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Phasor Discrete Particle Swarm Optimization Algorithm to Configure Micro-grids

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Abstract – The present study presents the Phasor Discrete Particle Swarm Optimization (PDPSO) algorithm, an effective optimization technique, the multi-dimensional vectors of which consist of magnitudes and phase angles. PDPSO is employed in the configuration of micro-grids. Micro-grids are concepts of distribution system that directly unifies customers and distributed generations (DGs). Micro-grids could supply electric power to customers and conduct power transaction via a power market by operating economic dispatch of diverse cost functions through several DGs. If a large number of micro-grids exist in one distribution system, the algorithm needs to adjust the configuration of numerous micro-grids in order to supply electric power with minimum generation cost for all customers under the distribution system.

Keywords: Phasor Discrete Particle Swarm Optimization (Phasor DPSO), Micro-grid, Distributed Generation (DG)

1. Introduction

A micro-grid is a modular system that operates independently and directly unifies customers and distributed generations (DGs) within the distribution system. Micro-grid is a new paradigm that could increase energy efficiency by using renewable energy and heat energy. It is geographically close to customers and thus, it could reduce transmission loss as well [1]. A micro-grid could be classified into energy supplier group consisting of distributed generations (DGs) and demander group comprising customers. If the electric power supplied to the demander group is deficient, sufficient supply can be possibly channeled from the power market. In a situation where there is surplus, power can be sold to the market through the reverse power flow. Nevertheless, the availability of heat energy totally depends on the supply group capacity of the inner micro-grid [2, 3].

Each micro-grid conducts economic dispatch of DGs to provide energy to the demander groups at minimum costs. In this system, it is possible to apply the classical numerical analysis technique. Dimeas [4] and Hernandez [5] studied techniques for DGs to arrive at minimal fuel costs. In the present paper, the modified economic dispatch of DGs includes the trade process of power market and heat load. In addition, combined heat and power (CHP) is considered in supplying heat energy, as well as electric power, based on the study conducted by Chang [6].

The process of obtaining the result of the optimization problem, which is the determination of the configuration of two or more micro-grids, needs heuristic techniques. There are objective functions which involve minimization of the geographic distance, transmission loss, generation costs, and so on that can be employed to determine optimal micro-grid configuration. Ghiani [7] and Vallem [8] suggested a micro-grid configuration to minimize distance and loss. The current paper, based on the studies conducted by Caldon [9] and Pudjianto [10] on the power market participation model of a micro-grid, puts forward a configuration that can supply energy to all customers with a minimum average cost.

Discrete particle swarm optimization (DPSO) algorithm is one of the typical heuristic techniques that can be applied to the problem of configuring power systems [11]. This modified PSO algorithm obtains result from continuous search space to discrete solution and achieves fast and correct convergence and wide search space of the PSO algorithm [12]. However, if the system has more than one micro-grid, the DPSO algorithm will converge to local, instead of global optimum. Therefore, this paper introduces a Phasor DPSO (PDPSO) algorithm as an explained particle of multi-dimensional phasor form rather than as a particle of multi-dimensional vector.

In the case studies, the proposed PDPSO algorithm was compared with the DPSO algorithm. The result confirmed the accuracy of the PDPSO algorithm in relation to the configuration problems of micro-grids.

2. Economic Dispatch of Distributed Generation

In the present paper, photovoltaic generation (PV), diesel

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generator, boiler, and CHP are considered among the various types of DGs. Each micro-grid, which comprises some or all these four kinds of DGs, individually supplies power and heat energy to its customers. The problem of determining DG output of each group corresponds to the economic dispatch of balancing energy supply and demand with minimum cost in the independent system [13, 14]. However, the economic dispatch, which is different from preexisting ones, includes a penalty for lack of heat energy and power transactions through external power market.

Because each micro-grid is an independent system, each has its own objective function. At arbitrary time *t*, Eqs. (1) and (2) describe the objective function and constraints of m^{th} micro-grid for economic dispatch.

