm with the generator of chaos sequences and sequential quadratic programming technique. Aniruddha et. Al., [17] offered a hybrid combination of DE with BBO to accelerate the convergence speed and to improve the quality of the ELD solutions. During 2007, R.Balamurugan et Al. [18] presented a Self-Adaptive Differential Evolution Based Power Economic Dispatch of Generators with Valve-Point Effects and Multiple Fuel Options. Ali Keles in [19], has reported the results of experiments performed on a series of the UCP test data using the binary differential evolution approach combined with a simple local search mechanism. S. Patra et Al. [20] developed a DE approach for solving the UC problem using binary and integer code. It was observed that both the techniques converged towards the same optimal solution with different number of generations.

In all the literatures listed, either the Unit Commitment or the Economic Load Dispatch problem is solved individually. Solving UC-ELD problems using hybrid techniques generates a complete solution for the real time power system thereby justifying the advantages of the proposed techniques. In this paper, GA-SADE is applied to solve the UC-ELD problem. To alleviate the disadvantages of the algorithms explained in the literature, a combination of GA and PSO is adopted. The Genetic algorithm is used to solve the UC problem. From results of the UC procedure, ELD problem is solved using the SADE algorithm for the generating units available online.

3. Mathematical Formulation

The ideal method of solving the generator scheduling problem involves an exhaustive trial of all the possible solutions and then choosing the best amongst these solutions. This straightforward method would test all combinations of units that can supply the load and reserve requirements. The combination that has the least operating cost is taken as the optimal schedule. This enumerative process is guaranteed to find the optimal solution but the solution must be obtained within a time that makes it useful for the intended purpose. Even when the problem is highly constrained, the efficiency of the solution is poor except for the simplest of cases [21].

The generator scheduling problem involves the determination of the start up/shut down times and the power output levels of all the generating units at each time step, over a specified scheduling period *T*, so that the total start up, shut down and running costs are minimized subject to system and unit constraints.

The major component of the operating cost for thermal units is the power production cost of the committed units that is conventionally taken in a quadratic form. The fuel cost, FC_i per unit in any given time interval is a function of the generator power output as given in Equ. 1.

$$F_T = \sum_{i=1}^{n} F_i(P_i) = \sum_{i=1}^{n} a_i + b_i P_i + c_i P_i^2 \text{ \$/Hr} \qquad (1)$$

where a_i, b_i, c_i represents unit cost coefficients, and P_i is the unit power output.

The start-up cost (SC) depends upon the down time of the unit, which can vary from maximum value, when the unit is started from cold state, to a much smaller value, if the unit was turned off recently. The start-up cost calculation depends also on the treatment method for the thermal unit during down time periods. It can be represented by an exponential cost curve as shown in Equ. 2.

$$SC_i = \sigma_i + \delta_i * \{1 - \exp(-T_{off} / \tau_i)\} \quad (2)$$

where σ_i is the hot start up cost, δ_i the cold start up cost, τ_i the unit cooling time constant and T_{off}, is the time at which the unit has been turned off.

The total production cost, F_T for the scheduling period is the sum of the running cost, start up cost and shut down cost for all the units is as shown in Equ. 3

$$F_T = \sum_{t=1}^{T} \sum_{i=1}^{N} FC_{i.t} + SC_{i,t} + SD_{i,t} \quad (3)$$

where N is the number of generating units and T is the number of different load demands for which the commitment has to be estimated. The shut down cost, SD is usually a constant value for each unit. The overall objective is to minimize F_T subject to a number of constraints as follows:

(i) System hourly power balance is given in Equ. 4, where the total power generated must supply the load demand (P_D) and system losses (P_L).

$$\sum_{i=1}^{N} P_i u_i - (P_D + P_L) = 0 \quad (4)$$

(ii) Hourly spinning reserve requirements (R) must be met. This is mathematically represented using Equ. 5.

$$\sum_{i=1}^{N} P_i^{\max} u_i - (P_D + P_L) = R \quad (5)$$

(iii) Unit rated minimum and maximum capacities must not be violated. The power allocated to each unit should be within their minimum and maximum generating capacity as shown in Equ. 6. $P_i^{\min} \le P_i \le P_i^{\max}$ (6)

(iv) The initial states of each generating unit at the start of the scheduling period must be taken in to account.

(v) Minimum up/down (*MUT/MDT*) time limits of units must not be violated. This is expressed in Equ. 7 and Equ. 8 respectively.

$$(T_{t-1,i}^{on} - MUT_i) * (u_{t-1,i} - u_{t,i}) \ge 0 \quad (7)$$

$$(T_{t-1,i}^{off} - MDT_i) * (u_{t,i} - u_{t-1,i}) \ge 0 \quad (8)$$

where T_{off} / T_{on} is the unit off / on time, while $u_{t,i}$ denotes the unit off / on [0,1] status.

