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A variable scaling hybrid differential evolution for solving large-scale power dispatch problems

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Abstract: A variable scaling hybrid differential evolution (VSHDE) is used to solve the large-scale power dispatch problems. The hybrid differential evolution (HDE) method has been presented as a method using the parallel processors of the two-membered evolution strategy ((1 p 1)-ES). In this way, the global search ability for the HDE can be inspected. To accelerate the search for the global solution, the concept of the variable scaling factor based on the one-fifth success rule of evolution strategies is embedded in the original HDE. The use of the variable scaling factor in the VSHDE can overcome the drawback of the need for fixed and random scaling factors in an HDE. To realise the dynamic economic dispatch (DED) system, the valve-point loading effect, system load demand, power losses, spinning reserve capacity, ramp rate limits and prohibited operation zones are considered here. Two test problems and two DED systems including those of 10 units and 20 units are used to compare the performance of the proposed method with an HDE. Numerical results show that the performance of the proposed method is better than that of the HDE method.

Nomenclature

i index of dispatchable units
t index of time intervals
F_{it} fuel cost function of unit i at the tth time interval
P_{it} power generation of unit i at the tth time interval
n the number of generating units
T the number of intervals in the entire dispatchperiod
a_i, b_i, c_i fuel cost coefficients of unit i
e_i, f_i constants from the valve-point effects of unit i
$P_{it\min}$ minimum generation limit of unit i at the tth time interval
P_{Dt} load demand at the tth time interval
P_{Lt} power loss at the tth time interval
B_{ii} power loss coefficient
$P_{i\min}$ minimum generation limit of unit i
$P_{i\max}$ maximum generation limit of unit i
$P_{i(t-1)}$ power generation of unit i at the $(t-1)$th time interval
UR_i the up ramp limit of the ith unit
DR_i the down ramp limit of the ith unit
S_{it} spinning reserve of unit i at the tth time interval
S_{Rt} system spinning reserve requirement at the tth time interval
$S_{i\max}$ maximum spinning reserve of unit i
c set of all dispatchable units with prohibited zones
C set of all dispatchable units
$P^l_{i,1}$ lower bound of the first prohibited zone of unit i
$P^l_{i,j}$ lower bound of the jth prohibited zone of unit i
$P^u_{i,j-1}$ upper bound of the $(j-1)$th prohibited zone of unit i

$P_{it\max}$ maximum generation limit of unit *i* at the *t*th time
u
i,*ni*
upper bound of the n_ith prohibited zone of unit *i*
interval
$_i$ number of prohibited zones in unit *i*

1 ntroduction

The aim of the dynamic economic dispatch (DED) problem is to schedule the generator outputs with predicated load demand and the various systemic and operating constraints over a certain period of time economically. Thus, the objective of the DED is to minimise the cost of energy subject to the various constraints. Different from the conventional economic dispatch problem, the DED problem takes into consideration the limits on the generator ramping rate to maintain the life of generation equipment [1–7]. It is a dynamic optimisation problem that is difficult to solve because of its non-convex property. However, the DED problem can divide the entire dispatch period into a number of small time intervals and a static economic dispatch has been employed to solve the problem in each interval [8]. Attaviriyanupap *et al.* [8] proposed a hybrid evolutionary programming and sequential quadratic programming (SQP) method to solve the DED problem considering the non-smooth fuel cost function. A robust heuristic method was used by Ham *et al.* [5] to solve the DED problem. Victoire and Jeyakumar [9] proposed a hybrid solution methodology integrating a particle swarm optimisation (PSO) algorithm with the SQP method for the DED problem. However, these three methods required two-phase computations. The PSO method proposed by Gaing
[10] for solving the DED problem. The population size is set to 100 *x*, where *x* is the number of decision parameters. In so doing, much more computation time is required to evaluate the fitness function.

A hybrid differential evolution (HDE) [11, 12] is a stochastic search and optimisation method. The fittest ofan offspring competes one-to-one with the corresponding
respectively. However, Chiou *et al.* [14, 15] used the VSHDE method to solve the static and integerprogramming systems, respectively.

