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An Improved Mean-Variance Optimization for Nonconvex Economic Dispatch Problems

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Abstract – This paper presents an efficient approach for solving economic dispatch (ED) problems with nonconvex cost functions using a 'Mean-Variance Optimization (MVO)' algorithm with Kuhn-Tucker condition and swap process. The aim of the ED problem, one of the most important activities in power system operation and planning, is to determine the optimal combination of power outputs of all generating units so as to meet the required load demand at minimum operating cost while satisfying system equality and inequality constraints. This paper applies Kuhn-Tucker condition and swap process to a MVO algorithm to improve a global minimum searching capability. The proposed MVO is applied to three different nonconvex ED problems with valve-point effects, prohibited operating zones, transmission network losses, and multi-fuels with valve-point effects. Additionally, it is applied to the large-scale power system of Korea. The results are compared with those of the state-of-the-art methods as well.

Keywords: Nonconvex optimization, Economic dispatch, Mean-variance optimization, Kuhn-Tucker condition

1. Introduction

Many power system optimization problems including economic dispatch (ED) have nonconvex characteristics with heavy equality and inequality constraints [1]. The aim of the ED problem is to determine the optimal combination of power outputs of all generating units so as to meet the required load demand at minimum operating cost while satisfying system equality and inequality constraints. In ED problems, the cost function of each generator has been approximately expressed by a quadratic function and is solved using mathematical programming [2]. However, each generator has nonconvex input-output characteristics due to prohibited operating zones, valve-point loadings, multi-fuel effects, etc. Therefore it is difficult to solve ED by using the traditional mathematical methods because ED problems should be represented as a nonconvex optimization problem with constraints. Dynamic programming [3] can treat such types of problems, but it suffers from the curse of dimensionality. Over the past decade, many salient methods have been developed to solve these problems, such as the hierarchical numerical method [4], genetic algorithm (GA) [5-7], evolutionary programming [8-10], Tabu search [11], neural network approaches [12, 13], differential evolution [14], particle swarm optimization [15-18], hybrid artificial intelligence (AI) method [19], improved PSO [20] and Immune-PSO(IPSO) [21].

MVO suggested by Erlich, Venayagamoorthy and Worawat is one of the stochastic optimization algorithms which is simple to implement. It falls into the category of the so-called "population-based stochastic optimization technique". Its concepts share some similarities and differences from other known stochastic algorithms. Like other algorithms such as differential evolution, genetic algorithm, and particle swarm optimization, it borrows ideas of selection, mutation and crossover from evolutionary computation algorithms. The main distinct feature of the MVO algorithms is a strategic transformation of mutated genes of the offspring based on the mean-variance of the *n*-best population [22].

This paper proposes an improved MVO algorithm with Kuhn-Tucker condition and swap process (KMVO) for the nonconvex ED problems with heavy constraints. Kuhn-Tucker condition is a mathematical judgment for heuristic method that is experience-based techniques for problem solving. Swap process is a method that changes the generator outputs in the direction of reducing total generation cost for searching local minimum. These two methods are applied to MVO algorithm so that optimal solution can be obtained. The suggested KMVO is applied to three different nonconvex ED problems and the large-scale power system of Korea. The solutions are compared with those of existing AI methods.

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2. Formulation of Economic Dispatch Problem

2.1 Objective function

The objective of an ED problem is to determine the optimal generation outputs that minimize the total fuel cost while satisfying equality and inequality constraints. The total fuel cost for all the generators in the system and simplified cost function of each generating unit can be represented as (1, 2), respectively:

$$F_T = \sum_{i=1}^{n} F_i(P_i) \tag{1}$$

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

where

F_T total fuel cost,
F_i cost function of generator *i*,
a_i, b_i, c_i cost coefficients of generator *i*,
P_i power output of generator *i*,
n number of generators.

1) ED Problem Considering Valve-Point Effects: The generating units with multi-valve steam turbines exhibit a greater variation in the fuel cost function. Because of the valve point effects, a cost function contains higher order of nonlinearity. Therefore, the cost function (2) is described as the superposition of sinusoidal functions and quadratic functions in (3):

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

where e_i and f_i are the cost coefficients of generator *i* reflecting valve-point effects [10].

2) ED Problem Considering Multi-Fuels with Valve-Point Effects: Since the dispatching units can be supplied with multi-fuel sources, each unit can be represented with several piecewise quadratic functions reflecting the effects of different fuel types. In general, the objective function is expressed as the piecewise quadratic functions to represent the input-output curve of a generator with multiple fuels [4] and described as in (4):

$$F_i(P_i) = \begin{cases} a_{i1} + b_{i1} P_i + c_{i1} P_i^2, & \text{fuel } 1, \quad P_{i,\min} \le P_i \le P_{i1} \\ a_{i2} + b_{i2} P_i + c_{i2} P_i^2, & \text{fuel } 2, \quad P_{i1} \le P_i \le P_{i2} \\ \quad \vdots & \qquad \vdots \\ a_{ik} + b_{ik} P_i + c_{ik} P_i^2, & \text{fuel } k, \quad P_{ik-1} \le P_i \le P_{i,\max} \end{cases} \tag{4}$$

where a_{ik}, b_{ik}, c_{ik} are the cost coefficients of generator *i* for fuel type *k*. To obtain an accurate and practical ED solution, the fuel cost function should be considered with both multi-fuels and valve-point effects simultaneously [7]. Thus, the fuel cost function (3) should be combined with (4), and can be represented as follows:

$$F_i(P_i) = \begin{cases} F_{i1}(P_i), & \text{fuel } 1, \quad P_{i,\min} \le P_i \le P_{i1} \\ F_{i2}(P_i), & \text{fuel } 2, \quad P_{i1} \le P_i \le P_{i2} \\ \quad \vdots & \qquad \vdots \\ F_{ik}(P_i), & \text{fuel } k, \quad P_{ik-1} \le P_i \le P_{i,\max} \end{cases} \tag{5}$$

where

$$F_{ik}(P_i) = a_{ik} + b_{ik} P_i + c_{ik} P_i^2 + \left| e_{ik} \times \sin\left(f_{ik} \times \left(P_{ik,\min} - P_i \right) \right) \right| \tag{6}$$

and e_{ik} and f_{ik} are the cost coefficients of generator *i* reflecting valve-point effects for fuel type *k*, and $P_{ik,\min}$ is the minimum output of generator *i* using fuel type *k*.

