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Simulated Annealing Algorithm for Combined Economic and Emission Dispatch

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Abstract—

This paper presents a Simulated Annealing (SA) algorithm for multi-objective optimization problem in power system. Considering the environmental impacts that grow from the emissions produced by fossil-fuelled power plant, the economic dispatch that minimizes only the total fuel cost can no longer be considered as single objective. Simulated Annealing algorithm strategy based on mathematical modeling to solve economic, emission and combined economic and emissions dispatch problems by a single equivalent objective function. Simulated Annealing algorithm has been applied to two realistic systems at different load condition. Results obtained with proposed method are compared with other techniques presented in literature. SA algorithm is easy to implement and capable of searching near global optimum solution at fast convergence and efficiency.

Keywords—**Economic dispatch; Emission dispatch; Combined economic and emission dispatch; Mathematical modeling.**

I. Introduction

This paper introduce the economic dispatch problem in a power system is to determine the optimal combination of power output for all generating units which will minimize the total fuel cost while satisfying load and operational constraints. The economic dispatch problem is very complex to solve because of its colossal dimension, a non-linear objective function, and a large number of constraints.

Well known long-established techniques such as integer programming [2], dynamic programming [3], and lagarangian relaxation [4] have been used to solve the economic dispatch problem. Recently other optimization methods such as Simulated Annealing [5], Genetic Algorithm [6], Particle Swarm optimization [9], and Tabu Search Algorithm [10] are presented to solve the economic dispatch problem. This single objective economic dispatch can no longer be considered along due to the environmental concerns that arise from the emission produced by fossil-fuelled electric power plants. Economic and environmental dispatch is a multi-objective

problem. Various Multi-objective evolutionary algorithms have been applied to the economic dispatch problem [11-13] based on mathematical approximations have been developed, which directly give the solution faster. In [14-15] including emission constrains to the economic dispatch and unit commitment problems have been presented, under cost-minimization environment.

The paper is organized as follows:

Section 3 is an overview of the SA algorithm is presented.

Section 4 formulates the SA algorithm for CEED Problem.

The feasibility of the proposed approach is evaluated through two test systems consisting of three and six generating unit and the results are compared with the available methods, which is presented in Section 5. Finally, Section 6 presents the conclusions.

II. combined environmental Economic dispatch

The traditional economic dispatch problem has been defined as minimizing of an objective function i.e. the generation cost function subject to equality constraints (total power generated should be equal to total system load plus losses for all solutions) and inequality constraints (generations should lie between their respective maximum and minimum specified values)

Minimize $\Phi(x, p)$ $\quad \Phi_t(P_i) = \sum_{i=1}^{n} \Phi_i(P_i)$;

Objective function (1)

Subject to g(x, p) $\quad \sum_{i=1}^{n} P_i - P_L - P_D = 0$;

Equality constraint (2)

The transmission losses are given by:

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{n} P_i B_{ij} P_i \quad (3)$$

Where $B_{ij} =$ transmission loss coefficient

$$H(x,P) \le 0 \qquad P_{i\min} \le P_i \le P_{i\max} \quad ;$$

Inequality constraint (4)

Where x is a state variable, P_i is the control variable, i.e., real power setting of i th generator and n is the number of units or generators.

There are several ways to include emission into the problem of economic dispatch. One approach is to include the reduction of emission as an objective. In this work, only NO_x reduction is considered because it is a significant issue at the global level. A price penalty factor (h) is used in the objective function to combine the fuel cost, Rs/hr and emission functions, kg/hr of quadric form.

