Network and Generator Constrained Economic Dispatch Using Hybrid PSO-QP Algorithm

Keerati Chayakulkheeree, *Member, IEEE* and Wattanapon Kamklar

Abstract-- **This paper proposes a hybrid particle swarm optimization (PSO) and quadratic programming (QP) algorithm for power system economic dispatch (ED) with transmission line limit and transformer loading and generator prohibited operating zones constraints. In the proposed PSO-QP-ED algorithm, the sets of real power generation at generator bus are used as particles in the PSO. The quadratic programming ED with transmission line limit and transformer loading constrained is performed every generation to obtain the best solution of each population search. The proposed PSO-QP-ED is tested with the IEEE 30 bus system and compared to the PSO-ED. The proposed PSO-QP-ED results in more probability to obtain global minimum total system operating cost in the constrained ED than the PSOED considering generator prohibited operating zones constraints.**

Index Terms-- **economic dispatch, particle swarm optimization, quadratic programming, generator prohibit operating zone.**

I. Introduction

ECONOMIC dispatch (ED) plays an importance role in power system operation. The principal objective of ED is to obtain the minimum operating cost satisfying power balance constraint. Currently, the ED problem includes generator and network limits constraints. The cost function for each generator is usually approximately represented by a single quadratic function and solved by mathematical programming based on optimization techniques such as gradient method, linear programming or quadratic programming (QP) [1]. However, the input output characteristics of large units are actually having discontinuously cost curves due to valve-point and multi-fuel effects [2-5]. These discontinuously cost curves were usually ignored in the ED method leading to inaccurate dispatch result. To obtain accurate dispatch results, approaches without restriction on the shape of incremental fuel cost functions are needed.

The practical ED problems with valve-point and multi-fuel effects are represented as a non-smooth optimization problem with equality and inequality constraints, and this makes the problem of finding the global optimum difficult. To solve this problem, many salient methods have been proposed such as genetic algorithm [3], evolutionary programming [4], Tabu search [5], and particle swarm optimization (PSO) are considered as powerful method to obtain the solutions in power system optimization problems [2], [6-8].

PSO [9] is one of the modern heuristic algorithms which gained lots of attention in various power system applications. PSO can be applied to nonlinear and non-continuous optimization problems with continuous variables. It has been developed through simulation of simplified social models. PSO is similar to the other evolutionary algorithms in that the system is initialized with a population of random solutions.

Generally, the PSO is characterized as a simple heuristic of well balanced mechanism with flexibility to enhance and adapt to both global and local exploration abilities [9]. It is a stochastic search technique with reduced memory requirement, computationally effective and easier to implement compared to other artificial intelligent technique. Also, PSO has a more global searching ability at the beginning of the run and a local search near the end of the run. Therefore, while solving problems with more local optima, there are more possibilities for the PSO to explore local optima at the end of the run.

In [2], a modified PSO mechanism was suggested to deal with the equality and inequality constraints in the ED problems. A PSO method for solving the ED problem with generator prohibited zone and non-smooth cost function was proposed in [6]. However, the methods require large number of population search in order to obtain global or near global optima. To overcome this drawback a hybrid method that integrates the PSO with sequential quadratic programming (SQP) was proposed in [7-8]. Nonetheless, transmission line and transformer loading limit constraints were not included in the problem formulation.

In this paper, hybrid particle swarm quadratic programming based economic dispatch (PSO-QP-ED) with network and generator constrained algorithm is proposed. The transmission line and transformer loading and generator prohibited operating zones constraints are taken into account. In the proposed PSO-QP-ED algorithm, the sets of real power generation at generator bus are used as particles in the PSO. The QP based ED with transmission line limit and transformer loading constraints is performed every generation to obtain the best solution of each population search. The proposed PSO-QP-ED is tested with the IEEE 30 bus system and compared to the PSOED (without QP) under transmission line and transformer loading limit constraints and generators discontinues operating cost functions.