The principal objective of the economic load dispatch problem is to find a set of active power delivered by the committed generators to satisfy the required demand subject to the unit technical limits at the lowest production cost. The optimization of the ELD problem is formulated in terms of the fuel cost expressed as,

$$F_T = \sum_{i=1}^{n} F_i(P_i) = \sum_{i=1}^{n} a_i + b_i P_i + c_i P_i^2 \quad (9)$$

Subject to the equality constraint,

$$\sum_{i=1}^{N} P_i = P_D + P_L \quad (10)$$

Subject to the inequality constraint,

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

4. Solving UC-ELD using GA and SADE

Genetic Algorithm and Self Adaptive Differential Evolutionary Algorithms are optimization techniques based on the concept of a population of individuals that evolve and improve their fitness through probabilistic operators like recombination and mutation. This section presents an algorithm for solving UC-ELD problem through the application of GA-SADE which results in high quality of solution and good computational performance. The UC problem is solved using Genetic algorithm that generates the schedule of each unit. Self Adaptive Differential Evolution algorithm solves the Economic Load Dispatch problem for generating units that distribute the load demand among the online units. As most utilities demand, a practical optimization technique should fulfill three requirements i.e., it should be capable of finding near global minimum, should converge very fast and should have minimum number of control parameters. Genetic Algorithm fulfills the first requirement whereas SADE has the advantage of satisfying the second and third requirement. This has urged to hybridize GA and SADE by exploiting their advantages. In SADE, the initial population is represented by trial vectors consisting of the real power output of each committed unit. The step by step procedure is as follows:

***Step* 1:** Read the input data that include generator limits, cost coefficients and forecasted load demand. Initialize the variables of GA including population size, selection type, crossover rate, mutation rate and total number of generations and SADE parameters like population member, crossover probability constant, step size (F), lower bound of F control parameter, upper bound of F control parameter, probability to adjust step size and maximum number of iterations.

***Step* 2:** Generate the initialization of unit schedule population that include the random chromosome consisting of ones and zeros where 'one' represents on status and 'zero' represents off status of the unit.
***Step* 3:** Calculation the total fuel cost including constraints.
***Step* 4:** Calculate the fitness function for the current population members based on Equ. 12.

$$f(x)=\sum_{i=1}^{N}F_iP_i+k_1(\sum_{i=1}^{N}P_i-P_L-P_D)^2+k_2\left(\sum_{i=1}^{N}V_i^R\right) \quad 12)$$

where P_L is the power loss; P_D is the power demand and V_i^R reckons the violation of the prohibited zone constraints for the individual i, and is defined as shown in Equ. 13.

$$V_i^R=\begin{cases}1 \ , & if \ \ P_i \ \ violates\ the\ \ prohibited\ zones \\ 0 \ , & otherwise\end{cases} \quad (13)$$

In Equ. 12, k_1 and k_2 are penalty factors associated with power balance and prohibited constraints, respectively. For the ELD problems with transmission loss and prohibited zone constraints these factors are tuned empirically and their values were set as $k_1 = 1$ and $k_2 = 5 * N$ in all cases.
***Step* 5:** The current population is rated according to their fitness and the best chromosomes are retained for the next generation.
***Step* 6:** Apply the crossover operation to the current population to complete the new population.
***Step* 7:** Apply the flip bit mutation operator to the members of the new population.
***Step* 8:** Steps 2 to 7 are repeated until an optimized solution is obtained. The result obtained in the final iteration is the Unit Commitment solution which generates the on/off status of each unit for the specified load demand.
***Step* 9:** The problem variables to be determined are represented as a n-dimensional trial vector, where each vector is an individual of the population to be evolved.
***Step* 10:** An initial population of parent vectors, Qi, for i=1,2,…Np, is selected at random from the feasible range in each dimension. The distribution of these initial parent vectors is uniform.
***Step* 11:** Calculate the fitness value of each individual in the population using the evaluation function given by Equ. 12.
***Step* 12:** An offspring (Qi') is generated from the parent by using Equ. 14 and Equ. 15 through mutation and crossover.

$$v_i = P_{i,G}+\lambda*(P_{best,G}-P_{i,G})+F*(P_{r2,G}-P_{r3,G}) \quad (14)$$

where v_i is the donor vector, $P_{i,G}$ is the individual, mutation factor F is Self Adaptive, r2 and r3 are random numbers. The idea behind the introduction of the additional control variable λ is to provide a means to enhance the greediness of the scheme by incorporating the current best vector

$$u_{j,i,G+1}=\begin{cases} v_{j,i,G+1} & if \ \ rand_{j,i}\le CR \ \ or \ \ \ j=I_{rand} \\ P_{j,i,G+1} & if \ \ rand_{j,i}\ge CR \ \ and \ \ \ j\ne I_{rand}\end{cases} \quad (15)$$

where i=1, 2, …, NP , j=1, 2, …, n, $rand_{j,i} \sim U[0,1]$, I_{rand} is a random integer from [1,2, …, n], CR is crossover factor defined between [0,1], .
***Step* 13:** Fitness function is evaluated for each individual of both parent and child populations.
***Step* 14:** Comparison is made between Np parents and Np offspring and better ones are chosen as the target vector (new parent vectors) in the next generation.
***Step* 15:** If current generation is greater than or equal to the maximum generation, print the result and stop; otherwise repeat the steps 11 to 15.
Thus by following the above procedure, a pareto-optimal solution is obtained for the UC-ELD problem.