2.2 Equality and inequality constraints

1) Active Power Balance Equation: The ED problem has an equality constraint that the total generation output of all units must be same as total load demand plus the total transmission network losses

$$\sum_{i=1}^{n} P_i = P_{load} + P_{loss} \tag{7}$$

where P_{load} is the total system load. The total transmission network loss, P_{loss}, is a function of the unit power outputs that can be represented using *B* coefficients [2] as in (8):

$$P_{loss} = \sum_{i=1}^{n} \sum_{j=1}^{n} P_i B_{ij} P_j + \sum_{i=1}^{n} B_{0i} P_i + B_{00} \tag{8}$$

2) Minimum and Maximum Power Limits: Power output of each generator should be within its minimum and maximum limits. The corresponding inequality constraint for each generator is;

$$P_{i,\min} \le P_i \le P_{i,\max} \tag{9}$$

where $P_{i,\min}$ and $P_{i,\max}$ are the minimum and maximum output of generator *i*, respectively.

3) ED Problem Considering Prohibited Operating Zones: In real power system operation, the entire operating range of a generating unit is not always available for load allocation due to physical operation limitations. Units may have prohibited operating zones due to robustness in the shaft bearing caused by the operation of steam values or to faults in machines themselves or associated auxiliaries. Such faults may lead to instability in certain ranges of generator power output [6]. Therefore, for units with prohibited operating zones, there are additional constraints on the unit operating range as in (10):

$$P_i \in \begin{cases} P_{i,\min} \le P_i \le P_{i,1}^l \\ P_{i,k-1}^u \le P_i \le P_{i,k}^l, \quad k = 2,3,\cdots,pz_i \\ P_{i,pz_i}^u \le P_i \le P_{i,\max} \end{cases}$$
$$i = 1,2,\cdots,\ n_{PZ} \quad (10)$$

where $P_{i,k}^l$ and $P_{i,k}^u$ are, respectively, the lower and upper bounds of prohibited operating zone of unit *i*. Here, pz_i is the number of prohibited zones of unit *i* and n_{PZ} is the number of units which have prohibited operating zones.

3. Overview of Mean-Variance Optimization

A 'Mean-Variance Optimization' (MVO) algorithm is a new stochastic optimization algorithm referred to by Erlich, Venayagamoorthy and Worawat. MVO falls into the category of the so-called "population-based stochastic optimization technique" [22]. The MVO algorithm utilizes a single parent-offspring pair concept using the information of performance of the mean $\overline{x}_i$ and variance, v_i of n generators.

$$\overline{x}_i = \frac{1}{n}\sum_{j=1}^{n} x_i(j) \quad (11)$$

$$v_i = \frac{1}{n}\sum_{j=1}^{n} (x_i(j) - \overline{x}_i)^2 \quad i = 1,2,\cdots,k \quad (12)$$

where *n* is population size, *k* is the numbers of problem variables. The range of variables initialized within the allowed limits is [0, 1]. After computing mean and variance, the fitness of each population is evaluated. For fitness evaluation, however, de-normalization is carried out in every single iteration to calculate fitness using the actual values. The individual with the best fitness, f_{best} and its corresponding optimization values, x_{best} are '*parent*' of the population for that iteration. And this '*parent*' is used for creation of offspring which involves three common evolutionary computation algorithms' operations – selection, mutation and crossover.

m of *k* variables of the optimization problem are selected for mutation operation in accordance with the following mutation strategies:

A) Random selection
B) Neighbor group selection
  a) Moving the group forward in multiple steps
  b) Moving the group forward in single steps
C) Sequential selection of the first variable and the selection of the rest randomly (or) and random selection for the rest

Mutation procedure has the transformation and the corresponding function, which are the key features of the MVO algorithm. A transformation function, *h*, is based on the mean and shape factor, s_i as in (13).

m variables selected from *k* variables are transformed using transformation function

$$h(\overline{x}_i, s_{i1}, s_{i2}, u_i) = \overline{x}_i \cdot \left(1 - e^{-u_i \cdot s_{i1}}\right) + \left(1 - \overline{x}_i\right) \cdot e^{-(1-u_i) \cdot s_{i2}} \quad (13)$$

where

$$x_i = h_x + \left(1 - h_1 + h_0\right) \cdot x_i^{'} - h_0 \quad (14)$$

$$s_i = -\ln\left(v_i\right) \cdot f_S \quad (15)$$

The scaling factor f_s is constant between 0.9 and 10 that allows for controlling the search process.

$h_x = h\left(u_i = x_i^{'}\right)$, $h_0 = h\left(u_i = 0\right)$, $h_1 = h\left(u_i = 1\right)$ and $x_i^{'}$ is a uniform distribution in the range of [0,1].

This paper sets two shape factors, s_{i1} and s_{i2} to be equal. The values of remaining un-mutated (*k-m*) variables are clones of the parent. That is, the offspring is created by combining the '*parent*' and *m* mutated variables [22].

4. Improved MVO Algorithm with Kuhn-Tucker Condition and Swap Process

4.1 Application of Kuhn-Tucker condition

Economic dispatch problem is a constrained optimization that may be solved using advanced calculus methods that involve the Lagrange function. This is that the constraint function is added to the objective function after the constraint function has been multiplied by an undetermined multiplier as (16):

$$\ell = F_T + \lambda\left(P_{load} + P_{loss} - \sum_{i=1}^{n} P_i\right) \quad (16)$$

To attain the optimal value for the objective function, the first derivative of the Lagrange function with respect to each of the independent variables are taken and set to be zero. The derivative of the Lagrange function with respect to the undetermined multiplier returns the constraint equation [2]. In the power system, generator has not only an equality constraint like active power balance equation but also an inequality constraint such as minimum and maximum power limit. Lagrange condition includes Kuhn-Tucker condition to consider the inequality constraints as additional term. Then the necessary conditions for optimal dispatch become:

$$\frac{dF_i}{dP_i} = \lambda \quad \text{for} \quad P_{i,\min} < P_i < P_{i,\max} \quad (17)$$

$$\frac{dF_i}{dP_i} \le \lambda \quad \text{for} \quad P_i = P_{i,\max} \tag{18}$$

$$\frac{dF_i}{dP_i} \ge \lambda \quad \text{for} \quad P_i = P_{i,\min} \tag{19}$$

If a generator's output is outside the limits of the generator, the output of the generator is fixed at that limit and the generator is no longer a participating one in the optimization of dispatch problem. Therefore, if some generators show same output limits - either $P_{\min}$ or $P_{\max}$ - through past 5 iterations, their outputs are fixed at their limits. That is, new economic dispatch problem is performed only with the remaining generators. It is easier to solve the new economic dispatch problem since the variables are reduced.

