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Efficient Evolutionary Particle Swarm Optimization Approach for Nonconvex Economic Load Dispatch Problem

Abstract. *The main objective of economic load dispatch (ELD) is to allocate the output power generator at minimum cost while satisfying all the operation constraints. This paper presents a new hybrid method by integrating particle swarm optimization with time varying acceleration coefficients and evolutionary programming (TVAC-EPSO) for solving nonconvex ELD problem. The competition, sorting and selection in EP method are used to determine the best particle in PSO for finding the optimum solution efficiently. The proposed TVAC-EPSO has been tested on three different power system benchmarks. The simulation results have demonstrated the effectiveness of the proposed method in solving nonconvex ELD problem.*

Streszczenie. *W artykule przedstawiono hybrydową metodę ekonomicznie uzasadnionego określenia założeń dotyczących generowanej energii elektrycznej (ang. Economic Load Dispatch - ELD). Algorytm oparty jest na wykorzystaniu metody optymalizacji roju cząstek ze współczynnikami zmiennymi w czasie i programowaniu ewolucyjnym. (ang. TVAC-EPSO). Proponowana metoda została poddana weryfikacji na trzech różnych systemach energetycznych. Wyniki symulacyjne potwierdzają jej efektywność w analizie problemu ELD. (**Zagadnienie ekonomicznie uzasadnionego określenia wytwarzanej energii elektrycznej o charakterystyce niewypukłej – wykorzystanie metody optymalizacji roju cząstek**).*

Keywords: Economic load dispatch, particle swarm optimization, evolutionary programming, time varying acceleration coefficients.
Słowa kluczowe: zapotrzebowanie energetyczne, optymalizacja roju cząstek, programowanie ewolucyjne, zmienne w czasie współczynniki przyspieszenia.

Introduction

The economic load dispatch (ELD) is about minimizing the total generation cost of generating units in order to meet the power demand while satisfying equality and inequality constraints. Traditionally, the cost function of the generator is assumed to be piecewise linear and represented by a quadratic function. However, in practical, this assumption is no longer valid due to the valve point effect and prohibited operating zones (POZ) of generating units. This makes the ELD problem highly non linear and nonconvex optimization problem, which is difficult to be solved by mathematical approach. Moreover, the ELD problem becomes more complicated when ramp-rate limits and transmission losses are taken into account.

Many optimization methods have been used for solving classical ELD problem, such as lambda iteration, gradient method, linear programming and quadratic programming [1]. Most of these methods might be unable to solve nonconvex and discontinuous ELD problem efficiently. This is because these methods required monotonically increasing of incremental cost function, where the derivative information of the cost function exists.

In order to solve nonconvex ELD problem, heuristic methods such as evolutionary programming (EP), genetic algorithm, artificial immune system, tabu search, ant colony optimization and particle swarm optimization (PSO) have been implemented to solve nonconvex and discontinuous ELD problems [2]. These methods do not require the derivative information of the cost function. Thus, it can be used to solve nonconvex ELD problem due to valve point effects, prohibited operating zones, multi fuels options and nonlinear power flow constraints that cannot be solve by classical methods. However, these methods are not guaranteed in finding the optimum solution due to premature convergence.

Among these methods, the PSO method is widely used for solving ELD problem due to its simple implementation, less memory storage and able to find global solution. Many modifications and hybrid of PSO methods were proposed for solving the nonconvex ELD problem such as IPSO [3], SOH-PSO [4], PSO-MSAF [5], GA-PSO [6] and hybrid CPSO-SQP [7]. Nevertheless, the classical PSO can be further improved to obtain a good solution.

In this paper, a new hybrid approach is proposed by integrating particle swarm optimization with time varying acceleration coefficients and evolutionary programming named TVAC-EPSO for solving nonconvex ELD problem. The concepts of EP method based on competition, sorting and selection are applied for finding the best individual and group particle in PSO method. In addition, the time varying acceleration coefficients for both cognitive and social components are used to find the global optimum solution. The performance of the proposed TVAC-EPSO is tested on different power system which consists of 3, 6 and 15 generating units. The results obtained by TVAC-EPSO were compared with the existing results from the literature in terms of optimum cost and execution times.

