A New Algorithm for Solving Environmental Issues in Power Engineering

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Abstract. Operating at absolute minimum cost can no longer be the only criterion for dispatching electric power due to increasing concern the environmental consideration. The environmentally constrained economic dispatch problem which accounts for minimization of both cost and emission is a multiple objective function problem. In this paper, tabu search is used to solve the economic dispatch problems for a couple of reasons. The modified tabu search algorithm uses a real-valued solution vector and adaptive mechanism for producing neighbors. However, the classical TS algorithm uses a binary solution vector. The neighbors are produced by adding an adjusted coefficient at each iteration. This neighbor production mechanism enables us to find the most promising region of the searched space. The proposed method has achieved efficient and accurate solutions for power systems with 3, 6, 10, 20, 40, 80, 120, 160 and 240 units respectively. The results of the proposed method are compared with those of an improved Hopfield neural network approach, an advance engineered-conditioning genetic approach, an advance Hopfield neural network approach and a fuzzy logic controlled genetic algorithm. It will demonstrate that the proposed method is superior in providing optimal allocation of generation units which minimizes the total fuel cost. Simulation results show that the proposed method yields better solutions when compared to the alternate techniques.

1. Introduction
Nowadays, taking in consideration the development of modern power systems, economic dispatch problem has received an increasing attention. The economic dispatch problem in a power system is to determine the optimal combination of power outputs for all generating units, which minimizes the total fuel cost while satisfying load and operational constraints [1, 2].

Economic dispatch (ED) is used in real-time energy management power system control by most background programs to allocate the total generation among the available units, as well as in interchange costing and billing, unit commitment and some other operational functions [3, 4, 5].

Operating at absolute minimum cost can no longer be the only criterion for dispatching electric power due to increasing concern the environmental consideration. The environmentally constrained economic dispatch problem which accounts for minimization of both cost and emission is a multiple objective function problem.

Different optimisation methods have been used to solve economic dispatch problems.
Classical optimisation methods such as dynamic programming, integer programming, Lagrangian relaxation and linear programming are well-documented methods to solve the ED problem [5-7]. Most of these economical dispatch issues are related to the operational service of classic coal based power plants, still in use. Some of these methods give good results, while others such as dynamic programming face the problem of dimensionality. New methods such as artificial intelligence methods, neural networks (NN), decision trees, expert systems, genetic algorithm, simulated annealing, fuzzy logic and tabu search have been also applied for solving the ED problem [1-4, 8-9].

Recently, global optimization techniques such as genetic algorithm (GA), tabu search (TS) and simulated annealing (SA), a particle swarm optimization (PSO) technique have been studied to solve the power optimization problems [2, 3, 6, 10]. These methods are meta-heuristic algorithms for optimization problems. They are described as iterative methods that use simple rules or heuristics to obtain an approximate solution of a global minimum.

In this paper, tabu search is used to solve the economic dispatch problems for a couple of reasons. Among meta-heuristic algorithms, TS finds more accurate solutions for complex optimisation problems. No single method or algorithm can solve all these complex issues.

Algorithm parameters of TS are adjusted easily for optimisation problems. Some previous research [11] has shown that the computational efficiency of TS is better than that of the genetic algorithm. Tabu search has been applied for solving some power system problems, such as maintenance scheduling [12], network synthesis [13], the capacitor placement problem in a radial distribution system [14], alarm processing [15] and unit commitment [16].

A hybrid algorithm, which integrates evolutionary programming, tabu search and quadratic programming methods, has been proposed for solving the nonconvex economic dispatch problem [13]. The test systems have 10 generating units and 15 generating units.

In this paper, the modified tabu search algorithm proposed by Karaboga et al. [16] is used for solving the economic and environmental economic dispatch problems. The classic TS algorithm [17] uses a solution vector consisting of a string of bits. Thus the transformation from binary to real numbers should be used for solving a numerical problem. However the modified TS algorithm uses a real-valued solution vector and an adaptive mechanism for producing neighbors.