The combined economic and emission dispatch problem can be formulated as to minimize

$$\varphi_t = \sum_{i=1}^{n} F_i(P_i) + h\sum_{i=1}^{n} E_i(P_i) \text{ Rs/h} \quad (5)$$

$$\varphi_i = \sum_{i=1}^{n}(a_i P_i^2 + b_i P_i + c_i) + h\sum_{i=1}^{n}(d_i P_i^2 + e_i P_i + f_i) Rs/h \quad (6)$$

Subject to equality and inequality constraint defined by equations (2), (4). Once price penalty factor (h) is known, equation (5) can be rewritten as

$$\varphi_i = \sum_{i=1}^{n}\{(a_i + hd_i)P_i^2 + (b_i + he_i)P_i + (c_i + hf_i)\} Rs/h \quad (7)$$

This has the resemblance of the familiar fuel cost equation, once h is determined. A practical way of determining h is discussed by Palanichamy and Srikrishan [7]. Consider that the system is operating with a load of P_D MW, it is necessary to evaluate the maximum cost of each generator at its maximum output, ie,

(i) Evaluate the maximum cost of each generator at its maximum output, ie,

$$F_i(P_{i\max}) = \left(a_i P_{i\max}^2 + b_i P_{i\max} + c_i\right) \text{ Rs/hr} \quad (8)$$

(ii) Evaluate the maximum NOx emission of each generator at its maximum output, ie,

$$E_i(P_{i\max}) = \left(d_i P_{i\max}^2 + e_i P_{i\max} + f_i\right) \text{ kg/hr} \quad (9)$$

(iii) Divide the maximum cost of each generator by its maximum NOx emission, i.e.,

$$\frac{F_i(P_{i\max})}{E_i(P_{i\max})} = \frac{\left(a_i P_{i\max}^2 + b_i P_{i\max} + c_i\right)}{\left(d_i P_{i\max}^2 + e_i P_{i\max} + c_i\right)} \text{ Rs/kg} \quad (10)$$

Recalling that

$$\frac{F_i(P_{i\max})}{E_i(P_{i\max})} = h_i \text{ Rs/kg} \quad (11)$$

(iv) Arrange $h_i (I = 1,2,......,n)$ in ascending order.

(v) Add the maximum capacity of each unit, $(P_{i\max})$ one at a time, starting from the smallest hi unit until total demand is met as shown below.

$$\sum_{i=1}^{n} P_{i\max} \ge P_D \quad (12)$$

(vi) At this stage, h_i associated with the last unit in the process is the price penalty factor h Rs/Kg for the given load.

Arrange h_i in ascending order. Let 'h' be a vector having 'h' values in ascending order.

$$h = \left[h_1, h_2, h_3, ..., h_n\right] \quad (13)$$

For a load of P_D starting from the lowest h_i value unit, maximum capacity of unit is added one by one and when this total equals or exceeds the load, h_i associated with the last unit in the process is the price penalty factor for the given P_D. Then equation (6) can be solved to obtain environmental economic dispatch using lamda iteration method [1].

III. Simulated Annealiling Method

Simulated Annealing (SA) is a stochastic optimization technique which is based on the principles of statistical engineering. The search for a global minimum of a multidimensional cost function is a quite complex problem especially when a big number of local minimums correspond to the respective function. The main purpose of the optimization is to prevent hemming about to local minimums.

The originality of the SA method lies in the application of a mechanism that guarantees the avoidance of local minimums.

Following its introduction from Kirkpatrick et al [16], simulated annealing is mainly applied to large-scale combinatorial optimization problems.

A. The Process of Annealing in Thermodynamics

At high temperatures, the metal is in liquid phase. The molecules of liquidated metal move freely with respect to each other. By gradually cooling (thermodynamic process of annealing) thermal mobility is lost. The atoms start to get arranged and finally form crystals, having the minimum energy which depends on the cooling rate. If the temperature is reduced at a very fast rate, the crystalline state transforms to an amorphous structure, a meta-stable state that corresponds to a local minimum of energy. [17,23]

The annealing process of metal influences SA algorithm.

If the system is at a thermal balance for given temperature T, then the probability $P_T(s)$ that it has a configuration s depends on the energy of the corresponding configuration *E(s)*, and is subject to the Boltzmann distribution

$$P_T(s) = \frac{e^{-E(s)/kT}}{\sum_W e^{-E(w)/kT}} \tag{14}$$

Where, κ is the Boltzmann constant and the sum Σ_W includes all possible states *W*.

Metropolis et al [18] were the first to suggest a method for calculating a distribution of a system of elementary particles (molecules) at the thermal balance state.