Problem formulation

The objective of the ELD problem is to determine the optimal output power of a scheduled generator that minimizes the total generation cost (F_c) while equality and inequality constraints are satisfied as follows:

$$\text{Minimize } F_C = \sum_{i=1}^{N} F_i(P_i) \tag{1}$$

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i \tag{2}$$

When the valve point effect is considered, the generation cost function in (2) is added with rectified sinusoidal function to obtain an accurate ED modelling,

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i + \left| e_i \sin(f_i(P_i^{\min} - P_i)) \right| \tag{3}$$

where $F_i(P_i)$ is the total generation cost for generator i, P_i is the real power output of generator i, a_i, b_i and c_i are the cost coefficients for unit i and e_i and f_i are the cost coefficients for unit i with presence valve point effects.

Power balance constraints

The total power generated should be equal to the total power demand and transmission loss,

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

where P_D and P_L are the total real power demand and total transmission loss respectively.
The transmission loss can be calculated by using B-coefficient approach as

(5) $$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N} P_i B_{ij} P_j + \sum_{i=1}^{N} B_{0i} P_i + B_{00}$$

where, B_{ij}, B_{0i} and B_{00} are network loss coefficients.

Generator constraints
Each unit has a generation range which is represented as

(6) $$P_i^{\min} \le P \le P_i^{\max}$$

where P_i^{min} and P_i^{max} are the minimum and maximum limits of real power output for unit *i.*

Ramp rate limits
The effective generator limit with the presence ramp rate limits can be written as

(7) $$\max(P_i^{\min}, P_i^0 - DR_i) \le P_i \le \min(P_i^{\max}, P_i^0 + UR_i)$$

where P^0 is the previous real power output of unit *i* (MW), DR_i and UR_i are the upper and lower ramp rate limits of unit *i* (MW/time period) respectively.

Prohibited operating zones
The generating unit with prohibited operating zones have discontinuous and nonlinear cost characteristics. This characteristic can be formulated in ELD problem as follows:

(8) $$P_i \in \begin{cases} P_i^{\min} \le P_i \le P_{i,1}^{LB} \\ P_{i,z-1}^{UB} \le P_i \le P_{i,z}^{LB} \\ P_{i,Nz}^{UB} \le P_i \le P_i^{\max} \end{cases} \qquad z=2,3\ldots,Nz$$

where $P_{i,z}^{LB}$ and $P_{i,z}^{UB}$ are the lower and upper limits of POZ of generator *i* in (MW) respectively and N_z is the number of POZ of *i*-th generator.

Review PSO method
The particle swarm optimization is developed by Kennedy and Eberhart in 1995 based on of bird flocking and fish schooling [8]. This method is a population based optimization approach, where each particle represents the possible solution in *d* dimensional search space. Each particle will fly around the possible search space according to their own previous experience and the group experience. The position of each particle (*X*) is updated using the following formulas:

(9) $$V_{id}^{j+1} = wV_{id}^{j} + c_1 r_1 (pbest_{id}^{j} - X_{id}^{j}) + c_2 r_2 (gbest_d^{j} - X_{id}^{j})$$

(10) $$X_{id}^{j+1} = X_{id}^{j} + V_{id}^{j}$$

where V_{id}^{j+1} is the updated velocity of *i*-th particle in dimension *d*, *w* is the inertia weight factor, c_1 and c_2 are acceleration coefficient for cognitive and social components respectively, r_1 an r_2 are uniform random number between 0 and 1 respectively, X_{id}^{J+1} is the update position of *i*-th particle in dimension, X_{id}^{j} is the position of *i*-th particle in current iteration *j*, *pbest* is the best position reached by *i*-th particle and *gbest* is the best position found in a population.

The linearly decreasing of *w* with increasing iteration *j* is computed using (11) [9].

(11) $$w = w_{\max} - (\frac{w_{\max} - w_{\min}}{j_{\max}}) \times j \qquad j=1,2,...,iter_{max}$$

w_{min} and w_{max} are the initial and final value of inertia weights respectively and j_{max} is the maximum number of iteration.

Proposed TVAC-EPSO
In order to improve the performance of PSO, the hybrid particle swarm optimization and evolutionary optimization (EPSO) was proposed by P.J. Angeline [10]. This method was successfully applied in power system application [11]. The performance of heuristic method like PSO algorithm depends on the parameters selection. Therefore, it should be tuned properly to obtain the best solution. However, in EPSO method, the value of acceleration coefficients (c_1 and c_2) for cognitive and social component is fixed to a constant value during iteration process.