Objective function:

$$\begin{aligned}
&\min C_m(t)\\
&=\left[\begin{array}{l}
\displaystyle\sum_{n\in MG_m} C_{DG,n}(t)\\
+\left\{\begin{array}{l}
\displaystyle C_{mk}^{buy}(t)\times u\left(\sum_{n\in MG_m} L_n(t)-\sum_{n\in MG_m} p_n(t)\right)\\
\displaystyle +C_{mk}^{sell}(t)\times u\left(\sum_{n\in MG_m} p_n(t)-\sum_{n\in MG_m} L_n(t)\right)
\end{array}\right\}\\
\displaystyle\times\left\{\sum_{n\in MG_m} L_n(t)-\sum_{n\in MG_m} p_n(t)\right\}\\
\displaystyle +C_{pt}(t)\left\{\sum_{n\in MG_m} L_n^h(t)-\sum_{n\in MG_m} h_n(t)\right\}\\
\displaystyle\times u\left(\sum_{n\in MG_m} L_n^h(t)-\sum_{n\in MG_m} h_n(t)\right)
\end{array}\right].
\end{aligned}\tag{1}$$

Constraints:

$$\begin{aligned}
p_n^{\min} &\le p_n(t)\le p_n^{\max}\\
h_n^{\min} &\le h_n(t)\le h_n^{\max}
\end{aligned}\tag{2}$$

where n is the given number of customers or DGs and MG_m is the m^{th} micro-grid. $p_n(t)$ and $h_n(t)$ are the power and heat output of the n^{th} DG, respectively. $C_m(t)$ is the energy supply cost of the m^{th} micro-grid in arbitrary time t. $C_{DG,n}(t)$ is the fuel cost of the n^{th} DG, and $C_{mk}{}^{buy}(t)$ and $C_{mk}{}^{sell}(t)$ are the power selling and purchase prices in the power market, respectively. $C_{pt}(t)$ is the penalty for shortage of thermal energy, $L_n(t)$ and $L_n{}^h(t)$ are the n^{th} customer's electric and the heat loads, respectively, and $u(t)$ is the unit step function. The subscript *max* or *min* refers to a maximum or minimum value of any variables, respectively.

Depending on the kind of DGs, the values that are substituted for the objective function of Eq. (1) and constraints of Eq. (2) are as follows.

PV:

$$\begin{aligned}
&C_{DG,n}(t)=0\\
&p_n^{\max}=\eta_{C,n}K_{P,n}A_{array,n}G(t)\\
&p_n^{\min}=h_n^{\min}=h_n^{\max}=0
\end{aligned}\tag{3}$$

where $\eta_{C,n}$ is the conversion efficiency of n^{th} DG, $K_{P,n}$ is the correction factor, $A_{array,n}$ is the gross area of solar cells, and $G(t)$ is the solar radiation in time t [15].

Diesel generator:

$$\begin{aligned}
&C_{DG,n}(t)=\alpha_n+\beta_n p_n(t)+\gamma_n\{p_n(t)\}^2\\
&h_n^{\min}=h_n^{\max}=0
\end{aligned}.\tag{4}$$

Boiler:

$$\begin{aligned}
&C_{DG,n}(t)=\alpha_n^h+\beta_n^h h_n(t)+\gamma_n^h\{h_n(t)\}^2\\
&p_n^{\min}=p_n^{\max}=0
\end{aligned}.\tag{5}$$

CHP:

$$\begin{aligned}
C_{DG,n}(t)&=\alpha_n+\beta_n p_n(t)+\gamma_n\{p_n(t)\}^2\\
&\quad+\alpha_n^h+\beta_n^h h_n(t)+\gamma_n^h\{h_n(t)\}^2+\chi_n p_n(t)h_n(t)\\
&=\alpha_n+\alpha_n^h+\left(\beta_n\eta_{CHP,n}+\beta_n^h\right)h_n(t)\\
&\quad+\left\{\gamma_n\left(\eta_{CHP,n}\right)^2+\gamma_n^h+\chi_n\eta_{CHP,n}\right\}\{h_n(t)\}^2\\
p_n^{\min}&=\eta_{CHP,n}h_n^{\min}\\
p_n^{\max}&=\eta_{CHP,n}h_n^{\max}
\end{aligned}\tag{6}$$

where $\eta_{CHP,n}$ is the ratio of the electric output to the heat output of the CHP [6].

In the current paper, the problems of DG economic dispatch are solved by the Newton–Raphson method among other typical numerical analyses [14].