The modified TS algorithm has been successfully applied for computing the various parameters of microstrip antennas [17]. Here, the effectiveness of the proposed method is demonstrated for different sizes of systems having 3 and 240 units.

A comparison is made between the proposed method and different methods such as genetic algorithm, neural networks, and fuzzy logic in terms of solution accuracy [18]. Nowadays, all renewable energy sources have gathered more and more importance worldwide. The PV systems are representing a very important and dynamic category from the renewable electric energy generation point of view [1], [2].

2. Formulation of Economical Dispatch Issues

The economic dispatch problem aims to supply the required quantity of power at the lowest possible cost [7]. The dispatch problem can be described mathematically as an objective function with two main constraints.

The total fuel cost at thermal plants should be minimized as proposed mathematical model for the external characteristics \( U = f(I) \) has the following form:

\[
C_f = \text{Min} \sum_{i=1}^{n} F_i(P_i) \quad \text{where: } \quad F_i(P_i) = (a_i + b_i P_i + c_i P_i^2)
\]  

(1)

In this case, \( F_i \) is cost function for unit \( i \) and \( a_i, b_i \) and \( c_i \) are cost coefficients of unit \( i \). \( P_i \) is the power output of the \( i \)-th generator and \( n \) is the number of generators committed to the operating system. There are no limitation for the unit number and their individual powers.
The economic dispatch problem subjects to the following constraints:

\[ \sum_{i=1}^{n} P_i - P_D - P_L = 0 \]  
(2)

\[ P_L = \sum_{i=1}^{n} B_i P_i^2 \]  
(3)

In these equations, \( P_D \) is total load demand and \( P_L \) is transmission loss. The inequality constraint of limits on the generator outputs is:

\[ P_{\text{min},i} \leq P_i \leq P_{\text{max},i} \]  
(4)

Where, \( P_{\text{min},i} \) and \( P_{\text{max},i} \) are minimum and maximum generation output of the \( i \)-th generator. However there is a large financial beneficial from the classical dispatch strategy described above, it tends to produce high \( \text{SO}_2 \) and \( \text{NO}_x \) emissions. An alternative dispatch strategy to satisfy the environmental requirement is to minimize operation cost under environmental constraints. Emission control can be included in conventional economic dispatch by adding the environmental cost to the normal dispatch. The emissions need to be converted as an environmental cost and added to the generation cost. The objective function then becomes a minimized \( C = w_0 \, C_T + w_1 \, E_S + w_2 \, E_N \) value. In this expression \( E_S \) is the \( \text{SO}_2 \) emission function, \( E_N \) is the \( \text{NO}_x \) emission function. \( w_0, w_1 \) and \( w_2 \) are costs \( \text{SO}_2 \) emission and \( \text{NO}_x \) emission weights respectively.

In this paper, like fuel cost curves, the \( \text{SO}_2 \) and the \( \text{NO}_x \) curves can be expressed as follows:

\[ E_S = \sum_{i=1}^{n} (d_i + e_i P_i + f_i P_i^2) \]  
(5)

And:

\[ E_N = \sum_{i=1}^{n} (g_i + h_i P_i + k_i P_i^2) \]  
(6)

Where \( d_i, e_i, f_i, g_i, h_i \) and \( k_i \) are parameters estimated on the basis of unit emissions test results.

In this model, if considering emission own weights as almost zero, the objective function becomes a classical economic dispatch problem. In this economic dispatch option, units are to minimize the total system production costs. When cost weight is set to zero, the problem becomes emission minimization. In this case, units are to minimize the amount of emissions. In case emission own weights are not equal to zero on the considered objective function, the problem is given like minimizing the fuel cost plus emission at the same time.

3. Modified Tabu Search Algorithm

Heuristic search methodologies in general do not guarantee optimality as they may converge at a local optimum solution. This is the case, quite often, when using local searching procedures. In order to “escape” from local optimum and explore a larger portion of the feasible region, a tabu search heuristic methodology is used in this paper.