The organization of this paper is as follows. Section 2 addresses the PSO-QP-ED problem formulation. The Hybrid PSO-QP algorithm for PSO-QP-ED problem is given in

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Section 3. Numerical results on the IEEE 30 bus test system are illustrated in Section 4. Lastly, the conclusion is given.

II. PSO-QP-ED Problem Formulation

The PSO-QP-ED objective function can be expressed as, Minimize total system operating cost,

$$FC = \sum_{i \in BG} F(P_{Gi}), \tag{1}$$

subject to the power balance constraints,

$$P_{Gi} - P_{Di} = \sum_{j=1}^{NB} |V_i||V_j||y_{ij}|\cos(\theta_{ij} - \delta_{ij}), i = 1,...,NB, \tag{2}$$

$$Q_{Gi} - Q_{Di} = -\sum_{j=1}^{NB} |V_i||V_j||y_{ij}|\sin(\theta_{ij} - \delta_{ij}), i = 1,...,NB, \tag{3}$$

and the line flow limit and transformer loading constraints,

$$|f_l| \le f_l^{\max}, \text{ for } l=1, \ldots, NL, \tag{4}$$

and generator minimum, maximum, and prohibited operating zones limits constraints,

$$P_{Gi}^{l,j} \le P_{Gi} \le P_{Gi}^{u,j}, \ i \in BG, j = 1,\ldots,NZ_i, \tag{5}$$

$$P_{Gi}^{l,1} = P_{Gi}^{\min}, \tag{6}$$

$$P_{Gi}^{u,NZ_i} = P_{Gi}^{\max}, \tag{7}$$

where

FC is the total system operating cost (\$/h),

$F(P_{Gi})$ is the operating cost of the generator connected to bus i (\$/h),

P_{Gi} is the real power generation of the generator connected to bus i (MW),

P_{Di} is the real power load at bus i (MW),

$|V_i|$ is the voltage magnitude of bus i (V),

BG is the set of buses connected with generators,

$f_l^{\max}$ is the MVA flow limit of line or transformer l (MVA),

NB is the total number of buses,

$P_{Gi}^{\max}$ is the maximum real power generation at bus i (MW),

$P_{Gi}^{\min}$ is the minimum real power generation at bus i (MW),

Q_{Di} is the reactive power demand at bus i (MVAR),

$|y_{ij}|$ is the magnitude of the y_{ij} element of Y_{bus} (mho),

θ_{ij} is the angle of the y_{ij} element of Y_{bus} (radian),

f_l is the MVA flow of line or transformer l (MVA),

Q_{Gi} is the reactive power generation at bus i (MVAR),

δ_{ij} is the voltage angle difference between bus i and j (radian)

$P_{Gi}^{l,j}$ and $P_{Gi}^{u,j}$ are the boundary of the generator prohibited operating zone. P_{Gi}, $i \in BG$, is the output of the PSO-QP-ED algorithm. The method is intended to line flow and transformer loading limits constrained economic dispatch in power system. The bus voltages and reactive power controls are not included in the paper.

III. CFCOPD Algorithm

In a PSO system, particles fly around in a multidimensional search space. During flight, each particle adjusts its position according to its own experience, and the experience of neighboring particles, making use of the best position encountered by itself and its neighbors. The swarm direction of a particle is defined by the set of particles neighboring the particle and its history experience. In the proposed hybrid PSO-QP-ED algorithm, the set of particle is represented as,

$$\mathbf{P_{Gi}} = [\mathbf{P_{Gi}^1}, \mathbf{P_{Gi}^2}, ..., \mathbf{P_{Gi}^M}], \tag{8}$$

$$\mathbf{P_{Gi}^j} = [P_{G1}^j, P_{G2}^j, ..., P_{G,NG}^j]^T \tag{9}$$

Where P_{Gi} is the matrix representing the set of individual searches. More specifically, it is the set of the generator real power generations. The sub-matrix $\mathbf{P_{Gi}^j}$ is the set of current position of particle j representing the real power generation of the generator connected to bus i (P_{Gi}^j). Each particle is used to solve the quadratic programming optimal power flow (QPOPF) and the best previous position of the jth particle is recorded and represented as,