The proper selection of acceleration coefficients (c_1 and c_2) can help the algorithm to produce the global or near to the global solution. The time varying acceleration coefficients (TVAC) is used to control the exploration and exploitation of the algorithm in search space. If the coefficients value of c_1 is higher than c_2, the particles will guide the particles to explore the entire search space. However, a higher value of c_2 than c_1 will force the particles to obtain the better solution [12]. In the proposed TVAC-EPSO, the initial value of c_1 is set relatively higher than c_2 in order to increase the exploration capability throughout the possible solution. As number of iteration increases, the values of c_1 and c_2 will decrease and increase respectively. Thus, it can attract the particles to find the optimal solution. The TVAC are varies as the iteration increases and is computed as follows:

(12) $$c_1 = c_{1i} + (\frac{c_{1f} - c_{1i}}{j_{\max}}) \times j$$

(13) $$c_2 = c_{2i} + (\frac{c_{2f} - c_{2i}}{j_{\max}}) \times j$$

The PSO algorithm is used as the main optimization method in the proposed TVAC-EPSO method. In order to determine the *pbest* and *gbest* value, the concept of combination, tournament competition and sorting in EP are integrated in PSO. After combined the particles in previous and current iteration, the particle will compete with other particle based on the competition rate. Then, the winner position in *N* number of a population will be chosen as the survival positions. These results will used to determine the current *pbest* and *gbest* value for updating the new position. The procedures of the TVAC-EPSO method are summarized as follows:

Step 1: Initialization of PSO parameter.
Step 2: Evaluate the fitness function of every particle
Step 3: Initialize the *pbest* and *gbest* on fitness function.
Step 4: Implement the combination, tournament selection and sorting process using the EP concept.
Step 5: Determine the *pbest* and *gbest* value. The update of the particle position is based on (9) to (10).
Step 6: Step 4 is repeated until stopping criteria is satisfied.

Simulation results and analysis

In order to validate the feasibility of the proposed TVAC-EPSO method, it has been applied to solve ELD problems on three different test systems. To obtain the optimum solution using TVAC-EPSO method, the following parameters have been used for all test systems; population size = 30, c_{1i}=c_{2f}=0.2, c_{2i}=c_{1f}=1.0 and competition rate = 25%. The maximum number of iterations was used as the stopping criteria. The simulation was written in MATLAB 7.6 and was executed on Core 2 Quad processor, 4 GB RAM.

Test system 1: 3-unit system

The test system 1 consists of 3-generating units with valve point effects. The cost characteristic of the generators are modelled as in (3) with equality and inequality constraints in (4) to (6). All input data (fuel cost coefficients and generator limits) are given in [13]. For comparison with other methods, the transmission losses are not considered. The total real power demand is 850 MW.

The results obtained by the proposed TVAC-EPSO method have been compared with EP, PSO, EP-SQP and CPSO-SQP [7, 14]. Table 1 shows the comparison of the best results produced by various methods in term of generation cost and execution time. It can be seen that all methods can reach a global optimum solution (8234.07 $) due to the simple system. However, the execution time for the proposed method is less than other methods, as shown in Fig. 1. The execution time is measured based on the maximum number of iteration run by TVAC-EPSO. The convergence characteristic of TVAC-PSO is shown in Fig. 2. It is obvious that the proposed method can reach a global solution after 30 iterations. Therefore, this method can increase the capability of the algorithm to reach the optimum solution within shorter execution time.

Test system 2: 6-unit system

The second test system consists of 6-generating units. All input data for this system are given in [15] and the total real power demand is 1260 MW. In this test system, the POZ and ramp rate limit of the generator in (7) and (8) are considered as inequality constraints. The transmission losses are calculated using (5). This system has non-continuous fuel cost characteristic with multiple local minima due to POZ and transmission loss.

Table 2 shows the best results achieved by the proposed TVAC-EPSO method. It can be seen that the proposed method can produce lower generation cost than GA [15], PSO [15] and NPSO_LRS [16]. Moreover, the execution time of the proposed method is less than other methods, as shown in Table 2. The convergence characteristic of the proposed method is shown in Fig. 3.

For this case, the TVAC-EPSO method is better than other techniques in obtaining the best generation cost. In addition, it can provide significant reduction in simulation time execution.

Test system 3: 15-unit system

The input data of 15-generating units are given in [15]. The total real power demand is 2630 MW. For this test system, large number of generators is used to validate the effectiveness of the proposed method. The POZ and ramp rate limits are considered as the generator constraints. The transmission losses are calculated using (5).