The detailed Kuhn-Tucker process is summarized in the following steps:

Step 1) Implement algorithm more than 5 iterations
Step 2) If m of n generators are fixed at same limit through 5 iterations, their outputs are fixed as limits
Step 3) New ED is implemented without m generators in step 2
Step 4) Go to step 1 until the stopping criteria of algorithm is satisfied

4.2 Application of swap process

Swap process can be applied in following situation: The biggest cost reduction when output is reduced by α MW is compared with the smallest cost increase when output is increased by α MW. The ith generator output which has minimum cost increase is reduced by α MW and the kth generator output which has maximum cost reduction is increased by α MW. The total generating cost is reduced through this process. The process is terminated when the minimum cost increase is bigger than the maximum cost reduction or swap process occurs in the same generator.

For searching local minimum, this process is applied to MVO algorithm. The detailed Swap process is summarized as in the following steps.

Step 1) Calculate the cost of n generator outputs, cost_p when $P = [P_1, P_2, \cdots, P_n]$
Step 2) Calculate cost of $(P-\alpha)$MW and $(P+\alpha)$MW for all generators, cost_minus and cost_plus, respectively
Step 3) Select two generators which maximize [cost_p - cost_minus] and minimize [cost_plus - cost_p]
Step 4) Modify each generator's output selected in step 3
Step 5) Go to step 1 until the stopping criteria is satisfied

In this paper, 5, 4, 3, 2, 1, 0.1 and 0.01 are used successively as the value of α in swap process.

5. Implementation of Improved MVO Algorithm for Economic Dispatch Problems

Since improved MVO algorithm uses normalized values, normalization and de-normalization are carried out in every single iteration during optimization. For obtaining mean and variance, the population size n should be the minimum of the two.

Step 1) Initialize the variables while satisfying the constraints and normalize optimization variables
Step 2) Evaluate fitness using de-normalized variables and store f_{best} and x_{best}.
Step 3) Calculate means and variances of the normalized variables using (11) and (12).
Step 4) Create offspring through selection, mutation and crossover processes.
Step 5) Apply Kuhn-Tucker condition to best fitness
Step 6) Go to Step 2 until the stopping criteria is satisfied.
Step 7) If stopping criteria is satisfied, implement swap process to get x_{best}.

In the following, the detailed implementation strategies of the proposed method are described.

1) Normalization and de-normalization of optimization variables

After initializing variables satisfying the minimum and maximum limits, all variables are normalized as follows:

$$P_{i,nor} = (P_i - P_{i,\min})/(P_{i,\max} - P_{i,\min}) \tag{20}$$

For evaluating the fitness of objective function, de-normalization is carried out using (21).

$$P_i = P_{i,nor}(P_{i,\max} - P_{i,\min}) + P_{i,\min} \tag{21}$$

2) Stopping Criteria

The improved MVO algorithm is terminated if the iteration reaches a predefined maximum iteration.

6. Numerical Tests

The proposed KMVO approach is applied to four different power systems; (i) 40-unit system with valve-point effects, (ii) 15-unit system with prohibited operating zones and transmission network losses, (iii) 10-unit system considering multiple fuels with valve-point effects, and (iv) 140-unit Korean power system with valve-point effects and prohibited operating zones. For each case, 100 independent trials are conducted to compare the solution quality.

Before implementing the proposed algorithm, some KMVO parameters must be determined in advance. The population size *NP* and maximum iteration number $iter_{max}$ are set as 40 and 10,000, respectively. Since the performance of MVO algorithm depends on the parameters such as shape factor, scaling factor and selection strategies, it is important to determine suitable values of these parameters. To determine the shape factor, the case in which s_i is variable according to variance, that is, f_s is constant, is compared with other case in which s_i is constant. For each case, 100 independent tests are executed for system 1. In the case in which f_s is varied from 1 to 10 with the step size of 1, there is no f_s value that makes minimum cost and average cost coincide. The other case in which s_i is varied from 0 to 50 with step size of 5 shows that the optimal value for s_i is 30. Therefore s_i is fixed as 30 for four test simulations. As selection strategies, all strategies are applied to each case and the best value is used as a result. After all simulations, it is observed that the mutation strategy C is superior to other strategies.

1) Test System 1: System with Valve-point Effects

The test system consists of 40 generating units and the input data are described in [10]. The total demand is set as 10,500MW.

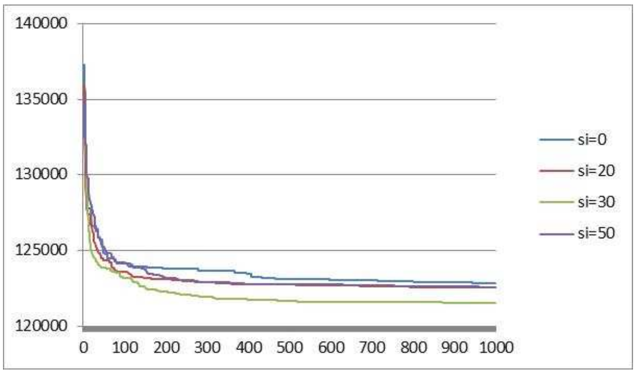

Fig. 1. Convergence characteristics of the shape factor for Test system 1

Table 1. Determination of shape factor for test system 1

Case	s_i	Minimum Cost ($)	Average Cost ($)
1	0	121,668.1040	122,114.2391
2	5	121,539.4381	121,898.9609
3	10	121,502.3348	121,848.1305
4	15	121,521.8453	121,918.7053
5	20	121,534.8039	121,889.0578
6	25	121,531.7715	121,890.3810
7	**30**	**121,487.3600**	**121,845.6700**
8	35	121,512.9815	121,876.6371
9	40	121,551.4565	121,866.3985
10	45	121,515.6051	121,857.4572
11	50	121,515.4220	121,859.9668