Tabu search is a higher-level method or meta-heuristic algorithm for solving combinatorial optimization problems [23, 24]. As opposed to classical local search procedures, tabu search does not stop at the first local optimum when no improvement is possible. The best solution in the neighborhood is always selected, even if it is worse than the current solution. This allows it to explore more solutions from the feasible region.

It is an iterative procedure that starts from some initial feasible solution and attempts to determine a better solution, which minimizes an objective function. The tabu search makes several neighborhood moves and selects the next move by generating the best moving solution among all resulting candidate moves in case of that specific current iteration.
In our current article, the modified tabu search algorithm described by Karaboga et. al. [17] is used for solving the economic dispatch. The modified tabu search algorithm uses a real-valued solution vector and adaptive mechanism for producing neighbors. However the classical and tested TS algorithm implies a binary vector as solution. The use of real valued representation in the TS is to offer a number of advantages in numerical function optimization over binary representation. Efficiency of the TS is increased as there is no need to convert binary numbers to real numbers; less memory is required as efficient floating-point internal computer representations can be used directly and there is no loss in precision by discretisation to binary or other values.

The design of the neighborhood is a key element in the formulation of the proposed method as it may considerably increase the computational and searching efficiency. Karaboga et. al. [22] proposed a new neighbor generation mechanism for that modified TS algorithm. In our case, all requested neighbors are generated by adding an adjusted coefficient at each iteration. This neighbor production mechanism enables us to find the most promising region of the search space. For the economic dispatch problem, the coefficient for the \( i \)-th generator is defined as:

\[
\Delta_i = (-\text{P}_{\text{min},i} / 2 + \text{random}(\text{P}_{\text{min},i}))
\]

where \( \text{P}_{\text{min},i} \) is minimum generation output of the \( i \)-th generator.

In the proposed methodologies, a Tabu Search module is used as part of an iterative process; where in each iteration a potential schedule is evaluated. The number of iteration (\( N \)) is arbitrarily set. It starts by selecting a feasible schedule of generators for the ED to be the initial schedule and proceeds by selecting feasible schedules from the neighborhood of that initial selection. The schedule with the lowest total fuel cost of the economic dispatch among the new set of candidate schedules is selected as the next schedule to move to. A solution is represented with a vector of generation outputs for the ED problem and an associated set of neighbors. A neighbor is reached directly from the present solution. A succession of moves is carried out to transform the arbitrary solution to an optimal one. The new solution is the highest evaluation move among the neighbors in terms of the performance value and tabu restrictions that exist to avoid new moves that were evaluated in earlier iterations.

The modified tabu search algorithm uses an adaptive mechanism for producing neighbors. The neighbors of a present solution for the economic dispatch are created by the following procedure.

The solution vector \( S_k \) at the \( k \)-th iteration can be defined as follows:

\[
S_k = [ P_{k1}, P_{k2}, \ldots, P_{kn} ]
\]

where \( P_{ki} \) is the generation power of the \( i \)-th unit at \( k \)-th iteration. The neighbor of the solution is produced by:

\[
S_k^{\text{new}} = S_k + \Delta
\]

where \( \Delta \) is a coefficient vector with the same dimension as \( S_k \) at the \( k \)-th iteration.

One of the parameters of the algorithm is the size of the tabu list. A tabu list is maintained to prevent returning to previously visited solutions. The list contains information that to some extent forbids the search from returning to previously visited solutions. In this study, tabu restrictions are based on the recency and frequency memory storing the information about the past steps of the search [15]. The recency-based memory avoids cycles of length less than or equal to a predetermined number of iterations from occurring in the trajectory.