Let's suppose that the system has a configuration *g*, which corresponds to energy *E(g)*. When one of the molecules of the system is displaced from its starting position, a new state *σ* occurs which corresponds to energy *E(σ)*. The new configuration is compared with the old one. If $E(\sigma) \leq E(g)$, then the new state is accepted. If $E(\sigma)>E(g)$, then the new state is accepted with probability :

$$e^{-(E(\sigma)-E(g))}\big/_{kT}$$

Where, κ is the Boltzmann constant.

TABLE I. CONNECTION BETWEEN THERMODYNAMIC SIMULATION AND COMINATORIAL OPTIMIZATION

Thermodynamics simulation	**Combinatorial Optimization**
System state	Feasible Solutions
Energy	Cost
Change of state	Neighboring Solutions
Temperature	Control Parameter
Frozen state	Heuristic Solution

The basic step of the simulated annealing algorithm is presented with the following Pseudo-code.

- *Get the initial solution "S".*
- *Get the initial Temp T>0*
- *While not yet frozen*

(a)perform the following loop L times

**peak the random neighbor, S' of S*

**let Δ=cost(S')-cost(S)*

**If Δ≤0 ,set S'=S*

**If Δ>0, set S=S' with probability* $e^{-\Delta/T}$

(b)set T=αT (reduce Temperature)

Return S

B. Control parameters of SA algorithm

For the successful application of the SA algorithm is the annealing schedule is vital, which refers to four control parameters that directly influence its convergence (to an optimized solution) and consequently its efficiency [19]. The parameters are the following:

- Starting Temperature
- Final Temperature
- Temperature Decrement
- Iterations at each Temperature

a) Starting Temperature

The starting temperature must be set to a big enough value, in order to make possible a big probability of acceptance non optimized solutions during the first stages of the algorithm's application.

However, if the value of the starting temperature gets too big, SA algorithm becomes non-effective because of its slow convergence and in general, the optimization process degenerates to a random walk. On the contrary, if the starting temperature is low then there is a big probability to hem about at one of the local minimums.There is no particular method for finding the proper starting temperature that deals with the entire range of problems. Various techniques for finding the proper starting temperature have been developed.

Dowsland [20], suggests to quickly raise the temperature of the system initially up to the point where a certain percentage of the worst solutions is acceptable and after that point, a gradual decrement of temperature.

b) Final Temperature

During the application of the SA algorithm it is common to let the temperature fall to zero degrees. However, if the decrement of the temperature becomes exponential, SA algorithm can be executed for much longer. Finally, the stopping criteria can either be a suitable low temperature or the point when the system is "frozen" at current temperature.

C) Temperature Decrement

Since the starting and final temperatures have been defined, it is necessary to find the way of transition from the starting to the final temperature. The way of the temperature decrement is very important for the success of the algorithm.

Aart et al [21] suggested the following way to decrement the temperature:

$$T(t) = d\big/_{\log(t)} \tag{15}$$

Where *d* is a positive constant.

An alternative is the geometric relation:

$$T(t) = a.t \tag{16}$$

Where parameter *a*, is a constant near 1. In effect, its typical values range between 0.8 and 0.99.

d) Iterations at each Temperature

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For increased efficiency of the algorithm, the number of iterations is very important. Using a certain number of iterations for each temperature is the proper solution.

Lundy [22] suggests the realization of only one, iteration for each temperature, while the temperature decrement should take place at a really slow pace that can be expressed as:

$$T(t) = t/(1+\beta . t) \quad (17)$$

Where, β takes a very low value.

IV. SA algorithm Implementation of ceed problem

Step 1: Initialization of the values temperature, T, parameter α and iterations number criterion. Find, randomly, an initial feasible solution, which is assigned as the current solution S_i and perform CEED in order to calculate the total cost, F_{cost}, with the preconditions (2) and (4) fulfilled.

Step 2: Set the iteration counter to μ=1

Step 3: Find a neighboring solution S_j through a random perturbation of the counter one and calculate the new total cost, F_{cost}.