In Table 2, the results of the proposed KMVO algorithm are compared with those of evolutionary programming (EP) [10], MPSO [16], PSO-SQP [17], DEC-SQP [14], NPSO [18], NPSO-LRS [18], CTPSO [20], CSPSO [20],

Table 2. Comparison of the result of each method for test system 1

Methods	Minimum Cost ($)	Average Cost ($)
EP [10]	122,624.3500	123,382.0000
MPSO [16]	122,252.2650	N/A
PSO-SQP [17]	122,094.6700	122,245.2500
DEC-SQP [14]	121,741.9793	122,295.1278
NPSO [18]	121,704.7391	122,221.3697
NPSO-LRS [18]	121,664.4308	122,209.3185
CTPSO[20]	121,703.6056	121,953.3959
CSPSO[20]	121,444.9581	121,954.0564
COPSO[20]	121,420.8975	121,508.9769
CCPSO[20]	121,412.5483	121,454.3269
KMVO	121,412.5363	121,437.8247

Table 3. Generation output of each generator and the corresponding cost in 40-unit test system 1 of NPSO-LRS, CCPSO, and KMVO

Unit	NPSO-LRS[18]	CCPSO[20]	KMVO
1	113.9761	110.7998	110.7998
2	113.9986	110.7999	110.7998
3	97.4241	97.3999	97.3999
4	179.7327	179.7331	179.7331
5	89.6511	87.7999	87.7999
6	105.4044	140.0000	140.0000
7	259.7502	259.5997	259.5997
8	288.4534	284.5997	284.5997
9	284.6460	284.5997	284.5997
10	204.8120	130.0000	130.0000
11	168.8311	94.0000	94.0000
12	94.0000	94.0000	94.0000
13	214.7663	214.7598	214.7598
14	394.2852	394.2794	394.2794
15	304.5187	394.2794	394.2794
16	394.2811	394.2794	394.2794
17	489.2807	489.2794	489.2794
18	489.2832	489.2794	489.2794
19	511.2845	511.2794	511.2794
20	511.3049	511.2794	511.2794
21	523.2916	523.2794	523.2794
22	523.2853	523.2794	523.2794
23	523.2797	523.2794	523.2794
24	523.2994	523.2794	523.2794
25	523.2865	523.2794	523.2794
26	523.2936	523.2794	523.2794
27	10.0000	10.0000	10.0000
28	10.0001	10.0000	10.0000
29	10.0000	10.0000	10.0000
30	89.0139	87.8000	87.7999
31	190.0000	190.0000	190.0000
32	190.0000	190.0000	190.0000
33	190.0000	190.0000	190.0000
34	199.9998	164.7998	164.7998
35	165.1397	194.3976	194.3977
36	172.0275	200.0000	200.0000
37	110.0000	110.0000	110.0000
38	110.0000	110.0000	110.0000
39	93.0962	110.0000	110.0000
40	511.2996	511.2794	511.2794
TP	10500	10500	10500
TC	121664.4308	121412.5483	121412.5363

* TP: total power [MW], TC: total generation cost [$].

COPSO [20], and CCPSO[20]. The result of KMVO is similar to the best solution previously found by CCPSO and has shown the superiority to other algorithms, so it is almost the global solution.

2) Test System 2: System with Prohibited Operating Zones, Ramp Rate Limits, and Transmission Network Losses

Experiments are performed on the 15-unit power system, which considers the prohibited operating zones and transmission network losses. Units 2, 5, 6, and 12 have two or three prohibited operating zones. The system supplies a load of 2,630MW. The input data and *B* coefficients for transmission network losses are provided in [15].

Table 4. Comparison of the results of each method for test system 2

Unit	GA [15]	PSO [15]	CCPSO[20]	KMVO
1	415.3108	439.1162	455.0000	454.9993
2	359.7206	407.9727	380.0000	454.9676
3	104.4250	119.6324	130.0000	129.9999
4	74.9853	129.9925	130.0000	130.0000
5	380.2844	151.0681	170.0000	235.1029
6	426.7902	459.9978	460.0000	460.0000
7	341.3164	425.5601	430.0000	465.0000
8	124.7867	98.5699	71.7526	60.0000
9	133.1445	113.4936	58.9090	25.0000
10	89.2567	101.1142	160.0000	27.6110
11	60.0572	33.9116	80.0000	79.8528
12	49.9998	79.9583	80.0000	79.9863
13	38.7713	25.0042	25.0000	25.0000
14	41.9425	41.4140	15.0000	15.0036
15	22.6445	35.6140	15.0000	15.0000
TP	2668.4	2662.4	2660.6616	2657.5233
P_{loss}	38.2782	32.4306	30.6616	27.5233
TC	33,113	32,858	32,704	32,555

In Table 4, the best result of KMOV is compared with that of GA [15], PSO [15] and CCPSO [20]. As shown in table 4, KMVO provides the better solution than other solutions.

3) Test System 3: Multi-Fuels with Valve-Point Effect

The test system consists of 10 generating units considering multi-fuels with valve-point effects. The input data and related constraints of the test system are given in [7]. The total system demand is set as 2,700MW.

In Table 5, the generation outputs, fuel types, and corresponding costs of the best solution obtained from the proposed KMVO are compared with those of NPSO-LRS [18], CTPSO [20], CCPSO [20]. For accurate comparison, other results are recalculated using Microsoft Excel 2010. The result shows that KMVO provides best solution similar to CCPSO [20] while satisfying the system constraints exactly.

Table 5. Comparison of the results of each method for test system 3

Unit	NPSO-LRS[18]		CTPSO[20]		CCPSO[20]		KMVO	
	F	GEN	F	GEN	F	GEN	F	GEN
1	2	223.3352	2	218.6807	2	218.5940	2	218.5940
2	1	212.1957	1	211.4642	1	211.7117	1	211.7117
3	1	276.2167	1	280.6545	1	280.6571	1	280.6571
4	3	239.4187	3	240.4457	3	239.6394	3	239.6394
5	1	274.6470	1	276.4034	1	279.9346	1	279.9345
6	3	239.7974	3	240.1769	3	239.5051	3	239.6394
7	1	285.5388	1	287.8657	1	287.7275	1	287.7275
8	3	240.6323	3	240.5800	3	239.6394	3	239.6394
9	3	429.2637	3	428.5886	3	426.7226	3	426.5884
10	1	278.9541	1	275.1403	1	275.8686	1	275.8686
TP	2700.0000		2700.0000		2700.0000		2700.0000	
TC	624.1273		623.8593		623.8273		623.8267	

4) Large-scale Power System of Korea

To investigate the applicability of the proposed KMVO to the large-scale power systems, experiments are conducted on the Korean power system. The system consists of 140 thermal generating units. The input data are given in Table 10 of the Appendix. This system supplies a load of 49,342MW.