In this study, a VSHDE is discussed for use in solving the dynamic optimisation systems, that is large-scale DED systems. The HDE has previously been presented as a method using N_p parallel processors of the two- membered evolution strategy ((1 1)-ES), where N_p is the number of individuals in the solution space [11]. The scaling factor based on the one-fifth success rule of evolution strategies (ESs) [16, 17] is used in the VSHDE method to accelerate the search for the global
solution. According to the convergence property of the whole population, the scaling factor is adjusted based on the one-fifth success rule. A DED considering the various systemic and operating constraints, which include the system load demand, power losses, spinning reserve capacity, ramp rate limits and prohibited operation zones, is considered in this paper. To illustrate the convergence property of the proposed method, two test problems and two DED systems including those of 10 units and 20 units are used to compare the performance of the proposed method with that of the HDE.

2 Problem formulation

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The DED problem considering the various systemic and operating constraints can be mathematically described as follows
parent, which makes this one different from the other gives rise to a faster convergence rate. However, this faster convergence also leads to a higher probability of obtaining a local optimum because the diversity of the population descends faster during the solution process. To overcome this drawback, the migrating operator and accelerated operator act as trade-off operators for the diversity of population and convergence properties in the HDE. The migrating operator maintains the diversity of the population, which guarantees a high probability of obtaining the global optimum, and the accelerated operator is used to accelerate convergence. However, a fixed scaling factor is used in the HDE. Using a smaller scaling factor,

þ je$_i$ sin (f_i ($P_{it\,\min}$ — P_{it}))j] {1}

subject to the following constraints:

a. Power balance constraint

$$P_{it} ¼ P_{Dt} þ P_{Lt} \quad \overset{n}{\underset{i¼1}{}} \quad (2) \quad X$$

an HDE becomes increasingly robust. However, much computational time should be expended to evaluate the objective function. An HDE with a larger scaling factor would have results that generally fall into a local solution or misconvergence. Lin *et al.* [13] used a random number with a value between zero and one as a scaling factor. However, a random scaling factor could not guarantee fast

P_{Lt} ¼ X $B_{ii}P$

2
it

i¼1

b. Ramping rate limits
(3)
convergence. To overcome this drawback, Chiou *et al.* [14, 15] proposed the variable scaling hybrid differential evolution (VSHDE) method to solve the economic dispatch problems and the capacitor placement problems,

$P_{it\min} \le P_{it} \le P_{it\max}$ (4)

$P_{it\min}$ ¼ max ($P_{i\min}$, $P_{i(t—1)}$ — DR$_i$) (5)

$P_{it\max}$ ¼ min ($_{i\max}$, $P_{i(t—1)}$ þ UR$_i$) (6)

c. System spinning reserve constraints these constraints is rewritten from (1) as follows

X $S \ge S$

n

it i¼1Rt

(7)

n T

min

8
< X X

$F_{it}(P_{it})$ þ $q1$ X

X

t¼1 i¼1

2 !

P_{it} — P_{Dt} — P_{Lt}

X X

S_{it} ¼ min $P_{it\max}$ — P_{it} , $S_{i\max}$ } 8i [ðC — cþ (8)

P_{it} : t¼1 i¼1

þ $q2$ [max (max ($P_{i\min}$, $P_{i(t-1)}$ — DR_i) — P_{it} , 0)^2

t¼1 i¼1

S_{it} ¼ 0 8i [c (9)

2

þ max (P_{it} — min ($P_{i\max}$, $P_{i(t-1)}$ þ UR_i), 0)]

T X n X !!$_2$9=

d. Generation limits of units

þ $q3$

t¼1

max S_{Rt} —

i¼1

S_{it}, 0

;

(14)

Units with prohibited operating zones

where q_1, q_2 and q_3 are penalty factors when these terms are zero in (14), and no constraints are violated; otherwise, these terms are positive values. To solve the above-mentioned

$P_{it\min} \le P_{it} \le P^{l}_{i,1}$

or (10)

system, the VSHDE is proposed in this work.