The frequency-based memory keeps the number of changes of solution vector elements. If an element of the solution vector does not satisfy the following tabu restrictions, then it is accepted as tabu:

\[
\text{Tabu Restrictions} = \begin{cases} 
\text{recency(k)} > \text{recency limit} \\
\text{or} \\
\text{frequency(k)} < \text{frequency limit}
\end{cases}
\]
To select the new solution from the neighbors, performance values of all neighbors are evaluated in the objective function given by eq. (1) for the economic dispatch or by eq. (5) for environmental economic dispatch. The non-tabu neighbor producing the highest improvement according to the present solution is then selected as the next solution. If there are some tabu neighbors which are better than the best solution found so-far, then those tabu solutions are freed.

4. Simulation Results. Economic Dispatch Results

The proposed tabu search method (PTS) has been applied to different test systems ranging from 3 to 240 units. The cost function of each unit is chosen as a quadratic function for the test systems. The PTS is compared with an improved Hopfield NN approach (IHN) [1], a fuzzy logic controlled genetic algorithm (FLCGA) [2], an advance engineered-conditioning genetic approach (AECGA) [3] and an advance Hopfield NN approach (AHNN) [4]. The proposed method was implemented in Matlab. The first test system, which has three units - see reference [7], is chosen. Transmission losses are calculated using (3) where the transmission loss coefficients B are given by:

\[ B = \begin{bmatrix} 0.00003 & 0.00009 & 0.00012 \end{bmatrix} \]  

In Table 1, the results of the proposed method (PTS) are compared with the results of the classical method (CM), standard Hopfield NN (SHN), the IHN [1] and the AHNN [4] for 3 load levels for the 3-unit system.

The classical optimization program (CM) which is based on the Sequential Quadratic Programming method was written using the Matlab Optimization Toolbox. It is seen that there is negligible difference in operation costs between the PTS and the CM. PTS provides the best results among the compared methods. The second test system has six units and details of this test system are obtained from [2]. Table 2 presents the results of PTS, IHN, AHNN and FLCGA when the load demands are 800 MW and 1200 MW. The FLCGA produced the highest operation cost and the obtained operation cost by the PTS is smaller than the IHN [1] respectively. For 800 MW of load demand, the operation cost of the AHNN is slightly higher than the operation cost of the proposed method.

Table 1. Results of CM, SHN, AHNN, IHN and PTS for 3-unit system

| Methods | \(P_{D}+P_{L}\) (MW) | Generator output (MW) | Cost ($/h) |
|---------|---------------------|---------------------|-----------|
|         | P_1     | P_2     | P_3     |            |           |
| CM      | 342.762  | 152.18  | 140.762 | 50.00     | 3742.9    |
|         | 867.14   | 401.22  | 341.08  | 124.84    | 8351.4    |
|         | 1179.1   | 592.33  | 400.00  | 186.77    | 11295     |
| SHN     | 342.754  | 170.35  | 104.18  | 68.211    | 3748.5    |
|         | 867.12   | 373.73  | 310.27  | 183.12    | 8370.6    |
|         | 1179.07  | 583.55  | 397.93  | 197.58    | 11297     |
| AHNN    | 342.762  | 159.64  | 133.02  | 50.092    | 3734.3    |
|         | 867.14   | 383.79  | 331.98  | 151.362   | 8355.4    |
|         | 1179.1   | 582.96  | 398.77  | 197.36    | 11297     |
| IHN     | 342.762  | 152.52  | 139.85  | 50.381    | 3742.9    |
|         | 867.14   | 401.67  | 340.66  | 124.81    | 8351.4    |
|         | 1179.1   | 592.12  | 399.57  | 187.01    | 11296     |
| PTS     | 342.000  | 151.74  | 140.25  | 50.000    | 3736.5    |
|         | 867.14   | 401.22  | 341.08  | 124.84    | 8351.4    |
|         | 1179.0   | 592.12  | 400.00  | 186.87    | 11294     |
Table 2. Results of FLCGA, IHN, AHNN and PTS for 6-unit system

| Methods | Load (MW) | Cost ($/h) | Load (MW) | Cost ($/h) |
|---------|-----------|------------|-----------|------------|
| FLCGA   | 800.0     | 8231.03    | 1200.0    | 11480.03   |
| IHN     | 8228.05   | 11477.20   |           |            |
| AHNN    | 8227.11   | 11477.09   |           |            |
| PTS     | 8227.09   | 11477.09   |           |            |

Table 3 will provide a comparison between all the economic dispatch results obtained by applying AECGA, IHN, AHNN or PTS in case of the 1520 MW as well as 2238 MW of necessary load demands.