Table 6. Convergence results for Korean power system with convex cost functions

Methods	Minimum Cost ($)	Average Cost ($)	Maximum Cost ($)
CTPSO[20]	1,655,685	1,655,685	1,655,685
CSPSO[20]	1,655,685	1,655,685	1,655,685
COPSO[20]	1,655,685	1,655,685	1,655,685
CCPSO[20]	1,655,685	1,655,685	1,655,685
KMVO	1,577,607	1,586,547	1,594,251

Table 7. Generation output of each generator in Korean power system with convex cost function

Gen	Output	Gen	Output
COAL #01	116.3651	LNG CC #29	157.8965
COAL #02	186.7814	LNG CC #30	276.0046
COAL #03	184.1960	LNG CC #31	199.8780
COAL #04	151.1263	LNG CC #32	257.4908
COAL #05	115.4063	LNG CC #33	207.4134
COAL #06	170.4321	LNG CC #34	252.4126
COAL #07	488.5877	LNG CC #35	204.3870
COAL #08	486.6820	LNG CC #36	417.5256
COAL #09	496.0000	LNG CC #37	513.8888
COAL #10	495.9421	LNG CC #38	531.0000
COAL #11	496.0000	LNG CC #39	345.2138
COAL #12	495.2605	LNG CC #40	61.6248
COAL #13	505.9998	LNG CC #41	115.0000
COAL #14	507.8446	LNG CC #42	124.1302
COAL #15	504.3031	LNG CC #43	135.3891
COAL #16	503.2839	LNG CC #44	207.0000
COAL #17	506.0000	LNG CC #45	208.2738
COAL #18	506.0000	LNG CC #46	194.0125
COAL #19	484.7896	LNG CC #47	251.0230
COAL #20	505.0000	LNG CC #48	191.5331
COAL #21	505.0000	LNG CC #49	231.5253

COAL #22	489.5698	NUCLEAR#1	577.9281
COAL #23	497.3235	NUCLEAR#2	643.1416
COAL #24	493.7546	NUCLEAR#3	984.0000
COAL #25	531.9461	NUCLEAR#4	978.0000
COAL #26	533.3515	NUCLEAR#5	679.9139
COAL #27	549.0000	NUCLEAR#6	720.0000
COAL #28	540.8276	NUCLEAR#7	718.0000
COAL #29	480.6153	NUCLEAR#8	719.7980
COAL #30	499.6192	NUCLEAR#9	963.3888
COAL #31	502.9783	NUCLEAR#10	957.9991
COAL #32	499.7606	NUCLEAR#11	1001.9413
COAL #33	505.9990	NUCLEAR#12	1006.0000
COAL #34	505.9995	NUCLEAR#13	1013.0000
COAL #35	496.6364	NUCLEAR#14	1020.0000
COAL #36	500.0000	NUCLEAR#15	953.9991
COAL #37	237.6282	NUCLEAR#16	951.7433
COAL #38	239.4089	NUCLEAR#17	1006.0000
COAL #39	773.9897	NUCLEAR#18	1013.0000
COAL #40	768.7938	NUCLEAR#19	1021.0000
LNG #1	11.9754	NUCLEAR#20	1015.0000
LNG #2	5.7723	OIL #1	94.0000
LNG CC #01	193.2953	OIL #2	94.0000
LNG CC #02	204.9660	OIL #3	111.1225
LNG CC #03	201.5581	OIL #4	244.0655
LNG CC #04	240.1244	OIL #5	305.3824
LNG CC #05	213.2612	OIL #6	256.8998
LNG CC #06	214.9590	OIL #7	117.8872
LNG CC #07	249.3393	OIL #8	96.1081
LNG CC #08	238.9636	OIL #9	133.2779
LNG CC #09	183.6487	OIL #10	179.3312
LNG CC #10	185.6466	OIL #11	12.7716
LNG CC #11	226.3351	OIL #12	5.3750
LNG CC #12	196.5095	OIL #13	15.0001
LNG CC #13	180.0000	OIL #14	12.2708
LNG CC #14	192.9887	OIL #15	12.0000
LNG CC #15	108.1703	OIL #16	11.3371
LNG CC #16	199.0215	OIL #17	131.3862
LNG CC #17	201.7144	OIL #18	4.9092
LNG CC #18	224.6738	OIL #19	18.0074
LNG CC #19	166.3843	OIL #20	5.6798
LNG CC #20	95.0000	OIL #21	56.7364
LNG CC #21	218.6087	OIL #22	5.0000
LNG CC #22	160.0929	OIL #23	46.2592
LNG CC #23	339.4153	OIL #24	46.4731
LNG CC #24	396.3759	OIL #25	41.0000
LNG CC #25	421.6618	OIL #26	17.0027
LNG CC #26	219.9153	OIL #27	18.5819
LNG CC #27	144.8121	OIL #28	7.9656
LNG CC #28	287.0772	OIL #29	35.2237
	TP	49,342	
	TC	1,577,607	

In order to show the applicability of the KMVO to the large-scale power system, it is applied to Korean power system with convex cost function. The result is shown in table 6 and each generator's output and the corresponding total cost of KMOV are provided in table 7.