$P^{u}_{i,j-1} \le P_{it} \le P^{l}_{i,j}$, j ¼ 2, … , n_i

or (11)

3 Variable scaling hybrid

P u
i,*n*$_i$

$\leq P_{it}$
$\leq P_{it}$max
, 8*i* [*c* (12)

differential evolution

The basic structure of a VSHDE is shown in Table 1. Thisstructure is a parallel direct search algorithm which utilises N_p

Units without prohibited operating zones

vectors of the decision parameters *z* in the optimisation problem, that is, Z^G_k, *k* ¼ 1, 2, . . . , N_p as a population for

$$P_{it}\text{min} \leq P_{it} \leq P_{it}\text{max} \qquad (13)$$

each generation *G*. The initial population is randomly selected and should attempt to cover the entie search space uniformly as shown in the following form

In this study, the treatment of constraints is performedwith the penalty method. The penalty method, among

0
k min *Z* ¼ *z*
þ s_k · (z_{max}
— z_{min}), *k* ¼ 1, . . . , N_p
(15)

the most popular techniques used to handle constraints, is easy to implement and is considered efficient. The penalty method is usually close in degree to the nearest solution in a reasonable region, and it enables an objective function effort to arrive at the optimum solution. The penalty method used in DED systems is described as follows.

First, if the ED takes account of the prohibited zone constraints, the delimitation point divides the prohibited zone into two sub-zones, that is, the left and right prohibited sub-zones. The delimitation point is set in the middle point of each prohibited zone in this work. When a unit operates in one of its prohibited zones, the strategy is to force the unit to move either towards the lower bound of that zone from the left sub-zone or towards the upper bound of that zone from the right sub-zone. The unit power must conform to the constraint of (13) when the unit does not include prohibited zones. In addition to prohibited zone constraints, the computation results also must conform to the ramp rate limits in (4)–(6), the system spinning reserve requirement in (7)–(9) and the power balance condition in (2) and (3). The fuel cost function with
where s_k [(0, 1] denotes the uniformly distributed random numbers and z_{min} and z_{max} are the lower and upper bounds of the decision parameters, respectively.

The five main key operations in a VSHDE are as follows. The essential ingredient in the mutation operation is the difference vector. Each individual pair in a population at

Table 1 Basic structure of VSHDE

Step	Procedure
1	initialisation
2	mutation operation
3	crossover operation
4	evaluation operation
5	migration operator if necessary
6	acceleration operator if necessary
7	updating the scaling factor if necessary
8	repeat of steps 2 to 7

the (G 2 1)th generation defines a difference vector D_{lm} as
individual of Z^{G-1} are chosen by a binomial distribution to carry out the crossover operation to generate offspring. In

$$D_{lm} ¼ Z^{G-1} - Z^{G-1}$$

6)

this crossover operation, the uth gene of the kth individual

l m

at the next generation is produced from the perturbed

The mutation process at the (G 2 1)th generation begins by

individual Z^G ¼ [z^G, z^G, . . . , z^G] and the present

randomly selecting either two or four population individuals

k

individual; v

$1k$ $2k$ vk

Z^{G-1}, Z^{G-1}, Z^{G-1} and Z^{G-1} for any l, m, o and r. These is the number of the decision parameters. Thus

l m o r

four individuals are then combined to form a difference vector D as

z^{G-1}, if a random number . C

$lmor$

uk z^{G-1}, otherwise z^G ¼ u ¼ 1, . . . , v; k ¼ 1, . . . , N r

uk

$$D_{lmor} ¼ D_{lm} þ D_{or} ¼ (Z^{G-1} - Z^{G-1}) þ (Z^{G-1} - Z^{G-1})$$

p

(21)

l m o

(17)

where the crossover factor C_r [[0, 1] is assigned by the user.

A mutant vector $\hat{Z}_k^{G-1}$ is then generated based on the present individual Z_p^{G-1} in the mutation process by

In VSHDE, the evaluation function of an offspring competes one-to-one with that of its parent. This

$$\hat{Z}_k^{G-1} ¼ Z_p^{G-1} þ FD_{lmor}, \quad k ¼ 1, \dots, N_p \quad (18)$$

competition indicates that the parent is replaced by its offspring if the fitness of the offspring is better than that of its parent. On the other hand, the parent is retained in the