3. Configuration of Micro-grids

The problem in the configuration of all DGs and customers in the distribution system is the process of exchanging and mediating between the supply and demand groups in the micro-grids [16]. If an arbitrary micro-grid has relatively too many supply groups, the other micro-grid demander groups cannot be supplied with energy by the DG and will totally depend on power supply from the power market. In addition, several customers cannot be supplied with heat energy. This condition results in an increase of the energy supply cost in the micro-grids because of the insufficient capacity of the supplier group. However, when the energy cost in some micro-grids is increased, the entire micro-grids' average energy cost will go up. In this situation, the suitability of micro-grid configuration is estimated by the sum of all the energy-supply costs. The total cost becomes minimal in the optimal configuration using the PDPSO algorithm. The total energy cost for supplying energy to all customers is equal to the sum of the energy costs of all micro-grids because it is assumed that each customer is included in one of the micro-grid demand groups. Eventually, the optimization problem for the application of the PDPSO algorithm achieves the objective function expressed as Eq. (7).

$$\min\left\{\sum_{\forall t}\sum_{\forall m} C_m(t)\right\}. \tag{7}$$

4. PSO

4.1 Analog PSO

The PSO algorithm was developed for continuous variables. It is a technique that introduces the hypothesis that the entire swarm group shares information. Likewise, it presents the concept that the group’s own internal particles conduct their actions based on their previous experiences and information shared throughout the entire swarm. Every particle moves after correcting its velocity through the information of the particle located closest to the optimum of the whole group and the information of its own position closest to the optimum. The velocity required to start the motion at the (k+1)th iteration step after an ith particle finishes moving at the kth iteration is expressed as Eq. (8) [11, 12].

$$\begin{aligned} V_i^{k+1} &= W^{k+1}V_i^k + C_1 rand_1\left(Pbest_i^k - X_i^k\right) \\ &+ C_2 rand_2\left(Gbest^k - X_i^k\right) \end{aligned} \tag{8}$$

where X_i^k is the position of the ith particle on the kth iteration step. C_1 and C_2 are acceleration factors representing important particle and group information, respectively. $rand_1$ and $rand_2$ show the random numbers that equally occur from 0 to 1. $Pbest_i^k$ indicates the best position that the ith particle can be discovered until the iteration step, and $Gbest^k$ displays the best position found from all of the particles of the swarm.

The inertia of velocity W^{k+1} shows the effects of the velocity from the previous iteration step and is expressed as Eq. (9).

$$W^k = W^{\max} - \left(W^{\max} - W^{\min}\right)\left(\frac{k}{i^{\max}}\right). \tag{9}$$

In PSO algorithm, the inertia of the velocity has to be large to ensure a large navigation area at the beginning of iteration. The velocity gradually decreases to raise the convergent property in later iterations. Finally, on the k+1th iteration, the particles move as expressed in Eq. (10), by a velocity defined by Eq. (8).

$$X_i^{k+1} = X_i^k + V_i^{k+1}. \tag{10}$$

Generally, the PSO algorithm sets up an initial value of the particle velocity and position using random numbers. Due to the fast convergent property in later iterations, the algorithm repeats the process until it reaches the pre-decided number of iteration without fixing convergence conditions.

4.2 DPSO

The PSO algorithm for continuous variables is applicable to problems that include discrete variables. It is consistent even when continuous and discrete variables are mixed together. The DPSO algorithm for discrete variables applies rounding off to Eq. (10) when the position of the particle is renewed. In this case, it is expressed as Eq. (11) [12].

$$X_i^{k+1} = Round(X_i^k + V_i^{k+1}). \tag{11}$$

The method of applying the DPSO algorithm is analyzed by using a simple example that configures three micro-grids in the distribution system which consists of a total of five DGs. The position of each particle is expressed in a 5-dimensional vector because there are five DGs in total. The mathematical formulation for this problem can be stated as Eq. (12).

$$X_i^k = \left[x_{i,1}^k, x_{i,2}^k, x_{i,3}^k, x_{i,4}^k, x_{i,5}^k\right]. \tag{12}$$

All values in Eq. (12) are rounded off to transform the all the values into positive numbers. One value is taken among 1, 2, and 3, because three micro-grids are considered. The particle is positioned in the 5-dimensional vector, although each vector component of Eq. (12) independently moves at a linear space. As a result, if a value is higher than 3 or smaller than 1 in the vector's component, that value will be compulsorily fixed by the boundary condition of Eq. (13).