Table 8. Convergence results for Korean power system with nonconvex cost functions

Methods	Minimum Cost ($)	Average Cost ($)	Maximum Cost ($)
CTPSO[20]	1657962.73	1657964.06	1658002.79
CSPSO[20]	1657962.73	1657962.74	1657962.85
COPSO[20]	1657962.73	1657962.73	1657962.73
CCPSO[20]	1657962.73	1657962.73	1657962.73
KMVO	1568450.94	1590666.49	1609134.60

Table 9. Generation output of each generator in Korean power system with nonconvex cost function

Gen	Output	Gen	Output
COAL #01	82.5513	LNG CC #29	157.2506
COAL #02	188.6216	LNG CC #30	318.6942
COAL #03	189.9989	LNG CC #31	235.7487
COAL #04	182.3628	LNG CC #32	281.5549
COAL #05	90.0000	LNG CC #33	190.5204
COAL #06	187.4329	LNG CC #34	305.2888
COAL #07	490.0000	LNG CC #35	272.3050
COAL #08	490.0000	LNG CC #36	409.9372
COAL #09	489.9706	LNG CC #37	530.6425
COAL #10	495.9315	LNG CC #38	531.0000
COAL #11	495.9994	LNG CC #39	212.6973
COAL #12	496.0000	LNG CC #40	56.0000
COAL #13	505.9958	LNG CC #41	115.0000
COAL #14	509.0000	LNG CC #42	115.0000
COAL #15	506.0000	LNG CC #43	115.1458
COAL #16	505.0000	LNG CC #44	207.0000
COAL #17	506.0000	LNG CC #45	208.0936
COAL #18	506.0000	LNG CC #46	183.8922
COAL #19	505.0000	LNG CC #47	188.5782
COAL #20	505.0000	LNG CC #48	222.7599
COAL #21	505.0000	LNG CC #49	226.0267
COAL #22	504.9890	NUCLEAR#1	580.0000
COAL #23	505.0000	NUCLEAR#2	644.8960
COAL #24	505.0000	NUCLEAR#3	984.0000
COAL #25	536.9995	NUCLEAR#4	977.9915
COAL #26	537.0000	NUCLEAR#5	682.0000
COAL #27	549.0000	NUCLEAR#6	719.8723
COAL #28	549.0000	NUCLEAR#7	716.3277
COAL #29	501.0000	NUCLEAR#8	719.9999
COAL #30	501.0000	NUCLEAR#9	963.7387
COAL #31	505.6595	NUCLEAR#10	957.0750
COAL #32	506.0000	NUCLEAR#11	1007.0000
COAL #33	506.0000	NUCLEAR#12	1006.0000
COAL #34	506.0000	NUCLEAR#13	1013.0000
COAL #35	500.0000	NUCLEAR#14	1019.9919
COAL #36	487.7316	NUCLEAR#15	954.0000
COAL #37	241.0000	NUCLEAR#16	952.0000
COAL #38	241.0000	NUCLEAR#17	1005.9999
COAL #39	774.0000	NUCLEAR#18	1012.9999
COAL #40	768.5452	NUCLEAR#19	1020.9987
LNG #1	5.3027	NUCLEAR#20	1013.3990
LNG #2	3.0000	OIL #1	95.8236
LNG CC #01	206.6909	OIL #2	98.1712
LNG CC #02	183.3619	OIL #3	94.0000
LNG CC #03	215.0000	OIL #4	261.0264
LNG CC #04	248.6941	OIL #5	247.9809
LNG CC #05	250.0000	OIL #6	278.0867
LNG CC #06	241.7546	OIL #7	95.9819
LNG CC #07	160.0000	OIL #8	95.0000
LNG CC #08	210.0428	OIL #9	125.8192
LNG CC #09	208.6296	OIL #10	175.2850
LNG CC #10	165.0000	OIL #11	3.2382
LNG CC #11	201.4451	OIL #12	5.7585
LNG CC #12	165.4062	OIL #13	16.6915
LNG CC #13	184.5243	OIL #14	9.2993
LNG CC #14	180.0000	OIL #15	12.7125
LNG CC #15	166.6488	OIL #16	10.0000
LNG CC #16	198.0000	OIL #17	114.8288
LNG CC #17	311.1821	OIL #18	6.0628
LNG CC #18	198.6260	OIL #19	5.7295
LNG CC #19	164.9270	OIL #20	5.0000
LNG CC #20	95.0000	OIL #21	51.7665
LNG CC #21	181.5410	OIL #22	5.9033
LNG CC #22	171.8393	OIL #23	48.5351
LNG CC #23	358.9548	OIL #24	43.2163
LNG CC #24	347.2441	OIL #25	41.1533
LNG CC #25	376.8657	OIL #26	17.0000
LNG CC #26	371.0256	OIL #27	8.7338
LNG CC #27	140.0580	OIL #28	11.2042
LNG CC #28	229.6166	OIL #29	26.3946
	TP	49,342	
	TC	1,568,450.94	

Additionally, it is applied to Korean power system with nonconvex cost function. It is assumed that 12 generators have the cost function with valve-point effects and 4 generators are considered the prohibited operating zones. The data are given in Tables 11-12 in Appendix.

The Table 8 shows that results of KMVO are superior to CCPSO [20] and the average and maximum cost of KMVO are even better than the minimum cost of CCPSO. Each generator's outputs and the corresponding total cost are provided in Table 9.

7. Conclusions

This paper proposes an improved "Mean-variance optimization" algorithm for solving nonconvex ED problems. The proposed algorithm includes Kuhn-Tucker condition and swap process to improve the performance of MVO algorithm. Kuhn-Tucker condition is applied to MVO algorithm to enhance capability of searching global minimum by reducing the number of generators for economic dispatch problems. Also swap process is used to obtain the optimal solution. The proposed KMVO is successfully applied to three different nonconvex ED problems with valve-point effects, prohibited operating zones, transmission network losses and multi-fuels with valve-point effects. Also it is applied to the large-scale Korean power system with convex and nonconvex cost functions. The KMVO algorithm has found a better solution for the four test systems than other existing solutions. The results show that the proposed KMVO can successfully be applied and used for general nonconvex ED problems with several constraints.

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Appendix

The characteristics data of generating units for Korean power system are given in table 10-12.