The rule of updating scaling factor, F, based on the one-fifth success rule of ESs is used to adjust the scaling factor. The rule of updating the scaling factor is as follows

$$F^{t+1} = \begin{cases} c_d * F^t, & \text{if } p_s^t < 1/5 \\ c_j * F^t, & \text{if } p_s^t > 1/5 \\ F^t, & \text{if } p_s^t ¼ 1/5 \end{cases} \quad (19)$$

next generation if the fitness of the offspring is worse than that of its parent. This evaluation operation contains two selection steps. The first selection step is the one-to-one competition. The next step selects the best individual in the population. These steps are therefore expressed as

$$Z_k^G ¼ \arg\min \{ f(Z_k^{G-1}), f(\hat{Z}_k^G)\}, \quad k ¼ 1, \dots, N_p \quad (22)$$

where p_s^t is the frequency of successful mutations measured. The successful mutation defines the fitness value of the best individual in the next generation as better than the best individual in the current generation. The initial value of the scaling factor is set to 1.2 [18]. The factors of c_d ¼ 0:82 and c_j ¼ 1=0:82 [16, 17] are used for adjustment, which should take place for every q iterations. The iteration index q suggested by [17] is equal to 10 y, where y is a constant. When the migration operator is performed, the value of the scaling factor is defined as follows

$$F ¼ 1 - \frac{\text{iter}}{\text{itermax}} \quad (20)$$

where iter and itermax are the number of current iteration and the maximum iteration, respectively. The scaling factor can be reset as (20) when the scaling factor is too small to find a better solution in the solution process.

The scaling factor should be updated as (19) in every q iterations. When the migrating operation performed or the

$$Z_b ¼ \arg\min \{ f(Z_k), \quad k ¼ 1, \dots, N_p\} \quad (23)$$

where arg min

denotes the argument of the minimum.

To increase the capability of VSHDE to search out the global optimum, an acceptable trade-off between convergence and diversity must generally be determined. Convergence implies a fast convergence although it may be to a local optimum. On the other hand, diversity guarantees a high probability of obtaining the global optimum. When the fitness function value does not continuously descend from generation to generation by the use of the above-mentioned steps, that is, initialisation, mutation operation, crossover operation and an evaluation operation the acceleration operation is considered to mitigate this drawback, which means, the aim of using an acceleration operation in a VSHDE is to push the present best individual towards attaining a better point. Thus, the accelerated phase is expressed as follows

scaling factor is too small to find a better solution, the scaling factor is reset as (20). The resulting individual

p

8
< _G
G

G—1

(24)

parent individual Z^{G-1} in (18) is essentially a noisy replica of Z^{G-1}. Herein, the

$$Z_b^G = \begin{cases} \bar{Z}_b^G, & \text{if } f(\bar{Z}_b^G) < f(Z_b^{G-1}) \\ \bar{Z}_b^G - \alpha \nabla f, & \text{otherwise} \end{cases} \quad (24)$$

p depends on the circumstance in which the type of the mutation operators is employed. Stron and Price [18] proposed five types of mutationstrategies.

To extend the diversity of further individuals at the next generation, the perturbed individual of $\hat{Z}^G$ and the present

where $\bar{Z}_b^G$ denotes the best individual, as obtained from (23). The gradient of the objective function, ∇f, can be approximately calculated by the finite difference. The step size $\alpha \in (0, 1]$ in (24) is determined by the ~~descent~~ property. Initially, α is set to a value of one to obtain the new individual Z_b^N. The objective function $f(Z_b^N)$ is then

ompared with $f(Z_b^G)$. If the descent property is followed,that is

$$f(Z_b^N) < f(Z_b^G) \quad (25)$$

The solution process of the VSHDE method is statedusing a flowchart as shown in Fig. 1.

Application of the proposed

then Z_b^N becomes a candidate in the next generation and is added to this population replacing the worst individual. On the other hand, if the descent property fails, the step size is reduced by 0.5 or 0.8 and the descent method is repeatedto obtain Z_b^N until $\alpha \nabla f$ becomes sufficiently small or an iteration limit is exceeded. Consequently, according to (24), the best fitness should be at least equal to or smaller than $f(Z_b^{G-1})$.