5. Experimental Results

Experimental analysis is carried out with the goal of verifying or establishing the accuracy of a hypothesis. In this section, the simulation results of the proposed hybrid algorithms to optimize the Unit Commitment (UC) and Economic Load Dispatch (ELD) problem is discussed. The main objective of UC-ELD problem is to obtain minimum cost solution while satisfying various equality and inequality constraints. The effectiveness of the proposed algorithm is tested on a six unit IEEE 30 bus system and a ten unit power system. The costs incurred by each unit, fuel cost per hour, total and mean fuel costs per day, total execution time, mean time and algorithmic efficiency are evaluated. The algorithms are implemented in Turbo C and MATLAB R2007a platform on Intel dual core, 2.4 GHz, 1 GB RAM personal computer.

The control parameters for Genetic Algorithm include population size, selection type, crossover rate, mutation rate and total number of generations (Table 1). The population size decides the number of chromosomes in a single generation. A larger population size slows down the GA run, while a smaller value leads to exploration of a small search space. A reasonable range of the population size is between [20,100], based on the real valued encoding procedure in this work, the population size was set to

28. Single point crossover was used in this project with a crossover probability of 0.6 thus maintaining diversity in the population. The mutation type applied was flip bit with a mutation rate of 0.001. This value of mutation decreases the diversity of subsequent generations. A flip bit mutation changes the status of a unit from on to off or vice versa.

Table 1 GA Parameters

S.NO.	PARAMETER	VALUE
1	Maximum number of generations	2000
2	Population Size	28
3	Selection method	Roulette wheel
4	Crossover rate	0.6
5	Mutation rate	0.001

The parameters for Self Adaptive Differential Evolution are population size, crossover probability constant, step size (F), lower bound of F control parameter, upper bound of F control parameter, probability to adjust step size and maximum number of iterations. Population size is a critical choice for the performance of SADE because of its one-to-one reproduction strategy. Storn and Price [22] suggested a larger population size (between 5N and 10N, where N is the number of generating units) for SADE. However, for a given maximum number of function evaluations, smaller population size can be useful and hence the population size was set to 20.

Table 2 SADE Parameters

S.NO	PARAMETER	VALUE
1	Number of population member	20
2	Crossover probability constant	0.8
3	Step size (F)	Self adaptive
4	Lower bound of F control parameter	0.1
5	Upper bound of F control parameter	0.9
6	Probability to adjust step size	0.8
7	Maximum number of iterations	400

The crossover probability constant was set to 0.8. If the child chromosome is less fit than the parent chromosome, it will be eliminated in the subsequent generation. Hence the selection of crossover value is as specified to obtain better individuals. The step size in SADE is Self Adaptive i.e., it changes for every generation. To control the value of step size, the lower bound and upper bound control parameter F was set to 0.1 and 0.9 respectively. The probability to adjust the step size was set to 0.8. The maximum number of iterations was set to 400 where the solution converges. The control parameters of SADE and their settings are shown in Table 2.

5.1 IEEE 30 Bus System

The Six-unit test system chosen in this experiment is the IEEE 30 bus system [22] in which cost coefficients of the generating units, generating capacity of each unit and transmission, loss matrix and 24 hours power demand requirements are specified. The test system comprises of 6 generators, 41 transmission lines and 30 buses. The IEEE 30 bus system has a minimum generation capacity of 117 MW and a maximum generation capacity of 435 MW. The Load demand for 24 hours and the characteristics of the Six- unit test system are detailed in Table 3 and Table 4 respectively.