$$\begin{cases} x_{i,n}^{k} = x^{\max} & if\ x_{i,n}^{k} > x^{\max} \\ x_{i,n}^{k} = x^{\min} & if\ x_{i,n}^{k} < x^{\min} \end{cases}. \tag{13}$$

n takes a value from 1 to 5 in this example. If the position of the particle is the same as that of Eq. (14), a micro-grid configuration similar to the one shown in Fig. 1 is expressed.

$$X_i^k = [1, 3, 2, 3, 1]. \tag{14}$$

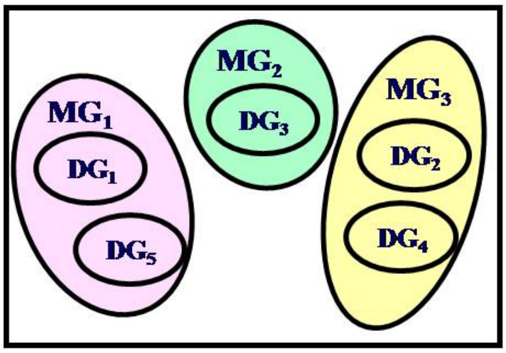

Fig. 1. Simple example of micro-grid configuration

One of the vectors of the particle's position expresses the configured state of the entire micro-grid in the distribution system. The total energy supply cost of Eq. (7) should be calculated $i^{\max}$ times to discriminate suitability of all configured states at each iteration. However, the same configured state, which is repeatedly processed, can be calculated in a shorter time using the value calculated above [17].

If the DPSO algorithm is directly applied to the micro-grid configuration problem, the disadvantages can be explained by the above simple example as follows:

First, the DG (that is, the vector component of the position of the particle) will be concentrated in the micro-grid that has either the lowest or highest number due to the boundary condition of Eq. (13), which occurs in the early search of large velocity inertia. The velocity of the DPSO algorithm has inertia. Once the DG's position gets out of the boundary condition, it has a velocity value that allows it to exit from the boundary condition for a specific time, even after the position has been corrected by the boundary value.

Second, in the later search for small velocity inertia, the DG in the boundary section (that is, the first or third micro-grid) has difficulty reaching global optimum that will allow the DG to go beyond the local optimum. The position where the particle can move to is only a one-way direction defined by the boundary condition. As a result, the specific particle hardly moves during the later search. This phenomenon is frequently observed when the distance between two end boundaries becomes increasingly large because of the presence of a huge number of micro-grids.

4.3 Phasor DPSO

One way of removing the boundary conditions of DPSO imposed by Eq. (13) is by moving the vector component of particle position to a circumferential space, which connects either of the end boundary values, instead of moving the component to a linear space. However, the linear and circumferential spaces should have the same dimensions under each micro-grid. In other words, the three micro-grids in the example shown in Fig. 1 should have sections that are 0.5~1.5, 1.5~2.5, and 2.5~3.5 in linear space and sections that are 0°~120°, 120°~240°, and 240°~360° in the circumferential space. In the PDPSO algorithm proposed in the current paper, each vector component of the position of the particle has a phasor form where the vector component moves within a 2-D phasor space instead of within the linear or circumferential space. The phasor consists of a space that facilitates the arrival of the particle at each micro-grid section even if there is a wide gap between the numbers of micro-grids. The i^{th} particle's position at k^{th} iteration is expressed as Eq. (15) in the PDPSO algorithm.

$$\begin{aligned} X_i^k &= \left(W^{\max} + W^{\min} - W^k\right)\angle\Theta_i^k \\ &= R^k\angle\Theta_i^k = R^k\angle\left[\theta_{i,1}^k, \theta_{i,2}^k, \cdots, \theta_{i,n}^k, \cdots \theta_{i,n^{\max}}^k\right] \end{aligned}. \tag{15}$$

W^k, which is used to calculate the magnitude of the position phasor in Eq. (15), is the same as that in Eq. (9), which has been used in the DPSO algorithm. Based on progressive iteration, the position of the particle increasingly goes far from the zero point, thus narrowing the search area.

The equations of velocity and position transform into Eqs. (16)-(18), instead of Eqs. (8), (10), and (11).

$$\begin{aligned} V_i^{k+1} &= V_i^k + C_1 rand_1\left(Pbest_i^k - X_i^k\right) \\ &\quad + C_2 rand_2\left(Gbest^k - X_i^k\right) \end{aligned} \tag{16}$$

$$Z_i^{k+1} = X_i^k + V_i^{k+1} = \left|Z_i^{k+1}\right|\angle\Theta_i^{k+1} \tag{17}$$

$$X_i^{k+1} = R^k\angle\Theta_i^{k+1}. \tag{18}$$

The relationship among Eqs. (16)-(18) is shown in Fig. 2(a).