Table 3. Results obtained by AECGA, IHN, AHNN and PTS

| Methods | Load (MW) | Cost ($/h) | Load (MW) | Cost ($/h) |
|---------|-----------|------------|-----------|------------|
| AECGA   | 1520.0    | 14169.54   | 2238.0    | 20470.48   |
| IHN     | 14169.54  | 20465.44   |           |            |
| AHNN    | 14169.54  | 20465.24   |           |            |
| PTS     | 14169.54  | 20465.24   |           |            |

It can be easily observed that the proposed method (PTS) achieved lower operation costs for different load demands; in contrast, the AECGA and, also, the IHN methods are generating some higher operational costs in case of certain loading conditions. For a necessary load demand of 2238 MW, we observe that the operational cost of the AECGA method is increased with 5.24 $/h compared with the operation cost of the proposed method.

In Table 4 we can notice the results of applying PTS, FLCGA, AECGA, IHN and AHNN when the necessary load demand is around 1800 MW. We notice that there is a slightly difference between the values obtained with different methods. The FLCGA method produces a higher operational cost compared with the other methods. According to data from Table 2 and Table 4, it is obvious that the fuzzy logic based genetic algorithm [2] generates the worst economic results among all these compared methods. It is also clear that the proposed method will produce the best solutions between all compared methods in case of a 6-unit production system.

Table 4. Results after applying the FLCGA, AHNN, IHN, AECGA and PTS in case of a 6-unit system having a necessary load demand of 1800 MW

| Methods | P_1(MW) | P_2 | P_3 | P_4 | P_5 | P_6 | Cost ($/h) |
|---------|---------|-----|-----|-----|-----|-----|------------|
| FLCGA   | 250.49  | 215.43 | 109.92 | 572.84 | 325.66 | 325.66 | 16585.85   |
| AECGA   | 248.07  | 217.73 | 75.30 | 587.70 | 335.60 | 335.60 | 16579.33   |
| IHN     | 248.08  | 217.74 | 75.18 | 587.90 | 335.55 | 335.55 | 16579.33   |
| AHNN    | 248.14  | 217.74 | 75.20 | 587.80 | 335.56 | 335.56 | 16579.33   |
| PTS     | 248.20  | 217.64 | 75.20 | 587.95 | 335.67 | 335.32 | 16579.32   |

In order to prove the efficiency and the liability of the newly proposed genetic algorithm, a complex system having 20 units is considered. Table 5 provides us a clear comparison of the obtained economic dispatch results in case of IHN, AHNN and our proposed method in case of that 20 unit based system. It is obvious that the PTS will generate lower operation results for different necessary load demands. Finally, the proposed method is tested on large systems which have 40, 80, 120, 160 and 240 generating units respectively. The 40-unit test system is given in reference [12]. The 20 unit system has been derived from the 40-unit system. The larger test systems which have 80, 120, 160 and 240 units have been created simply by expanding the 40-unit test system. Table VI demonstrates simulation results of IHN, AHNN and PTS for a single load level in each case.
It is obvious that for large systems, the proposed method produced lower operation costs than the IHN and the AHNN produced. For an example, all operation cost belonging to the IHN and, respectively to the AHNN, are 4450 $/h with a 950 $/h higher value than those of the proposed method for 57000 MW of load demand.