Table 3 24-Hours Load Demand for Six-unit test system

Hour	Load (MW)	Hour	Load (MW)
1	166	13	170
2	196	14	185
3	229	15	208
4	267	16	232
5	283.4	17	246
6	272	18	241
7	246	19	236
8	213	20	225
9	192	21	204
10	161	22	182
11	147	23	161
12	160	24	131

Table 4 Generator Characteristics of Six-unit test system

UNITS	PARAMETERS				
	A ($/W-h^2)	B ($/W-h)	C ($)	Min Power (MW)	Max Power (MW)
1	.00375	2	0	50	200
2	.01750	1.75	0	20	80
3	.06250	1	0	15	50
4	.00834	3.25	0	10	35
5	.02500	3	0	10	30
6	.02500	3	0	12	40

The transmission loss coefficients of the test system are given in Eqn. 16,

$$B_{mn} = \begin{bmatrix} 0.000218 & 0.000103 & 0.000009 & -.000010 & 0.000002 & 0.000027 \\ 0.000103 & 0.000181 & 0.000004 & -.000015 & 0.000002 & 0.000030 \\ 0.000009 & 0.000004 & 0.000417 & -.000131 & -.000153 & -.000107 \\ -.000140 & -.000015 & -.000131 & 0.000221 & 0.000094 & 0.000050 \\ 0.000002 & 0.000002 & -.000153 & 0.000094 & 0.000243 & 0.000000 \\ 0.000027 & 0.000030 & -.000107 & 0.000050 & 0.000000 & 0.000358 \end{bmatrix} \quad (16)$$

5.2 Solution for IEEE 30 bus system

Unit Commitment solution is obtained using Genetic Algorithm by applying the control parameters as explained. The on/off (1/0) status of the Six-generating units for 24 hours load demand are determined and tabulated in Table 5. For each hour, load demand varies and hence the commitment of the units also varies. From the Table, it is clear that the unit P1 is ON for 24 hours because this unit generates power with minimum fuel cost as the value of coefficient ‘A’ is minimum for this unit. The computational time required to commit and decommit the units is recorded and results show that GA has a much faster convergence rate in solving the UC problem.

Table 5 Commitment of Units using GA for Six-unit test system

Hr	P_D (MW)	COMBINATION OF UNITS						CT (s)
		P1	P2	P3	P4	P5	P6	
1	166	1	0	1	1	0	1	1.21
2	196	1	0	1	1	1	1	1.33
3	229	1	0	1	1	1	1	1.25
4	267	1	1	1	1	1	0	1.24
5	283.4	1	1	1	1	1	0	1.31
6	272	1	1	1	1	1	0	1.28
7	246	1	1	1	1	1	0	1.34
8	213	1	1	1	1	1	0	1.24
9	192	1	1	1	1	0	0	1.26
10	161	1	1	1	0	0	0	1.29
11	147	1	1	0	0	0	0	1.33
12	160	1	1	0	0	0	0	1.35
13	170	1	1	0	0	0	0	1.34
14	185	1	1	0	0	0	0	1.26
15	208	1	1	0	0	0	0	1.22
16	232	1	1	1	0	0	0	1.27
17	246	1	1	1	0	0	1	1.22
18	241	1	1	1	0	0	1	1.26
19	236	1	1	1	0	0	1	1.37
20	225	1	1	1	0	0	1	1.22
21	204	1	1	1	0	0	1	1.24
22	182	1	1	1	0	0	1	1.29
23	161	1	1	1	0	0	1	1.31
24	131	1	1	1	0	0	0	1.26

Units P5 and P6 is OFF for most of the hours because the value of fuel cost coefficient is the maximum for these two units and hence the operating cost to generate power using these units is expensive when compared to other units. Thus the Unit Commitment using GA provides a cost effective solution by choosing the appropriate units for the forecasted load demand.

The ELD results computed using SADE for 24 hours is shown in Table 6. For each hour, the load demand varies between a minimum of 131 MW and a maximum of 283.4 MW. The ELD using SADE computes the power to be shared by units P1 to P6 for each load demand. A load demand of ‘0’ indicates that the unit is OFF.

Table 6 ELD results using SADE for six unit system

HOURS (h)	Power generated / unit (MW)					
	P1	P2	P3	P4	P5	P6
1	65.0905	0	41.0369	22.0266	0	39.8070
2	106.7262	0	42.9732	10	0	40
3	133.1112	0	15	15.8135	30	40
4	101.9565	80	43.4002	17.3732	30	0
5	136.2096	47.7649	48.8011	28.4165	28.7805	0
6	99.2443	80	43.7230	24.5987	30	0
7	102.0776	55.6852	42.0612	20.7715	30	0
8	71.9782	79.2974	15	20.4389	30	0
9	65.5326	80	40.2710	10	0	0
10	130.4511	20	15	0	0	0
11	101.6332	49.0823	0	0	0	0
12	112.7287	51.7271	0	0	0	0
13	121.2957	53.7789	0	0	0	0
14	134.1992	56.8852	0	0	0	0
15	154.1097	61.7165	0	0	0	0
16	141.6968	62.5783	35.2635	0	0	0
17	130.5494	62.9850	35.4860	0	0	24.0175
18	139.2623	61.9870	35.1698	0	0	12
19	119.5776	60.9924	34.8552	0	0	26.7946
20	117.2032	58.8156	34.1686	0	0	20.6334
21	98.5491	54.7028	32.8784	0	0	22.3769
22	86.2730	50.4533	31.5550	0	0	17.2989
23	75.0588	46.4517	30.3177	0	0	12
24	98.7269	20	15	0	0	0

The contribution of power by each unit per day is graphically depicted using Fig. 1. It can be seen that unit P1 which has the minimum cost fuel function contributes the maximum power thus producing a low cost ELD solution.