In the PDPSO algorithm, no boundary condition similar to Eq. (13) exists. When the phase angle in Eq. (16) or Eq. (17) is added to or subtracted from the other phase angle, the result is always between 0° to 360°. Thus, boundary conditions are not necessary. In addition, no rounding off of figures is performed compared with Eq. (11).

Relating each micro-grid and DG (or customer) can be achieved through the value of the phase angles. In other words, if the angle of the n^{th} component of i^{th} particle

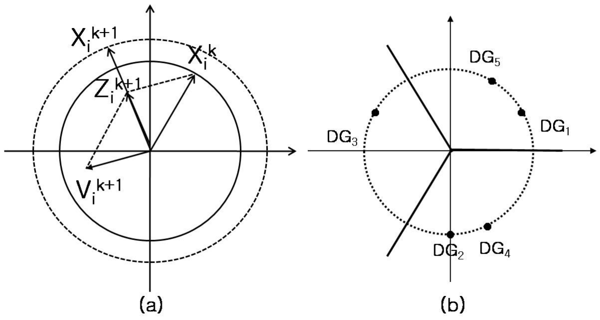

Fig. 2. Phasor space of PDPSO

satisfies Eq. (19), where there are m^{max} micro-grids in the distribution system, the n^{th} DG (or customer) is included in the m^{th} micro-grid.

$$\frac{360^\circ}{m^{\max}}(m-1) \le \theta_{i,n}^{k} < \frac{360^\circ}{m^{\max}} m . \tag{19}$$

If the particle position in the distribution system, where there are only three micro-grids, is the same as that in Eq. (20), a phasor space, such as that the one shown in Fig. 2(b), can be drawn, resulting in the micro-grids configuration similar to that in Fig. 1.

$$\Theta_i^k = [32°, 270°, 147°, 285°, 59°] . \tag{20}$$

The biggest difference between the PDPSO and DPSO algorithms is that the PDPSO algorithm eliminates the phenomenon of concentration of the movement of the particle on the boundary layer in the early search. This is achieved by removing the boundary condition. Another difference is that the PDPSO algorithm undertakes various movement directions by removing the boundary condition and expanding the configuration to two dimensions. This opens the possibility of escape from the local optimum in later search.

In addition, The PDPSO algorithm has the advantage of providing the particles a wider search area by moving to the zero point in the phasor space while keeping a powerful convergence of the existing DPSO algorithm through the increase of the distance between the particle and the zero point during later search.

5. Simulations and Comparative Studies

To compare the suggested PDPSO with the DPSO algorithm, the distribution system shown in Fig. 3 is simulated for 24 h. The test system has nine DGs, seven electric customers, and five heat customers.

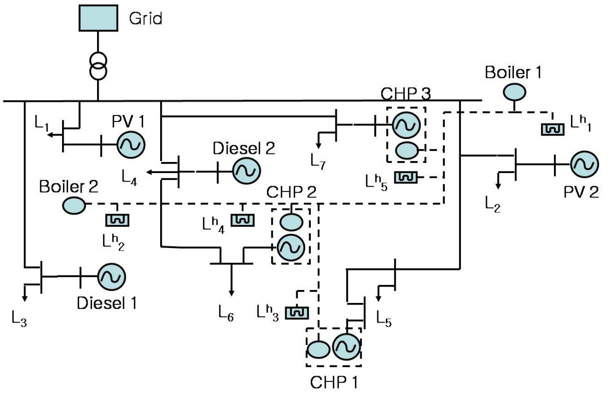

Fig. 3. Test system for case study

The parameters of the DGs are tabulated as follows:

Table 1. Parameters of the two PVs

	$A_{array,n}$ [m²]	p_n^{max} [kWp]	$\eta_{C,n}$	$K_{P,n}$
PV 1	3,000	345,6	0.12	0.8
PV 2	5,000	576	0.12	0.8