The best results produced by TVAC-EPSO are presented in Table 3. They were compared with the results reported in literatures, such as GA [15], PSO [15], SOH-PSO [4], GA-API [17] and PSO-MSAF [5]. From Table 3, it clearly shows that the proposed method yields lower generation cost and less execution time than other methods (except for SOH-PSO). Fig. 4 shows the potential cost saving of TVAC-EPSO and other methods (compared to GA). Therefore, this method can provide a significant cost saving compared to other methods. The convergence characteristic of the proposed method is shown in Fig. 5.

Table 1. Best result for 3-unit system

Power Output (MW)	EP	PSO	EP-SQP	CPSO-SQP	TVAC-EPSO
P_1	300.26	300.27	300.27	300.27	300.27
P_2	400.00	400.00	400.00	400.00	400.00
P_3	149.74	149.73	149.73	149.734	149.73
Total P	850.00	850.00	850.00	850.00	850.00
Cost ($)	**8234.07**	**8234.07**	**8234.07**	**8234.07**	**8234.07**
Time (S)	**6.78**	**4.37**	**5.12**	**2.06**	**1.03**

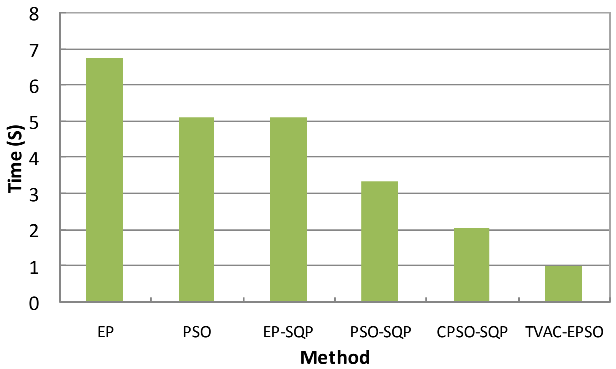

Fig.1. Comparison of execution times for different method for 3-unit system

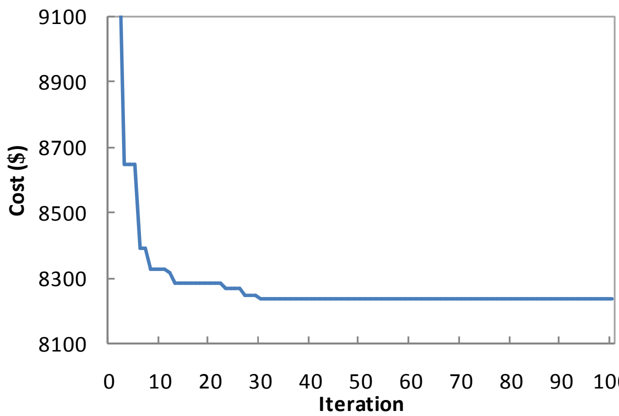

Fig.2. Convergence characteristic for 3-unit system

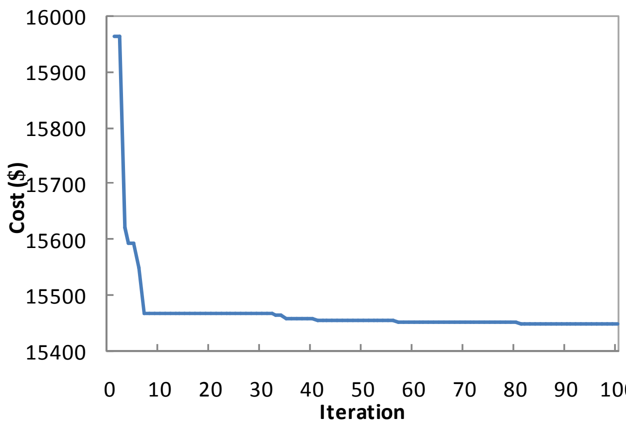

Fig.3. Convergence characteristic for 6-unit system

Table 2. Best result for 6-unit system

Method	Power (MW)								Cost ($)	Time (S)
	P1	P2	P3	P4	P5	P6	Total P	Loss		
GA	474.81	178.64	262.21	134.28	151.90	74.18	1276.03	13.02	**15459.0**	**26.59**
PSO	447.47	173.10	262.68	139.42	165.30	87.98	1275.95	12.95	**15450.0**	**49**
NPSO_LRS	446.96	173.39	262.34	139.51	164.71	89.02	1275.94	12.94	**15450.0**	**NA***
TVAC-EPSO	447.50	173.32	263.46	139.07	165.47	87.13	1275.96	12.96	**15449.9**	**1.61**