The total fuel cost for each power demand and the computational time of the SADE algorithm is shown in Table 7. From the table, it can be inferred that the operating cost is proportional to the load demand. The minimum fuel cost is \$ 297.43 for a load demand of 131 MW and the maximum fuel cost amounts to \$ 798.02 for a load demand of 283.4 MW.

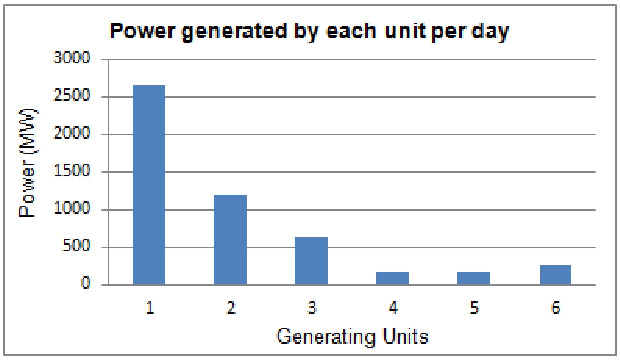

Fig. 1. Contribution of power per unit using SADE for six unit system

Table 7 Operating cost and Computational time using SADE for six unit system

Hour	Demand (MW)	Operating Cost ($)	Time (sec)
1	166	440.14	3.26
2	196	536.19	3.48
3	229	647.57	3.33
4	267	739.83	3.52
5	283.4	798.02	3.33
6	272	757.41	3.33
7	246	668.69	3.51
8	213	559.82	3.22
9	192	492.67	3.21
10	161	380.84	3.51
11	147	354.62	3.75
12	160	392.61	3.62
13	170	422.57	3.67
14	185	468.7	3.83
15	208	542.23	3.10
16	232	600.27	3.13
17	246	646.58	3.27
18	241	630.04	3.35
19	236	613.67	3.19
20	225	578.23	3.26
21	204	512.53	3.26
22	182	446.61	3.27
23	161	386.42	3.28
24	131	297.43	3.24

Analysis of Table 7 reveals that the total operating cost incurred per day totals to $ 12913.69 and the mean cost per day is $ 538.07. The total execution time of SADE is 83.94 seconds and the mean time is 3.49 seconds.

5.3 Ten Unit Test System

The second case study consists of a Ten- unit test system [23]. The input data includes the generator limits, fuel cost coefficients, transmission loss matrix and load profile for 24 hours. The minimum generating capacity of the system is 690 MW and the maximum generating capacity is 2358 MW. The load profile and the generator input data is given in Table 8 and Table 9 respectively. The minimum power demand requirement is 1036 MW and the maximum demand is 2220 MW.

Table 8 Load Demand for Ten- unit test system

Hour	Load (MW)	Hour	Load (MW)
1	1036	**13**	2072
2	1110	**14**	1924
3	1258	**15**	1776
4	1406	**16**	1554
5	1480	**17**	1480
6	1628	**18**	1628
7	1702	**19**	1776
8	1776	**20**	2072
9	1924	**21**	1924
10	2072	**22**	1628
11	2146	**23**	1332
12	2220	**24**	1184

Table 9 Generator Characteristics of Ten- unit test system

UNITS	PARAMETERS				
	A ($/W-h^2)	B ($/W-h)	C ($)	Min Power (MW)	Max Power (MW)
1	0.00043	21.60	958.2	150	470
2	0.00063	21.05	1313.6	135	460
3	0.00039	20.81	604.97	73	340
4	0.0007	23.9	471.6	60	300
5	0.00079	21.62	480.29	73	243
6	0.00056	17.87	601.75	57	160
7	0.00211	16.51	502.7	20	130
8	0.0048	23.23	639.4	47	120
9	0.10908	19.58	455.6	20	80
10	0.00951	22.54	692.4	55	55