Step 4: If the new solution is better, we accept it, if it is worse, we calculate the deviation of cost $\Delta S=S_j-S_i$ and generate a random number uniformly distributed over $\Omega \in (0, 1)$.

$$\text{If } e^{-\Delta S/t} \geq \Omega \in (0,1) \quad (18)$$

Accept the new solution S_j to replace $S_{i.}$

Step 5. If the stopping criterion is not satisfied, reduce temperature using parameter α:

$T\ (t) = \alpha .\ t$

And go to Step 2.

V. Results and Discussion

The applicability and validity of the SA algorithm for practical applications has been tested on two test cases. The programs are developed using MATLAB 7.1 and the system configuration is Pentium IV processor with 2.4 GHz speed and 512 MB RAM.

The Parameter for SA algorithm considered here are:

Initial Temperature=100, Final Temperature=1e-10; α=0.8 and Iteration in each temperature=100

Test case 1: The system consists of three thermal units. The parameters of all thermal units are presented in table: II and table: III, the summarized result of CEED problem for load demand of 400MW, 500MW and 700MW are obtained by the proposed SA algorithm is presented in Table: IV.

TABLE II. FUEL COST COEFFICIENT

unit	Fuel cost coefficient			$P_{Gmin\ (MW)}$	$P_{Gmax\ (MW)}$
	a_i	b_i	c_i		
G1	0.03546	38.30553	1243.53110	35	210
G2	0.02111	36.32782	1658.56960	130	325
G3	0.01799	38.27041	1356.65920	125	315

TABLE III. NO_X EMISSION EQUATION IN KG/H ARE GIVEN BELOW

unit	Emission coefficient			$P_{Gmin\ (MW)}$	$P_{Gmax\ (MW)}$
	di	ei	fi		
G1	0.00683	– 0.5455	40.26690	35	210
G2	0.00461	– 0.5116	42.89553	130	325
G3	0.00461	– 0.5116	42.89553	125	315

The Bmn loss coefficient matrix is

	0.0000 70	0.000025	0.000030
Bmn=	0.000030	0.000069	0.000032
	0.000025	0.000032	0.000080

TABLE IV. COMPARISON OF TEST RESULTS FOR THREE GENERATING UNIT SYSTEM

Pd MW	Performance	h Rs / Kg	Conventional Method [8]	SGA [8]	RGA [8]	Proposed Method
400	Fuel Cost Rs / hr	44.788	20898.83	2083. 54	20801. 81	20838
	Emission Kg / hr		201.5	201. 35	201. 21	200.2210
	P loss, MW		7.41	7.69	7.39	7. 4125
	Total operating Cost Rs / hr		29922	29820	29812	29804.16858
500	Fuel Cost Rs / hr	44. 788	25486. 64	25474. 56	25491. 64	25495
	Emission Kg / hr		312.0	311. 89	311. 33	311. 1553
	P loss, MW		11. 88	11. 80	11. 70	11. 6936
	Total operating Cost Rs / hr		39458	39441	39433	39428. 25258
700	Fuel Cost Rs / hr	47.82	35485.05	35478. 44	35471. 48	35464
	Emission Kg / hr		652. 55	652. 04	651. 60	651. 5772
	P loss, MW		23. 37	23. 29	23. 28	23. 3663
	Total operating Cost Rs / hr		66690	66659	66631	66622. 5190

Form Table: IV, it is clear that SA algorithm gives optimum result in terms of fuel cost, emission level and the total operating cost.

TABLE V. OPTIMUM POWER DISPATCH RESULTS BY PROPOSED METHOD FOR THREE UNITS SYSTEM

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PD MW	P1 MW	P2 MW	P3 MW	Escape Time (second)
400	102.5444	153.7298	151.1383	4.943824
500	128.8264	192.5833	190.2839	5.808751
700	182.6064	271.834	269.4765	5.174793

Table: V, gives the best optimum power output of generators for CEED problem using SA algorithm for load demand 400MW, 500MW and 700MW.

The convergence tendency of proposed SA based strategy for power demand of 400MW, 500MW and 700 MW is plotted in figure: 1, figure: 2 and figure: 3. It shows that the technique converges in relatively fewer cycles thereby possessing good convergence property and resulting in low operating cost.