$$\mathbf{pbest} = [pbest_1, pbest_2, ..., pbest_{NG}]^T. \tag{10}$$

The index of the best particle among all the particles in the group is represented by the $gbest^j$. The rate of the velocity for particle j is represented as,

$$\mathbf{u^j} = [u_1^j, u_2^j, \ldots, u_{NG}^j]^T \tag{11}$$

The modified velocity and position of each particle can be calculated using the current velocity and the distance from $pbest_i$ to $gbest_i$ as shown in the following formulas:

$$u_i^{j(t+1)} = w.u_i^{j(t)} + c_1 \cdot rand() \cdot (pbest_i - P_{Gi}^{j(t)}) + C_2 \cdot Rand() \cdot (gbest_i - P_{Gi}^{j(t)}), \quad j = 1,2,....,M, i = 1,2,...,NG, \tag{12}$$

$$P_{Gi}^{j(t+1)} = P_{Gi}^{j(t)} + v_i^{j(t+1)}, j = 1,2,....,M, i = 1,2,...,NG, \tag{13}$$

$$u_i^{\min} \le u_i^j \le u_i^{\max} \tag{14}$$

where

M is the number of particles in a group,

NG is the number of members in a particle,

t is the pointer of iterations (generations),

w is the inertia weight factor,

c_1, c_2 are the acceleration constants,

$rand(), Rand()$ are the uniform random values in the range [0,1],

$u_i^{j(t)}$ is the velocity of particle j corresponding to P_{Gi} at iteration t, and

$P_{Gi}^{j(t)}$ is the current position of particle j corresponding to P_{Gi} at iteration t.

The parameter V_i^{max} determined the resolution, or fitness, with which regions are to be searched between the present position and the target position. If u_i^{max} is too high, particles might fly past good solutions. If u_i^{max} is too small, particles may not explore sufficiently beyond local solutions. In many experiences with PSO, u_i^{max} was often set at 10–20% of the dynamic range of the variable on each dimension [2].

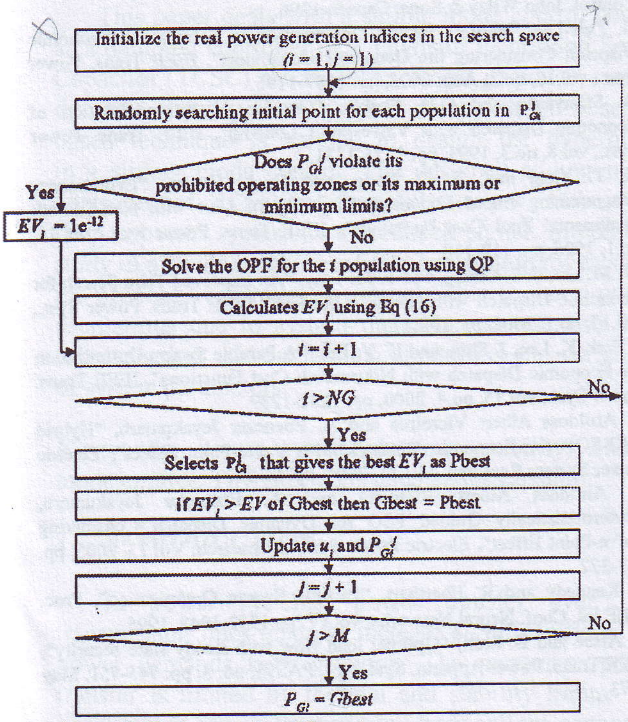

Fig. 1. PSO-QP-ED Computational Procedure

The constants c_1 and c_2 represent the weighting of the stochastic acceleration terms that pull each particle toward the $pbest_i$ and $gbest_i$ positions. Low values allow particles to roam far from the target regions before being tugged back. On the other hand, high values result in abrupt movement toward, or past, target regions. Hence, the acceleration constants c_1 and c_2 were often set to be 2.0 according to past experiences [2], [7]. Suitable selection of inertia weight w provides a balance between global and local explorations, thus requiring less iteration on average to find a sufficiently optimal solution. As originally developed, w often decreases linearly from about 0.9 to 0.4 during a run [2], [7]. In general, the inertia weight w is set according to the following equation:

$$w = w_{max} - \frac{w_{max} - w_{min}}{M} \cdot t. \quad (15)$$

The evaluation value is normalized into the range between 0 and 1 as,

$$EV = 1/(F_{cost} + P_{pbc}) \quad (16)$$

$$\text{where } F_{cost} = 1 + abs\frac{(\sum_{i \in BG} F(P_{Gi}) - F_{min})}{(F_{max} - F_{min})}, \quad (17)$$

$$P_{pbc} = 1 + \left(\sum_{i \in BG} P_{Gi} - \sum_{i=1}^{NB} P_{Di} - P_{loss} \right)^2, \quad (18)$$

F_{max} is the maximum generation cost among all individuals in the initial population, and

F_{min} is the minimum generation cost among all individuals in the initial population.

In order to limit the evaluation value of each individual of the population within a feasible range, before estimating the evaluation value of an individual, the generation power output must satisfy the constraints in (5). If one individual satisfies all constraints, then it is a feasible individual and F_{cost} has a small value. Otherwise, the F_{cost} value of the individual is penalized with a very large positive constant. The computational procedure is shown in Fig. 1.

IV. Numerical Results

The IEEE 30 bus system [10] is used as the test data. It network diagram is shown in Fig.2. The generator fuel cost functions and prohibited operating zones are given in Table 1. The parameters of the proposed PSO-QP-ED and the PSOED are as follows;

Population size = 200,
Generation (M) = 10,
$w_{min} = 0.4$, $w_{max} = 0.9$,
$u_i^{max} = 0.5 \cdot P_{Gi}^{max}$, $u_i^{min} = -0.5 \cdot P_{Gi}^{min}$,
$C_1 = 2$, and $C_2 = 2$.

Table 1
Generator operating cost functions and constraints

Gen Bus	$F(P_{Gi}) = a_i + b_i \cdot P_{Gi} + c_i \cdot P_{Gi}^2$			P_{Gi}^{min}	P_{Gi}^{max}	Generator Prohibited Operating Zone			
	a_i	b_i	c_i	MW	MW	From MW	To MW	From MW	To MW
1	0	2	0.00375	50	200	100	120	150	160
2	0	1.75	0.0175	20	80	25	30	40	60
5	0	1	0.0625	15	50	20	25	40	45
8	0	3.25	0.00834	10	35	15	20	25	30
11	0	3	0.025	10	30	15	18	22	25
13	0	3	0.025	12	40	20	25	30	35

Table 2
Results of IEEE 30 Bus Test System

	PSOED			PSO-QP-ED		
	Min	Aver.	Max	Min	Aver.	Max
Total System Operating Cost ($/h)	806.10	818.13	834.05	805.14	809.46	816.47
Computation Time of the Best Trial Solution (sec)	52.67			69.39		

Table 2 addresses the summary results of PSOED and the proposed PSO-QP-ED from 50 trials. The convergence property of the best solution of PSO-QP-ED and PSOED are shown in Fig.3. Figure 4 shows the total system operating cost from 50 trials of POSED and PSO-QP-ED. The results show that the total system operating costs of the proposed PSO-QP-ED are lower than that of the PSOED. The computational time of PSO-QP-ED is longer than that of the PSOED due to PSO-QP-ED solves QPOPF for each individual search in the search space. The computational time of the proposed method could be decreased by using parallel computation method. However, the PSO-QP-ED gives more probability to obtain the global minimum total system operating cost.