Although the convergence rate can be improved by the acceleration operation, this faster

b

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descent typically results in obtaining a local minimum or premature convergence. In addition, frequent performance of this operation causes the candidate individuals to gradually cluster around the best individual such that the population diversity is quickly decreased. Consequently, the migration phase must be performed to regenerate a new population, which restores the population diversity. The new candidates are regenerated on the basis of the best individual Z^G as follows
method
Two test problems and two DED systems, including the 10-unit and 20-unit systems, are investigated and the computational results are used to compare the performance of the proposed VSHDE method with that of the HDE method.

Simple examples

Example 1: Consider the maximisation problem [19] max $J(z_1, z_2)$ ¼ 21:5 þ z_1 sin(4pz_1) þ z_2 sin(20pz_2) (29)

where 3:0 z_1 12:1 and 4:1 z_2 5:8, A simple genetic algorithm using the population size of 20 has been

uk z^{G}þ1 ¼ z_{ub} þ s_k · (z_{umin} — z_{ub}), if d ¸ $\frac{z_{ub} - z_{umin}}{z_{umax} - z_{umin}}$

: z_{ub} þ s_k · (z_{umax} — z_{ub}), otherwise

(26)

where s_k and d denote the uniformly distributed random numbers. Herein, z_{umin} and z_{umax} are expressed as the lower and upper bounds, respectively, of the u th gene of the decision parameters. The diversified population is then used as the initial decision parameters to escape the local optimum points.

The migrating operation is executed only if a measure fails to match the desired tolerance of population diversity. The measure is defined as follows

XX Np v

¼ ¼ ¼ k 1 u 1 k=b 1

h_{uk}

$(v \cdot (N_p — 1))$

, 1_1

(27)

where

8

< 0, if 1

, $.z_{uk} — z_{ub}.$

h_{uk} ¼

2 : . z_{ub} ·

(28)

1, otherwise

Parameter 1_1, 1_2 [[0, 1] expresses the desired tolerance for the population diversity and the gene diversity with respect to the best individual. h_{uk} is the scale index. If 1 is smaller than 1_1, then the migrating operation is executed to generate a new population to escape the local point; otherwise, the migrating operation is turned off.

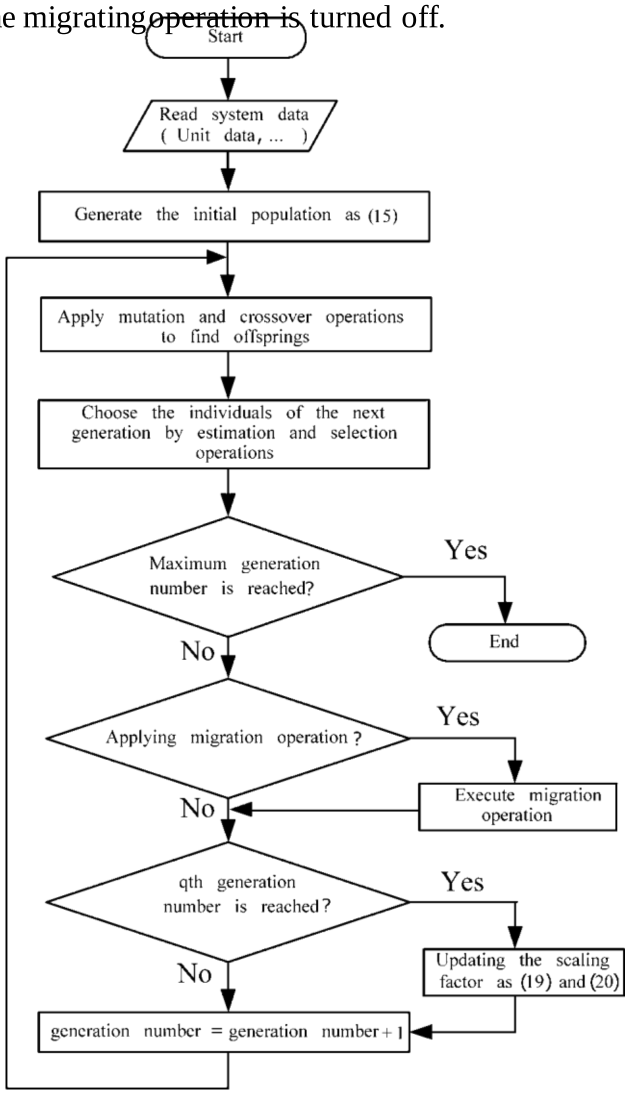


Figure 1 *Main calculation procedures of the proposedalgorithm*

used to solve this problem. The best result is found at generation 396 with the best objective function value of 38.827553, as also shown in [19].