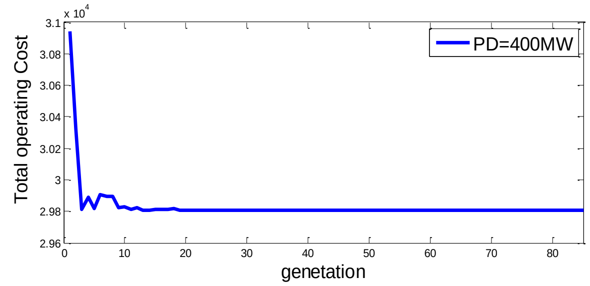

Figure 1. Convergence of Three Generating Unit system for PD=400MW

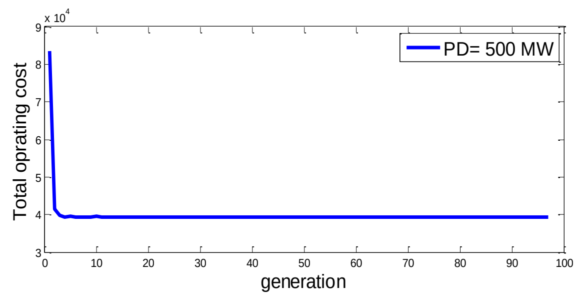

Figure 2. Convergence of Three Generating Unit system for PD=500MW

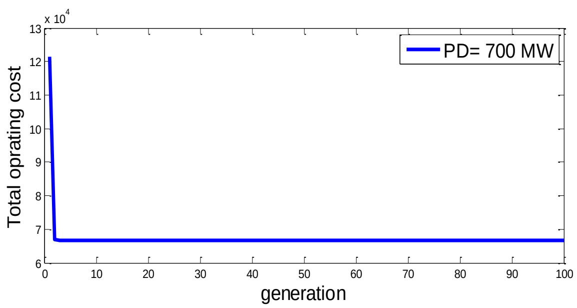

Figure 3. Convergence of Three Generating Unit system for PD=700MW

Test case II: The system consists of six thermal units. The parameters of all thermal units are presented in Table: VI and Table: VII.

The summarized result of CEED problem for load demand of 500MW and 900MW are obtained by the proposed SA algorithm is presented in, Table: VIII.

TABLE VI. FUEL COST COEFFICIENT

unit	Fuel cost coefficient a_i	b_i	c_i	P_{Gmin} (MW)	P_{Gmax} (MW)
G1	0.15247	38.53973	756.79886	10	125
G2	0.10587	46.15916	451.32513	20	150
G3	0.02803	40.39655	1049.99770	35	225
G4	0.03546	38.30552	1243.53110	35	210
G5	0.02111	36.32782	1658.55960	130	325
G6	0.01799	38.27041	1356.65920	125	325

TABLE VII. NO_X EMISSION EQUATION IN KG/H ARE GIVEN BELOW

unit	Emission coefficient di	ei	fi	P_{Gmin} (MW)	P_{Gmax} (MW)
G1	0.00419	0.32767	13.85932	10	125
G2	0.00419	0.32767	13.85932	20	150
G3	0.00683	– 0.54551	40.26690	35	225
G4	0.00683	– 0.54551	40.26690	35	210
G5	0.00461	– 0.51116	42.89553	130	325
G6	0.00461	– 0.51116	42.89553	125	325

Bmn loss coefficient matrix in the order of 10^{-4} is given as:

$$Bmn = \begin{matrix} 1.40 & 0.17 & 0.15 & 0.19 & 0.26 & 0.22 \\ 0.17 & 0.60 & 0.13 & 0.16 & 0.15 & 0.20 \\ 0.15 & 0.13 & 0.65 & 0.17 & 0.24 & 0.19 \\ 0.19 & 0.16 & 0.17 & 0.71 & 0.30 & 0.25 \\ 0.26 & 0.15 & 0.24 & 0.30 & 0.69 & 0.32 \\ 0.22 & 0.20 & 0.19 & 0.25 & 0.32 & 0.85 \end{matrix}$$

Form Table: VIII, it is clear that SA algorithm gives the optimum result in terms of minimum fuel cost, emission level and the total operating cost.