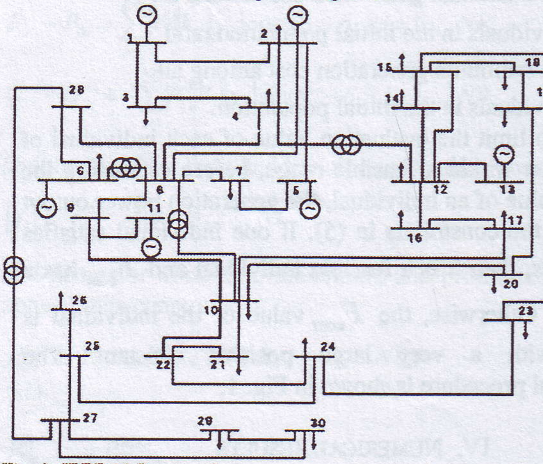

Fig. 2. IEEE 30 Bus test System

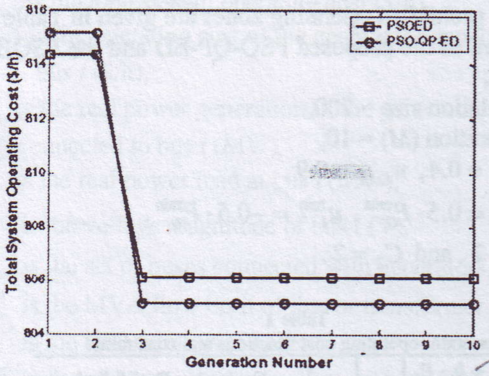

Fig. 3. Convergence properties of IEEE 30 bus test system

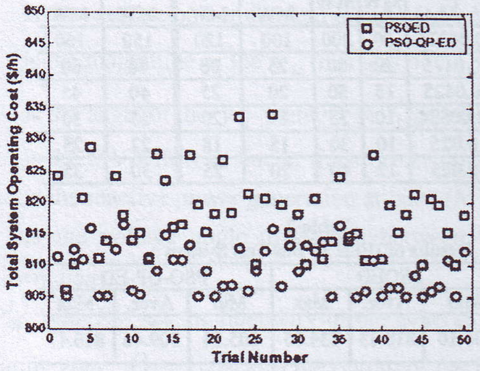

Fig. 4. The results from 50 trials of IEEE 30 bus test system

V. Conclusion

In this paper, a hybrid particle swarm optimization and quadratic programming for economic dispatch (PSO-QP-ED) is efficiently minimizing the total system operating cost satisfying transmission line limits and transformer loading constraints with the generator prohibited operating zones constraints. The proposed PSO-QP-ED results in more probability to obtain global minimum total system operating cost in the constrained ED with generator prohibited operating zones constraints than the PSOED.

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VII. Biographies

Dr. Keerati Chayakulkheeree received the M.Eng and D.Eng. degrees in Electric Power System Management from Asian Institute of Technology in 1999 and 2004, respectively. He is currently a Head of EE department, Sripatum University, Thailand. His research interests are in power system analysis, optimization and AI applications to power systems, and power system restructuring and deregulation.

Mr. Wattanapon Kamklar received the B.Eng (Honor) degrees in EE from Sripatum University in 1999. He is currently a lecturer of EE department, Sripatum University, Thailand.

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In [2], a modified PSO mechanism was suggested to deal with the equality and inequality constraints in the ED problems. A PSO method for solving the ED problem with generator prohibited zone and non-smooth cost function was proposed in [6]. However, the methods require large number of population search in order to obtain global or near global optima. To overcome this drawback a hybrid method that integrates the PSO with sequential quadratic programming (SQP) was proposed in [7-8]. Nonetheless, transmission line and transformer loading limit constraints were not included in the problem formulation.

In this paper, hybrid particle swarm quadratic programming based economic dispatch (PSO-QP-ED) with network and generator constrained algorithm is proposed. The transmission line and transformer loading and generator prohibited operating zones constraints are taken into account. In the proposed PSO-QP-ED algorithm, the sets of real power generation at generator bus are used as particles in the PSO. The QP based ED with transmission line limit and transformer loading constraints is performed every generation to obtain the best solution of each population search. The proposed PSO-QP-ED is tested with the IEEE 30 bus system and compared to the PSOED (without QP) under transmission line and transformer loading limit constraints and generators discontinues operating cost functions.