Table 2. Parameters of the two diesel generators

	Cost Coefficient [\$/kW]			
	α^p_n	β^p_n	γ^p_n	p_n^{max} [kW]
Diesel 1	33	0.0322	0.000054	1,200
Diesel 2	19.4	0.0592	0.000041	700

Table 3. Parameters of the two boilers

	Cost Coefficient [\$/kW]			
	α^h_n	β^h_n	γ^h_n	h_n^{max} [kW]
Boiler 1	24	0	0.0000752	800
Boiler 2	0	0.0622	0	500

Table 4. Parameters of the three CHPs

	Cost Coefficient [\$/kW]			
	α_n	β^p_n	β^h_n	γ^p_n
CHP 1	14.3	0.0152	0.0182	0.0000471
CHP 2	4	0.0502	0.0602	0.00008786
CHP 3	39.4	0.0142	0.0142	0.0000822
	Cost Coefficient [\$/kW]			
	γ^h_n	χ_n	$\eta_{CHP,n}$	h_n^{max} [kW]
CHP 1	0.0000601	0.0000553	0.577	1,300
CHP 2	0.00007786	0.000026	1	500
CHP 3	0.0000922	0.00007823	0.8	700

The heat unit [(J) or (cal)] was changed to an electric power unit (W), and the penalty fee for heat shortage was set at 12 \$/kWh. The electric load, heat load, solar radiation, and purchase price at the power market used were intended for a 24 h use, as shown in Figs. 4-6. The selling price to the power market used was at 90% of the purchase price.

Simulations using the PDPSO and DPSO algorithms were conducted under the same condition. Iteration of 100 times using 20 particles was accomplished, and the assumed coefficient values were $C_1 = C_2 = 2$, $W^{min} = 0.4$,

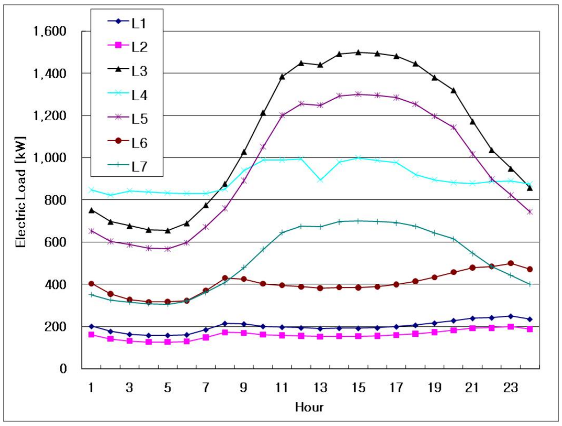

Fig. 4. Electric loads of the test system

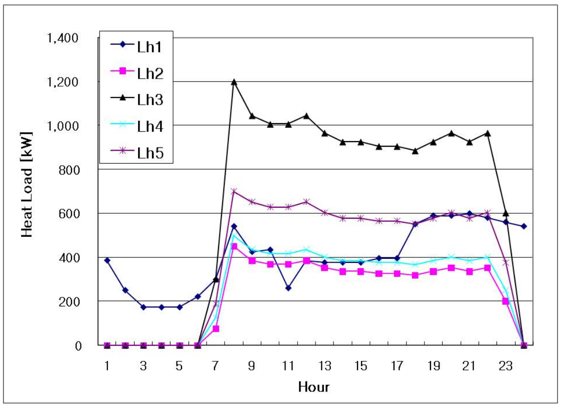

Fig. 5. Heat loads for the test system

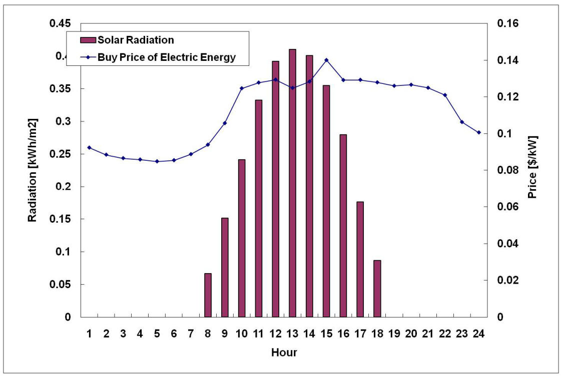

Fig. 6. Purchase power price and solar radiation for the test system

and $W^{max} = 0.9$, based on an earlier study [11].