### Table 5. Simulation results in case of a 20 unit system

| Load (MW) | Cost ($/h) | IHN [1] | AHNN[4] | PTS |
|-----------|------------|---------|---------|-----|
| 3150      | 46460.84   | 46068.90| 46026.90|
| 3800      | 53207.7    | 52981.76| 52852.36|
| 4600      | 63791.72   | 63566.14| 63401.27|

### Table 6. Simulation results in case of large systems

| Unit No. | Load (GW) | Cost (Thousand $/h) | IHN [1] | AHNN[4] | PTS |
|----------|-----------|---------------------|---------|---------|-----|
| 40       | 9.5       | 129.1               | 128.59  | 128.42  |
| 80       | 20        | 272.8               | 272.15  | 271.98  |
| 120      | 31.5      | 432.6               | 431.89  | 431.78  |
| 160      | 41        | 560.7               | 559.80  | 559.64  |
| 240      | 57        | 774.98              | 771.52  | 770.57  |

### Table 7. Simulation results for CIGRE test system

| Classical Economic Dispatch (minimum cost) | GA [16] | PTS |
|-------------------------------------------|---------|-----|
| Cost (million $ / h)                      | 3.7006  | 3.7005|
| Emission SO₂ (t/h)                        | 11.0353 | 11.054|
| Emission NOₓ (t/h)                        | 3078.6  | 3080.2|
| Emission SO₂ Dispatch (Minimum SO₂)       | 3.8719  | 3.8720|
| Emission SO₂ (t/h)                        | 9.2434  | 9.2433|
| Emission NOₓ (t/h)                        | 3254.8  | 3252.2|
| Emission NOₓ Dispatch (Minimum NOₓ)       | 3.9149  | 3.9160|
| Cost (million $ / h)                      | 3.9149  | 3.9160|
| Emission SO₂ (t/h)                        | 11.8918 | 11.917|
| Emission NOₓ (t/h)                        | 2718.0  | 2717.9|

5. Environmental Economic Dispatch Results

In order to validate the proposed procedure, the environmentally constrained economic dispatch has been solved for a CIGRE network. The test system is the CIGRE network described in [12]. The system has 10 units with a 1750 MW demand and without transmission losses. The proposed method has been applied to the classical economic dispatch, the SO₂ emission dispatch, the NOₓ emission dispatch and the emission constrained economic dispatch for the CIGRE test system.
The results given in Table 7 of the proposed tabu search algorithm (PTS) are compared with those of the genetic algorithm (GA) [16]. The classical ED produces a minimum cost dispatch and the emission dispatch produces minimum emission levels. The emission constrained economic dispatch produces reasonable results in terms of cost and emissions [17]. For all economic dispatch problems, the overall performance of the PTS is better than those of the GA. In the case of classical ED, the proposed genetic algorithm produces less operation cost compared to GA algorithm. Emissions produced by PTS are slightly higher than those of GA [18]. In the SO$_2$ emission dispatch, PTS approaches objection of lower SO$_2$ emission better than GA. It also produces less NOx emission compared to GA. The operation cost of PTS is slightly higher than the operation cost of GA. In the NOx emission dispatch, PTS approaches objection of lower NOx emission better than GA [19]. For emission constrained economic dispatch, the PTS produces less the operation cost but more SO$_2$ emission and NOx emission than those of GA.

6. Conclusions
In this paper, a modified version of the tabu search algorithm is proposed for solving the economic and environmental economic dispatch problems. The algorithm uses a real-valued solution vector and adaptive mechanism for producing neighbors. In the case studies, the PTS has been applied to the economic dispatch problems with different sizes of systems having between 3 and 240 generating units. Simulation results show that the proposed method can provide better solutions when compared to an improved Hopfield NN approach, a fuzzy logic controlled genetic algorithm, an advance engineered-conditioning genetic approach and an advance Hopfield NN approach. The proposed algorithm can be easily extended to solve practical economic dispatch problems for large scale systems with a large number of constraints.

7. References
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