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III. CFCOPD Algorithm

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The modified velocity and position of each particle can be calculated using the current velocity and the distance from $pbest_i$ to $gbest_i$ as shown in the following formulas:

$$\begin{aligned} u_i^{j(t+1)} &= w.u_i^{j(t)} + c_1 \cdot rand() \cdot (pbest_i - P_{Gi}^{j(t)}) \\ &+ C_2 \cdot Rand() \cdot (gbest_i - P_{Gi}^{j(t)}), \\ &j = 1,2,...., M, i = 1,2,..., NG, \end{aligned} \tag{12}$$

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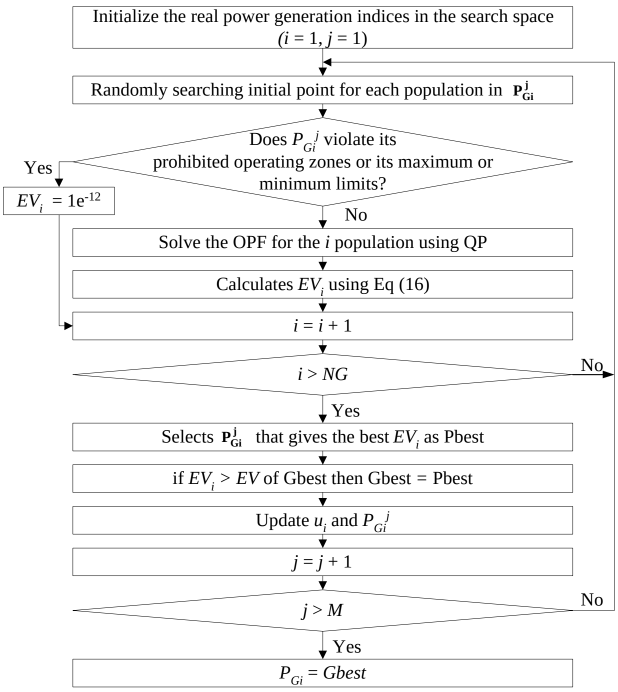

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$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{M} \cdot t \, . \qquad (15)$$

The evaluation value is normalized into the range between 0 and 1 as,

$$EV = 1/(F_{\cos t} + P_{pbc}) \qquad (16)$$

where $F_{\cos t} = 1 + abs \frac{\left(\sum_{i \in BG} F(P_{Gi}) - F_{\min}\right)}{(F_{\max} - F_{\min})}$, (17)

$$P_{pbc} = 1 + \left(\sum_{i \in BG} P_{Gi} - \sum_{i=1}^{NB} P_{Di} - P_{loss} \right)^2 , \qquad (18)$$

$F_{\max}$ is the maximum generation cost among all individuals in the initial population, and

$F_{\min}$ is the minimum generation cost among all individuals in the initial population.

In order to limit the evaluation value of each individual of the population within a feasible range, before estimating the evaluation value of an individual, the generation power output must satisfy the constraints in (5). If one individual satisfies all constraints, then it is a feasible individual and $F_{\cos t}$ has a small value. Otherwise, the $F_{\cos t}$ value of the individual is penalized with a very large positive constant. The computational procedure is shown in Fig. 1.

IV. Numerical Results

The IEEE 30 bus system [10] is used as the test data. It network diagram is shown in Fig.2. The generator fuel cost functions and prohibited operating zones are given in Table 1. The parameters of the proposed PSO-QP-ED and the PSOED are as follows;

Population size = 200,
Generation (M) = 10,
$w_{\min} = 0.4$, $w_{\max} = 0.9$,
$u_i^{\max} = 0.5 \cdot P_{Gi}^{\max}$, $u_i^{\min} = -0.5 \cdot P_{Gi}^{\min}$,
$C_1 = 2$, and $C_2 = 2$.