Table 10. Generating unit data of Korean power system

Gen	a	b	c	P_{min}	P_{max}	UR	DR	P^0
COAL#01	1220.645	61.242	0.032888	71	119	30	120	98.4
COAL#02	1315.118	41.095	0.008280	120	189	30	120	134.0
COAL#03	874.288	46.310	0.003849	125	190	60	60	141.5
COAL#04	874.288	46.310	0.003849	125	190	60	60	183.3
COAL#05	1976.469	54.242	0.042468	90	190	150	150	125.0
COAL#06	1338.087	61.215	0.014992	90	190	150	150	91.3
COAL#07	1818.299	11.791	0.007039	280	490	180	300	401.1
COAL#08	1133.978	15.055	0.003079	280	490	180	300	329.5
COAL#09	1320.636	13.226	0.005063	260	496	300	510	386.1
COAL#10	1320.636	13.226	0.005063	260	496	300	510	427.3
COAL#11	1320.636	13.226	0.005063	260	496	300	510	412.2
COAL#12	1106.539	14.498	0.003552	260	496	300	510	370.1
COAL#13	1176.504	14.651	0.003901	260	506	600	600	301.8
COAL#14	1176.504	14.651	0.003901	260	509	600	600	368.0
COAL#15	1176.504	14.651	0.003901	260	506	600	600	301.9
COAL#16	1176.504	14.651	0.003901	260	505	600	600	476.4
COAL#17	1017.406	15.669	0.002393	260	506	600	600	283.1
COAL#18	1017.406	15.669	0.002393	260	506	600	600	414.1
COAL#19	1229.131	14.656	0.003684	260	505	600	600	328.0
COAL#20	1229.131	14.656	0.003684	260	505	600	600	389.4
COAL#21	1229.131	14.656	0.003684	260	505	600	600	354.7
COAL#22	1229.131	14.656	0.003684	260	505	600	600	262.0
COAL#23	1267.894	14.378	0.004004	260	505	600	600	461.5
COAL#24	1229.131	14.656	0.003684	260	505	600	600	371.6
COAL#25	975.926	16.261	0.001619	280	537	300	300	462.6
COAL#26	1532.093	13.362	0.005093	280	537	300	300	379.2
COAL#27	641.989	17.203	0.000993	280	549	360	360	530.8
COAL#28	641.989	17.203	0.000993	280	549	360	360	391.9
COAL#29	911.533	15.274	0.002473	260	501	180	180	480.1
COAL#30	910.533	15.212	0.002547	260	501	180	180	319.0
COAL#31	1074.810	15.033	0.003542	260	506	600	600	329.5
COAL#32	1074.810	15.033	0.003542	260	506	600	600	333.8
COAL#33	1074.810	15.033	0.003542	260	506	600	600	390.0
COAL#34	1074.810	15.033	0.003542	260	506	600	600	432.0
COAL#35	1278.460	13.992	0.003132	260	500	660	660	402.0
COAL#36	861.742	15.679	0.001323	260	500	900	900	428.0
COAL#37	408.834	16.542	0.002950	120	241	180	180	178.4
COAL#38	408.834	16.542	0.002950	120	241	180	180	194.1
COAL#39	1288.815	16.518	0.000991	423	774	600	600	474.0
COAL#40	1436.251	15.815	0.001581	423	769	600	600	609.8
LNG#1	669.988	75.464	0.902360	3	19	210	210	17.8
LNG#2	134.544	129.544	0.110295	3	28	366	366	6.9
LNG_CC#01	3427.912	56.613	0.024493	160	250	702	702	224.3
LNG_CC#02	3751.772	54.451	0.029156	160	250	702	702	210.0
LNG_CC#03	3918.780	54.736	0.024667	160	250	702	702	212.0
LNG_CC#04	3379.580	58.034	0.016517	160	250	702	702	200.8
LNG_CC#05	3345.296	55.981	0.026584	160	250	702	702	220.0
LNG_CC#06	3138.754	61.520	0.007540	160	250	702	702	232.9
LNG_CC#07	3453.050	58.635	0.016430	160	250	702	702	168.0
LNG_CC#08	5119.300	44.647	0.045934	160	250	702	702	208.4
LNG_CC#09	1898.415	71.584	0.000044	165	504	1350	1350	443.9
LNG_CC#10	1898.415	71.584	0.000044	165	504	1350	1350	426.0
LNG_CC#11	1898.415	71.584	0.000044	165	504	1350	1350	434.1
LNG_CC#12	1898.415	71.584	0.000044	165	504	1350	1350	402.5
LNG_CC#13	2473.390	85.120	0.002528	180	471	1350	1350	357.4
LNG_CC#14	2781.705	87.682	0.000131	180	561	720	720	423.0
LNG_CC#15	5515.508	69.532	0.010372	103	341	720	720	220.0
LNG_CC#16	3478.300	78.339	0.007627	198	617	2700	2700	369.4
LNG_CC#17	6240.909	58.172	0.012464	100	312	1500	1500	273.5
LNG_CC#18	9960.110	46.636	0.039441	153	471	1656	1656	336.0
LNG_CC#19	3671.997	76.947	0.007278	163	500	2160	2160	432.0
LNG_CC#20	1837.383	80.761	0.000044	95	302	900	900	220.0
LNG_CC#21	3108.395	70.136	0.000044	160	511	1200	1200	410.6
LNG_CC#22	3108.395	70.136	0.000044	160	511	1200	1200	422.7
LNG_CC#23	7095.484	49.840	0.018827	196	490	1014	1014	351.0
LNG_CC#24	3392.732	65.404	0.010852	196	490	1014	1014	296.0
LNG_CC#25	7095.484	49.840	0.018827	196	490	1014	1014	411.1
LNG_CC#26	7095.484	49.840	0.018827	196	490	1014	1014	263.2
LNG_CC#27	4288.320	66.465	0.034560	130	432	1350	1350	370.3
LNG_CC#28	13813.001	22.941	0.081540	130	432	1350	1350	418.7
LNG_CC#29	4435.493	64.314	0.023534	137	455	1350	1350	409.6
LNG_CC#30	9750.750	45.017	0.035475	137	455	1350	1350	412.0
LNG_CC#31	1042.366	70.644	0.000915	195	541	780	780	423.2
LNG_CC#32	1159.895	70.959	0.000044	175	536	1650	1650	428.0
LNG_CC#33	1159.895	70.959	0.000044	175	540	1650	1650	436.0