The transmission loss coefficients are given in Eqn. 17,

$$B_{mn} = 1 * 10^{-3} * \begin{bmatrix} 8.700 & 0.430 & -4.61 & 0.360 & 0.320 & -0.66 & 0.960 & -1.60 & 0.800 & -0.10 \\ 0.430 & 8.300 & -0.97 & 0.220 & 0.750 & -0.28 & 5.040 & 1.700 & 0.540 & 7.200 \\ -4.61 & -0.97 & 9.000 & -2.0 & 0.630 & 3.00 & 1.700 & -4.30 & 3.100 & -2.00 \\ 0.360 & 0.220 & -200 & 5.300 & 0.470 & 2.600 & -1.96 & 2.100 & 0.670 & 1.800 \\ 0.320 & 0.750 & 0.630 & 0.470 & 8.600 & -0.80 & 0.370 & 0.720 & -0.90 & 0.670 \\ -0.66 & -0.28 & 3.000 & 2.620 & -0.80 & 11.80 & -4.90 & 0.300 & 3.000 & -3.00 \\ 0.960 & 5.040 & 1.700 & -1.96 & 0.370 & -4.90 & 8.240 & -0.90 & 5.900 & -0.60 \\ -1.60 & 1.700 & -4.30 & 2.100 & 0.720 & 0.300 & -0.90 & 1.200 & -0.96 & 0.560 \\ 0.800 & 0.540 & 3.100 & 0.670 & -0.90 & 3.000 & 5.900 & -0.96 & 0.930 & -0.30 \\ -0.10 & 7.200 & -2.00 & 1.800 & 0.690 & -3.00 & -0.60 & 0.560 & -0.30 & 0.990 \end{bmatrix} \tag{17}$$

Table 10 Commitment of Units using GA for Ten-unit test system

Hour	Demand (MW)	Combination of units										CT (s)
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	
1	1036	ON	OFF	OFF	ON	OFF	ON	ON	OFF	OFF	ON	2.08
2	1110	ON	OFF	OFF	ON	ON	ON	OFF	OFF	OFF	OFF	2.15
3	1258	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF	ON	2.31
4	1406	ON	ON	OFF	ON	OFF	ON	OFF	OFF	ON	ON	2.11
5	1480	ON	ON	ON	OFF	ON	OFF	OFF	OFF	ON	OFF	2.35
6	1628	ON	ON	ON	OFF	ON	ON	OFF	OFF	OFF	ON	2.18
7	1702	ON	ON	ON	ON	OFF	ON	OFF	OFF	OFF	ON	2.19
8	1776	ON	ON	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	2.17
9	1924	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF	ON	2.09
10	2072	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF	2.34
11	2146	ON	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	2.26
12	2220	ON	ON	ON	ON	ON	ON	ON	OFF	ON	ON	2.18
13	2072	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF	2.22
14	1924	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF	ON	2.25
15	1776	ON	ON	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	2.24
16	1554	ON	ON	ON	OFF	ON	OFF	ON	OFF	OFF	OFF	2.31
17	1480	ON	ON	ON	OFF	ON	OFF	OFF	OFF	ON	OFF	2.27
18	1628	ON	ON	ON	OFF	ON	ON	OFF	OFF	OFF	ON	2.29
19	1776	ON	ON	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	2.11
20	2072	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF	2.35
21	1924	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF	ON	2.33
22	1628	ON	ON	ON	OFF	ON	ON	OFF	OFF	OFF	ON	2.24
23	1332	ON	ON	OFF	OFF	ON	OFF	OFF	ON	ON	ON	2.16
24	1184	ON	ON	OFF	OFF	OFF	OFF	OFF	ON	ON	ON	2.06

Table 11 ELD results using SADE for ten unit system

HOURS (h)	Power generated / unit (MW)									
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
1	462.5504	0	0	228.4496	0	160	130	0	0	55
2	408.1866	0	0	298.8134	243	160	0	0	0	0
3	406	460	340	0	0	0	0	0	0	55
4	442.3920	460	0	268.6080	0	160	0	0	20	55
5	433.6076	460	340	0	226.3924	0	0	0	20	0
6	418.2523	460	340	0	194.7477	160	0	0	0	55
7	465.1427	460	340	221.8573	0	160	0	0	0	55
8	452.7074	460	340	280.2926	243	0	0	0	0	0
9	435.3397	460	340	230.6603	243	160	0	0	0	55
10	454.8155	460	340	284.1845	243	160	130	0	0	0
11	452.1137	460	340	300	243	160	130	47	0	0
12	469.9911	460	340	285.7821	243	160	130	0	79.8863	55
13	454.8155	460	340	284.1845	243	160	130	0	0	0
14	435.3397	460	340	230.6603	243	160	0	0	0	55
15	452.7074	460	340	280.2926	243	0	0	0	0	0
16	417.8935	460	340	206.1065	0	0	130	0	0	0
17	433.6076	460	340	0	226.3924	0	0	0	20	0
18	418.2523	460	340	0	194.7477	160	0	0	0	55
19	452.7074	460	340	280.2926	243	0	0	0	0	0
20	454.8155	460	340	284.1845	243	160	130	0	0	0
21	435.3397	460	340	230.6603	243	160	0	0	0	55
22	418.2523	460	340	0	194.7477	160	0	0	0	55
23	465.1632	460	0	0	243	0	0	88.8368	20	55
24	461.1791	460	0	0	0	0	130	57.8209	20	55