Table 5 presents the optimal configuration of four micro-grids by PDPSO algorithm as an example. The sum of the operation costs of four micro-grids is \$15,206.00, whereas the sum of the operation costs of DPSO is \$15,534.00. The first and second micro-grids in Table 5 have no heat customers and heat sources. Several, but not all, micro-grids specializing only in electric or heat energy may decrease the operation cost of the system.

Table 5. Optimal configuration of four micro-grids obtained by the PDPSO algorithm

	Initial DG	Optimal Configuration		
		DGs	Electric Loads	Heat Loads
MG 1	PV 1	PV 1, PV 2	L_1, L_2	
MG 2	Diesel 1	Diesel 1	L_4	
MG 3	Boiler 1	Boiler 1, CHP 2	L_6	L^h_4, L^h_5
MG 4	CHP 1	Diesel 2, Boiler 2, CHP 1, CHP 3	L_3, L_5, L_7	L^h_1, L^h_2, L^h_3

Based on the increase of the number of micro-grids, the supply cost of energy supplied to all customers in the optimum configuration for each algorithm is derived and shown in Fig. 7.

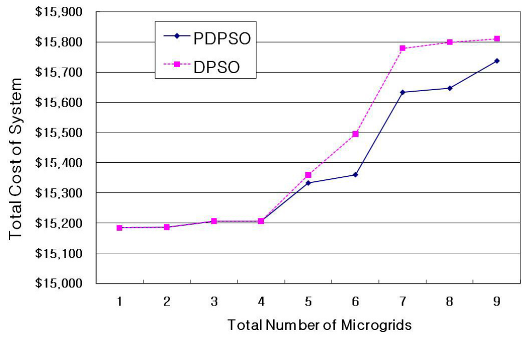

Fig. 7. Energy cost curve of the two algorithms

One of the results shown in Fig. 7 indicates that having more micro-grids results in higher energy supply costs in the distribution system. The present paper assumed that the micro-grid independently supplies power to each demander group. Each micro-grid is similar to the independent power system because there is no power or heat-energy trade between micro-grids. Disadvantages will be produced by the economic dispatch of the DG when one system divides into numerous subsystems, and the DGs would be required either to supply the shortage of energy from the electricity market or to pay for the penalty.

Result of comparison between the two algorithms, shown in Fig. 7, reveals a more exact configuration state for PDPSO algorithm. The result shows that the more micro-grids there are, the more gaps exist between the results of the DPSO and the PDPSO algorithms.

To study the convergence based on the search iteration, the convergence curves of the two algorithms, when there are four, six, and eight micro-grids, are drawn and shown in Fig. 8.

The two algorithms do not show a large difference in terms of convergence speed. The curves of the PDPSO algorithm reach an end value after converging more frequently than those of the DPSO curves. In addition, no change in the convergence value is observed after half of

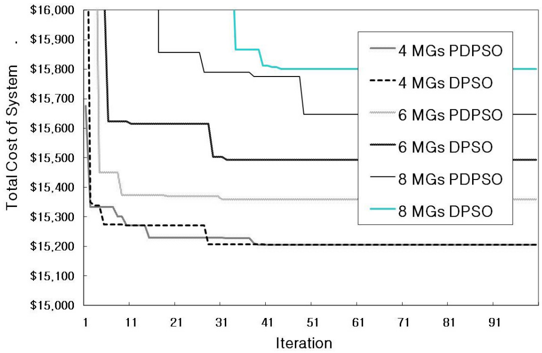

Fig. 8. Convergence curves of the two algorithms

the search frequency was performed in all cases. The micro-grid is divided into supply and the demander groups. Thus, when one group changes, the total energy cost increases and subsequently reverts back to the pre-iteration configuration. Based on these characteristics, the convergent step becomes infrequent over all steps, which is different from the other optimization problems. In particular, the value is hardly changed in the later search.

6. Conclusion

The present paper has proposed a new algorithm as an improvement over the existing DPSO algorithm to determine the configuration of multiple micro-grids. The proposed PDPSO algorithm, where each vector component is moving at the fanwise space of two dimensions, could address the linear space defect of the DPSO algorithm. The PDPSO algorithm solves the phenomenon of particles concentration at either end of the linear space in the early search. It shows a more improved convergence in reaching the global optimum in the later search stage. The suggested algorithm is a suitable heuristic technique, which configures micro-grids whose supply and demand groups have characteristics which are opposite to each other.

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