* NA is not available in the reference [16]

Table 3. Best result for 15-unit system

Power output (MW)	GA	PSO	SOH-PSO	GA-API	PSO-MSAF	TVAC-EPSO
P_1	415.31	439.12	455.00	454.70	455.00	455.00
P_2	359.72	407.97	380.00	380.00	379.99	379.96
P_3	104.43	119.63	130.00	130.00	130.00	130.00
P_4	74.99	129.99	130.00	129.53	130.00	130.00
P_5	380.28	151.07	170.00	170.00	169.99	170.00
P_6	426.79	460.00	459.96	460.00	459.99	460.00
P_7	341.32	425.56	430.00	429.71	429.99	430.00
P_8	124.79	98.57	117.53	75.35	127.82	93.02
P_9	133.14	113.49	77.90	34.96	33.36	34.29
P_{10}	89.26	101.11	119.54	160.00	126.34	160.00
P_{11}	60.06	33.91	54.50	79.75	79.99	79.17
P_{12}	50.00	79.96	80.00	80.00	80.00	80.00
P_{13}	38.77	25.00	25.00	34.21	25.00	25.00
P_{14}	41.94	41.41	17.86	21.14	17.87	15.00
P_{15}	22.64	35.61	15.00	21.02	15.15	19.38
Total Power	2668.4	2662.4	2662.29	2660.36	2660.49	2660.83
Loss	38.28	32.43	32.28	30.36	30.49	30.83
Cost ($)	**33113**	**32858**	**32751.39**	**32732.95**	**32713.09**	**32711.96**
Time (S)	**49.3**	**26.59**	**0.0936**	**NA***	**19.15**	**2.99**

*NA is not available in reference [17]

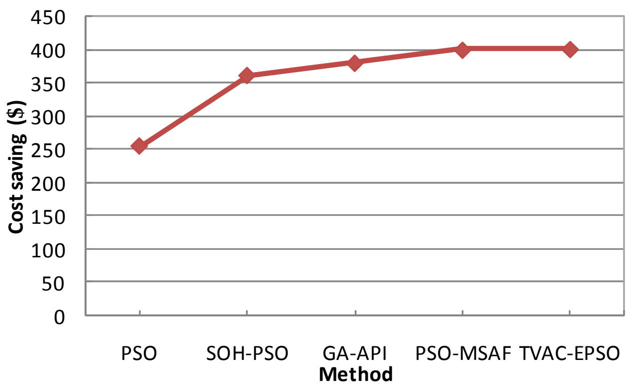

Fig.4. Potential cost saving compared to GA method (15-unit system)

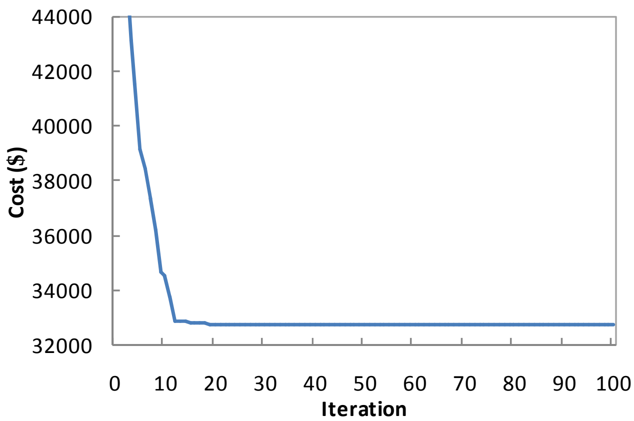

Fig. 5. Convergence characteristic for 15-unit system

Conclusion

In this paper, a hybrid method incorporating PSO with TVAC and EP, called TVAC-EPSO has been proposed to solve nonconvex ED problems. The performance of the proposed method has been tested on three different test systems which consider the practical generator constraints such as valve point effects, POZ and ramp rate limits. The results obtained by TVAC-EPSO method were compared with other methods reported in literatures. The comparison study was done based on the optimum generation cost and execution time for every test system. The proposed method is able to reduce the generation cost significantly especially for a large system (15-unit system). Also, this method is able to reach an optimum solution within less computation time. From this study, it can be concluded that the proposed TVAC-EPSO method can be an alternative approach in finding a better optimum solution for nonconvex ELD problems.

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