5.4 Results of Ten Unit System

The UC results obtained using GA for 24 hours load profile along with the computational time is tabulated in Table 10. It can be seen from the table that unit P1 is kept ON throughout the day because this unit generates power with minimum fuel cost as the cost coefficient 'A' is minimum for this unit. Similarly unit P9 is the most expensive unit and hence it is kept OFF during most hours of the day

The various GA and SADE parameters and their values used to implement UC-ELD problem are given in Table 1 and 2 respectively. SADE algorithm is run for 24 hours load profile in order to generate the load sharing of the online units determined by GA technique (Table 10). The ELD results obtained using SADE technique is summarized in Table 11 for units P1 to P10. For each hour, the power generated by the units differs because the combination of units that are ON varies. Based on the available online units, load demand is optimally distributed among the units. Unit P10 has a constant load of 55 MW because its maximum and minimum generation limits are equal i.e., it has to either generate 55 MW or to be kept in OFF state.

The load demand shared by units P1 to P10 during a day is graphically presented in Fig. 2. It can be seen that unit P1 shares most of the load and unit P8 shares the minimum MW of load. The maximum power is generated by Unit P1 (10601.17 MW) and unit P2 (10120 MW) and the minimum power is generated by P8 (193.6577 MW) and unit P9 (179.8863 MW).

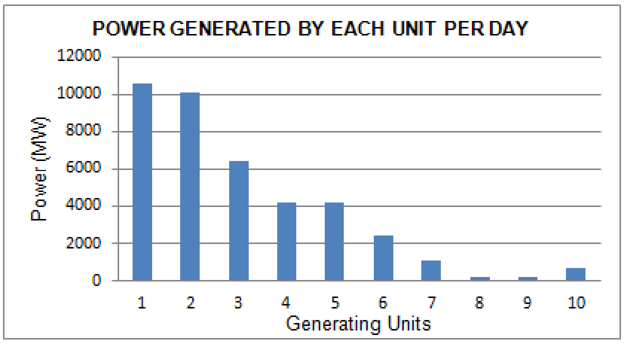

Fig. 2. Contribution of power per unit using SADE for ten unit system

The total fuel cost incurred to operate the units and the total computational time of the SADE algorithm is given in Table 12. The computational time for each hour is approximately equal to 5 seconds. The minimum operating cost is during the first hour for a load demand of 1036 MW which amounts to $ 25135. The maximum cost is incurred for a load demand of 2220 MW during the twelfth hour. The operating cost for a power demand of 2220 MW is $ 53989.

Table 12 Operating cost and Computational time using SADE for ten unit system

Hour	Demand (MW)	Operating Cost ($)	Time (sec)
1	1036	25135	5.55
2	1110	26778	5.07
3	1258	30549	5.53
4	1406	34997	5.30
5	1480	35567	5.3
6	1628	39080	5.32
7	1702	41198	5.26
8	1776	42686	5.53
9	1924	46537	5.27
10	2072	48987	5.02
11	2146	51359	5.55
12	2220	53989	5.52
13	2072	48987	5.02
14	1924	46537	5.27
15	1776	42686	5.53
16	1554	36570	5.52
17	1480	35567	5.73
18	1628	39080	5.32
19	1776	42686	5.53
20	2072	48987	5.02
21	1924	46537	5.27
22	1628	39080	5.32
23	1332	33602	5.09
24	1184	29676	5.08

The total operating expenses for the ten unit test system to generated power for 24 hours is $ 966857 and the average expense per hour is $ 40285. Similarly the execution time of the algorithm to compute solution for a day is 125 seconds and the mean time is 5.3 seconds.

5.5 Comparative Analysis

The obtained GA-SADE results for the UC-ELD problem are compared with Hybrid Genetic Algorithm (HGA) [22], Evolutionary Programming (EP) [23], Simple Genetic Algorithm (SGA) [24], Fast Genetic Algorithm (FGA) [24], Pattern Search (PS) [25], Genetic Algorithm (GA) [26], Hybrid GA and PS (GA-PS) [25], Ant Colony Optimization (ACO) [27], Self-adaptive Differential Evolution (SADE) [28], Weight-Improved Particle Swarm Optimization (WIPSO) [29], and Artificial Bee Colony (ABC) [30] for a demand of 283.4 MW as shown in Table 9. The results show that the fuel cost produced by the proposed technique is 798.02 $/hr which is less than those reported in literature. The computational time for the execution of the developed program is 3.33 sec comparatively less than GA, ACO, WIPSO, and ABC methods. The test system was considered with the transmission losses and the power loss generated by the proposed technique is also less (8.57 MW) compared to the other listed state-of-the-art methods.