TABLE VIII. COMPARISON OF TEST RESULTS FOR SIX GENERATING UNIT SYSTEM

PD MW	Performance	h Rs/kg	Conventional method [10]	RGA [10]	HGA [10]	Hybrid GTA [10]	Proposed method	Computational time for SA
500	Fuel cost Rs / hr	43.898	27692.1	27695	27695	27613.4	27613	4. 887728
	Emission Kg / hr		263.472	263.472	263. 37	263.000	263.0140	
	PL MW		10.172	10.172	10.135	8.930	8.9343	
	Total cost Rs / hr		39258. 100	39258. 10	39257. 5	39158.9	39156.9	
900	Fuel cost Rs / hr	47.822	48567.7	48567.7	48567. 5	48380.9	48351	5. 914351
	Emission Kg / hr		694.169	694.169	694. 172	693.570	693.7871	
	PL, MW		29.725	29.725	29.718	28.004	28.0094	
	Total cost, Rs / hr		81764.5	81764.5	81764. 4	81529. 100	81527.6	

Table: IX provides the best optimum power output of generators for CEED problem using SA algorithm for load demand 500MW and 900MW.

TABLE IX. OPTIMUM POWER DISPATCH RESULTS BY PROPOSED METHOD FOR SIX UNITS SYSTEM

PD MW	P1MW	P2 MW	P3 MW	P4 MW	P5 MW	P6 MW
500	33.2735	26.8470	89.9216	90.4804	135.6471	132.7647
900	92.3281	98.3940	150.1942	148.5696	220.4101	218.1134

The convergence tendency of proposed SA based strategy for power demand of 500MW and 900 MW is plotted in figure: 4 and figure: 5. it shows that the technique converges in relatively fewer cycles thereby possessing good convergence property and resulting in low operating cost.

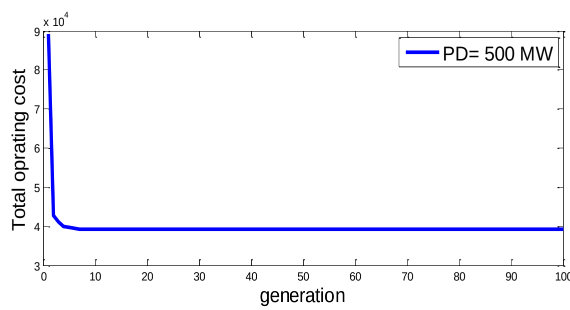

Figure 4. Convergence of Six Generating Unit system for PD=500MW

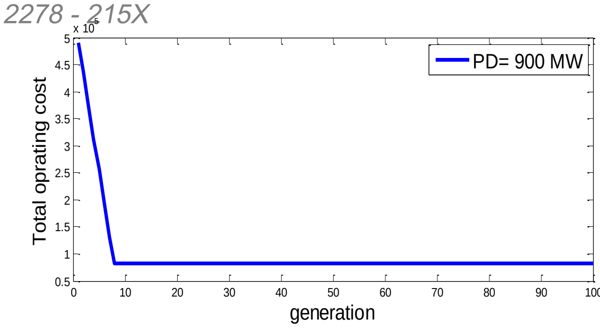

Figure 5. Convergence of six Generating Unit system for PD=900MW

VI. Conclusion

Simulated annealing (SA) algorithm is a probabilistic meta-heuristic method for global optimization problems. SA derives from annealing in metallurgy, a process involving heating and controlled cooling of a material to increase the size of its crystals and reduce their defects. In order to prove the effectiveness of algorithm it is applied to CEED problem with three and six generating unit. The results obtained by proposed method were compared to those obtained conventional method, RGA and SGA and Hybrid GA. The comparison shows that SA algorithm performs better then above mentioned methods. The SA algorithm has quality of solution, stable convergence characteristics and good computational efficiency. Therefore, results shows that SA based optimization is a promising technique for solving complicated problems in power system

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