Table 1
Generator operating cost functions and constraints

Gen Bus	$F(P_{Gi}) = a_i + b_i \cdot P_{Gi} + c_i \cdot P_{Gi}^2$			$P_{Gi}^{\min}$	$P_{Gi}^{\max}$	**Generator Prohibited Operating Zone**			
	a_i	b_i	c_i	**MW**	**MW**	**From** MW	**To** MW	**From** MW	**To** MW
1	0	2	0.00375	50	200	100	120	150	160
2	0	1.75	0.0175	20	80	25	30	40	60
5	0	1	0.0625	15	50	20	25	40	45
8	0	3.25	0.00834	10	35	15	20	25	30
11	0	3	0.025	10	30	15	18	22	25
13	0	3	0.025	12	40	20	25	30	35

Table 2
Results of IEEE 30 Bus Test System

	PSOED			PSO-QP-ED		
Total System Operating Cost ($/h)	Min	Aver.	Max	Min	Aver.	Max
	806.10	818.13	834.05	805.14	809.46	816.47
Computation Time of the Best Trial Solution (sec)	52.67			69.39		

Table 2 addresses the summary results of PSOED and the proposed PSO-QP-ED from 50 trials. The convergence property of the best solution of PSO-QP-ED and PSOED are shown in Fig.3. Figure 4 shows the total system operating cost from 50 trials of POSED and PSO-QP-ED. The results show that the total system operating costs of the proposed PSO-QP-ED are lower than that of the PSOED. The computational time of PSO-QP-ED is longer than that of the PSOED due to PSO-QP-ED solves QPOPF for each individual search in the search space. The computational time of the proposed method could be decreased by using parallel computation method. However, the PSO-QP-ED gives more probability to obtain the global minimum total system operating cost.

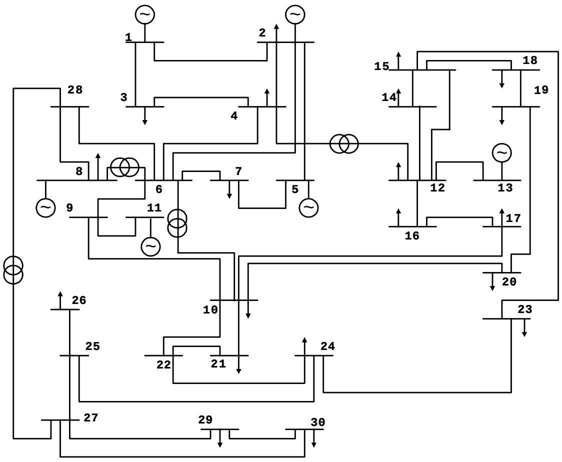

Fig. 2. IEEE 30 Bus test System

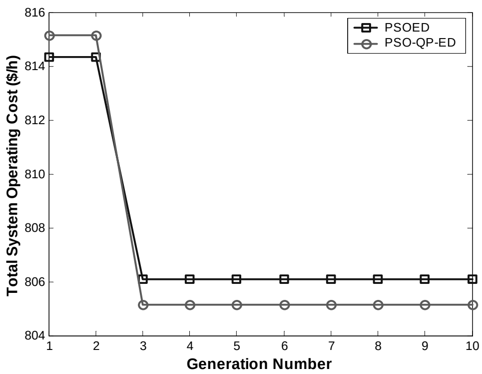

Fig. 3. Convergence properties of IEEE 30 bus test system

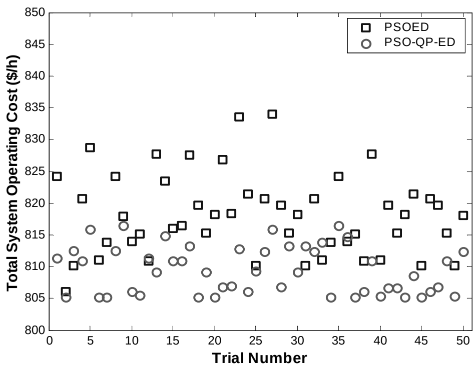

Fig. 4. The results from 50 trials of IEEE 30 bus test system

V. Conclusion

In this paper, a hybrid particle swarm optimization and quadratic programming for economic dispatch (PSO-QP-ED) is efficiently minimizing the total system operating cost satisfying transmission line limits and transformer loading constraints with the generator prohibited operating zones constraints. The proposed PSO-QP-ED results in more probability to obtain global minimum total system operating cost in the constrained ED with generator prohibited operating zones constraints than the PSOED.

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VII. Biographies

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