Table 9. Comparative Analysis for IEEE 30 bus system

Technique	Fuel cost ($/hr)	Total power P_G (MW)	Power loss (MW)	CT (s)
HGA	802.465	292.9105	9.5105	NA
EP	802.404	292.8791	9.4791	NA
SGA	799.384	292.6801	9.6825	0.483
FGA	799.823	292.8093	9.6897	0.125
PS	802.015	292.7344	9.3349	NA
GA	803.699	292.917	9.5177	315
GA-PS	802.0138	292.7287	9.3286	NA
ACO	803.123	292.8611	9.4616	20
SADE	802.404	292.8791	9.4791	NA
WIPSO	799.1665	292.0591	8.66	15.453
ABC	801.881	271.18	NA	8.94
Proposed	798.02	289.97	8.57	3.33

Table 10 presents a comparison of the total cost obtained from proposed GA-SADE algorithm with that of Enhanced Particle Swarm Optimization with Gaussian Mutation (EPSO-GM), Ant Directed Hybrid Differential Evolution (ADHDE) and ABC techniques. It is observed that the proposed method yields better results than the compared state-of-the-art methods, thus satisfying all the constraints considered in this work.

The total fuel cost of the 10 unit system obtained through the proposed method is also compared as shown in Table 11 with EPSO-GM [31], ADHDE, ABC [32], EP [33], SQP [33], EP-SQP [33], MHEP-SQP [34], PSO-SQP [35], PSO-SQP© [35], DGPSO [36], and EPSO [37] methods. The minimum cost obtained so far in literature was 1023691.11 $/hr (EPSO-GM technique), which is higher by 56834.11 $/hr than that obtained through GA-SADE method

Table 11. Total fuel cost comparison for Ten unit system

Technique	Fuel cost ($/hr)
EPSO-GM	1023691.11
ADHDE	1062372
ABC	1043378
EP	1048638
SQP	1051163
EP-SQP	1031746
MHEP-SQP	1028924
PSO-SQP	1030773
PSO-SQP(C)	1027334
DGPSO	1028835
EPSO	1023772.46
Proposed	966857

5.6 Summary of results

From the analysis of the results obtained by applying the GA-SADE algorithm to the Six-unit and the Ten-unit system, it can be concluded that the algorithm provides optimal solution to the Unit commitment and Economic Load Dispatch problem in terms of solution quality, robustness and algorithmic efficiency are summarized in this section.

Solution quality is justified based on the optimizing parameters that include total operating cost and the execution time. Robustness of an algorithm can be evaluated by testing the developed technique on different input cases. The proposed algorithm is applied to two test systems that include a Six- unit IEEE 30 bus system and the Ten- unit test system. Results obtained to the UC-ELD problem reveals that the technique is highly robust as it generates optimal solution for different test cases. Robustness of an algorithm can also be judged through repetitive runs in order to verify the consistency of the algorithm. To measure the robustness, the frequency of convergence to the minimum cost at different ranges of generation cost with fixed load demand is recorded. Experimental results show that the frequency of convergence for a 6 unit system and a 10 unit system using GA-SADE, towards the optimal fuel cost was 30 out of 30 trial runs for all power demands. The average computational time required for the execution of the 6 unit test system was found to be 1.28s (GA) and 3.37s (SADE), while the time required for 10 unit test systems was observed as 2.21s (GA) and 5.33s (SADE) respectively.

Algorithmic efficiency can be thought of as analogous to engineering productivity for a repeating or continuous process in order to minimize time taken for completion to some acceptable optimal level. The most frequently encountered and measurable metric of an algorithm is the speed or execution time. In addition to yielding optimal solution in terms of minimum fuel cost, the algorithm was tested for efficiency in terms of the time taken for completion of the MATLAB code with the sub-functions used. The convergence of an algorithm is determined by the number of iterations required to generate an optimal solution. Since convergence rate is proportional to the execution time of the algorithm, it highly influences the algorithmic efficiency of a technique. The efficiency of GA-SADE technique was 90.42% for a six unit test system and 92.32% for a ten unit system.

6. CONCLUSION

Unit Commitment (UC) and Economic Load Dispatch (ELD) problem has a significant influence on secure and economic operation of power systems. Optimal commitment scheduling and dispatching can save huge amount of costs to electric utilities thus improving reliability of operation. This paper presents a novel approach based on GA and SADE for solving the Unit Commitment and Economic Load Dispatch problem.

From the experimental results obtained, it can be seen that GA-SADE technique provides optimal solution in terms of total fuel cost, execution time, mean cost and algorithmic efficiency. In future, efforts will be taken to impose complex real time constraints to the UC-ELD problem that include spinning reserves, emission constraint and network security on the UC-ELD problem. This application can also be solved using new optimization techniques like Stud Genetic Algorithm, Population-based incremental learning, Intelligent water drop algorithm, Bio-Geography based algorithm and hybrid combination of these paradigms.

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