LNG_CC#34	1303.990	70.302	0.001307	175	538	1650	1650	428.0
LNG_CC#35	1156.193	70.662	0.000392	175	540	1650	1650	425.0
LNG_CC#36	2118.968	71.101	0.000087	330	574	1620	1620	497.2
LNG_CC#37	779.519	37.854	0.000521	160	531	1482	1482	510.0
LNG_CC#38	829.888	37.768	0.000498	160	531	1482	1482	470.0
LNG_CC#39	2333.690	67.983	0.001046	200	542	1668	1668	464.1
LNG_CC#40	2028.954	77.838	0.132050	56	132	120	120	118.1
LNG_CC#41	4412.017	63.671	0.096968	115	245	180	180	141.3
LNG_CC#42	2982.219	79.458	0.054868	115	245	120	180	132.0
LNG_CC#43	2982.219	79.458	0.054868	115	245	120	180	135.0
LNG_CC#44	3174.939	93.966	0.014382	207	307	120	180	252.0
LNG_CC#45	3218.359	94.723	0.013161	207	307	120	180	221.0
LNG_CC#46	3723.822	66.919	0.016033	175	345	318	318	245.9
LNG_CC#47	3551.405	68.185	0.013653	175	345	318	318	247.9
LNG_CC#48	4322.615	60.821	0.028148	175	345	318	318	183.6
LNG_CC#49	3493.739	68.551	0.013470	175	345	318	318	288.0
NUCLEAR#01	226.799	2.842	0.000064	360	580	18	18	557.4
NUCLEAR#02	382.932	2.946	0.000252	415	645	18	18	529.5
NUCLEAR#03	156.987	3.096	0.000022	795	984	36	36	800.8
NUCLEAR#04	154.484	3.040	0.000022	795	978	36	36	801.5
NUCLEAR#05	332.834	1.709	0.000203	578	682	138	204	582.7
NUCLEAR#06	326.599	1.668	0.000198	615	720	144	216	680.7
NUCLEAR#07	345.306	1.789	0.000215	612	718	144	216	670.7
NUCLEAR#08	350.372	1.815	0.000218	612	720	144	216	651.7
NUCLEAR#09	370.377	2.726	0.000193	758	964	48	48	921.0
NUCLEAR#10	367.067	2.732	0.000197	755	958	48	48	916.8
NUCLEAR#11	124.875	2.651	0.000324	750	1007	36	54	911.9
NUCLEAR#12	130.785	2.798	0.000344	750	1006	36	54	898.0
NUCLEAR#13	878.746	1.595	0.000690	713	1013	30	30	905.0
NUCLEAR#14	827.959	1.503	0.000650	718	1020	30	30	846.5
NUCLEAR#15	432.007	2.425	0.000233	791	954	30	30	850.9
NUCLEAR#16	445.606	2.499	0.000239	786	952	30	30	843.7
NUCLEAR#17	467.223	2.674	0.000261	795	1006	36	36	841.4
NUCLEAR#18	475.940	2.692	0.000259	795	1013	36	36	835.7
NUCLEAR#19	899.462	1.633	0.000707	795	1021	36	36	828.8
NUCLEAR#20	1000.367	1.816	0.000786	795	1015	36	36	846.0
OIL#01	1269.132	89.830	0.014355	94	203	120	120	179.0
OIL#02	1269.132	89.830	0.014355	94	203	120	120	120.8
OIL#03	1269.132	89.830	0.014355	94	203	120	120	121.0
OIL#04	4965.124	64.125	0.030266	244	379	480	480	317.4
OIL#05	4965.124	64.125	0.030266	244	379	480	480	318.4
OIL#06	4965.124	64.125	0.030266	244	379	480	480	335.8
OIL#07	2243.185	76.129	0.024027	95	190	240	240	151.0
OIL#08	2290.381	81.805	0.001580	95	189	240	240	129.5
OIL#09	1681.533	81.140	0.022095	116	194	120	120	130.0
OIL#10	6743.302	46.665	0.076810	175	321	180	180	218.9
OIL#11	394.398	78.412	0.953443	2	19	90	90	5.4
OIL#12	1243.165	112.088	0.000044	4	59	90	90	45.0
OIL#13	1454.740	90.871	0.072468	15	83	300	300	20.0
OIL#14	1011.051	97.116	0.000448	9	53	162	162	16.3
OIL#15	909.269	83.244	0.599112	12	37	114	114	20.0
OIL#16	689.378	95.665	0.244706	10	34	120	120	22.1
OIL#17	1443.792	91.202	0.000042	112	373	1080	1080	125.0
OIL#18	535.553	104.501	0.085145	4	20	60	60	10.0
OIL#19	617.734	83.015	0.524718	5	38	66	66	13.0
OIL#20	90.966	127.795	0.176515	5	19	12	6	7.5
OIL#21	974.447	77.929	0.063414	50	98	300	300	53.2
OIL#22	263.810	92.779	2.740485	5	10	6	6	6.4
OIL#23	1335.594	80.950	0.112438	42	74	60	60	69.1
OIL#24	1033.871	89.073	0.041529	42	74	60	60	49.9
OIL#25	1391.325	161.288	0.000911	41	105	528	528	91.0
OIL#26	4477.110	161.829	0.005245	17	51	300	300	41.0
OIL#27	57.794	84.972	0.234787	7	19	18	30	13.7
OIL#28	57.794	84.972	0.234787	7	19	18	30	7.4
OIL#29	1258.437	16.087	1.111878	26	40	72	120	28.6

Table 11. Unit data with valve-point loading

Generator	*a*	*b*	*c*	*e*	*f*
COAL#05	1976.469	54.242	0.042468	700	0.080
COAL#10	1320.636	13.226	0.005063	600	0.055
COAL#15	1176.504	14.651	0.003901	800	0.060
COAL#22	1229.131	14.656	0.003684	600	0.050
COAL#33	1074.810	15.033	0.003542	600	0.043
COAL#40	1436.251	15.815	0.001581	600	0.043
LNG_CC#10	1898.415	71.584	0.000044	1100	0.043
LNG_CC#28	13813.001	22.941	0.081540	1200	0.030
LNG_CC#30	9750.750	45.017	0.035475	1000	0.050
LNG_CC#42	2982.219	79.458	0.054868	1000	0.050
OIL#08	2290.381	81.805	0.001580	600	0.070
OIL#10	6743.302	46.665	0.076810	1200	0.043

Table 12. Prohibit zones of units

Generator	Zone 1	Zone 2	Zone 3
COAL#08	[305, 335]	[420, 450]	
COAL#32	[320, 350]	[390, 420]	
LNG_CC#32	[230, 255]	[365, 395]	[430, 455]
OIL#25	[50, 75]	[85, 95]	-

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