The initial-setting factors for the VSHDE method are the same as that of the HDE [11], except that the former uses a variable scaling factor; that is the iteration index q is set to 10, which means, population size N_p ¼ 5, crossover factor
C_r ¼ 0:5, maximum iterations itermax ¼ 300, and the two
tolerances, 1_1 and 1_2, are both set to 0.1. This test problem
is repeated 100 times. Comparing the results from the HDE [11] with that from this proposed method, the number of runs required to find a solution larger than 38.827553 is 7 for the third and fifth mutation operations for the VSHDE method. However, in the HDE [11], the third and fifth mutation operations cannot find any solution with a function value larger than 38.827553. Forthe second and fourth mutation operations, both theVSHDE and HDE methods can find solutions. It is observed that the problem of selection of the mutation
system are listed in Table 2. Table 3 lists the prohibited zones of units 2, 5, 6 and 9. These zones result in four disjoint feasible sub-regions for each of units 2, 5 and 6,and three for unit 9. Hence, those zones result in a non- convex decision space that consists of 192 convex sub- spaces for every dispatch interval of the example system. To overcome the operation of the units in the prohibited operating zones, a delimitation point, P^d_{ab} , is introduced for the bth prohibited zone of unit a. The delimitation point divides the prohibited zone into two sub-zones, that is, the left and right prohibited sub-zones with respect to the point. When a unit operates in one of its prohibited zones, the purpose of this strategy is to force the unit either to move towards the lower bound of that zone from the left sub-zone or to move towards the upper bound of that zone from the right sub-zone.

To attain valid movement of purpose of moving the unit, adelimitation ratio, q, is defined first as follows
operation is alleviated.

Example 2: Consider the minimisation problem of theShubert function [19]

$$P^d_{ab} \quad v \quad 4 \quad ab \quad ab$$

$$q ¼ \frac{P_{ab} - 4}{P - P} \quad (1)$$

where P^v_{ab} and P^4_{ab} are the upper and lower bounds of the bth prohibited zone of unit a, respectively. If the ratio, q, is smaller than 0.5, the delimitation point is closer to the

$$\min J(z_1, z_2) ¼ \sum^5 i \cos[(i þ 1)z_1 þ i] \sum^5 i \cos[(i þ 1)z_2 þ i]$$

$z1$,$z2$
i¼1i¼1
(30)
lower bound, P^{4} . On the other hand, if the ratio is $\geq$ 0.5,
the point is closer to the upper bound, P^{v} . To determine ab
which bound the unit should move to, a uniformly
where ¼10 z_i 10 ¼for i 1, 2. This function has 760 localminima. The given global minimum is 2186.73.

To solve this problem, the initial-setting factors for the VSHDE method are the same as that of the HDE [11], except that the former uses a variable scaling factor; that is the iteration index q is set to 10, which means population size N_p ¼ 5, crossover factor C_r ¼ 0.5, maximum iterations itermax ¼ 100, and the two tolerances, 1_1 and 1_2, are both set to 0.3. Five strategies of the mutation operation are, respectively, used to solve this example. Following the similar to those discussed in Example 1, this problem is, respectively, solved for 100 runs. With the VSHDE method, the numbers of successful runs to achieve the global minimum are 95, 98, 98, 94 and 94 for the five different strategies of the mutation operation by using the VSHDE method. On the other hand, with HDE~~, they ar~~e 93, 96, 89, 93 and 82. Obviously, the probability of finding the global minimum can be seen from the above results.

Case studies

Example 3: The modified 10-unit DED system [8] is usedto illustrate the performance of the proposed algorithm. In this system, four units have prohibited operating zones, and the remaining six units contribute the required spinning reserve to the system. The valve-point effects are also considered in this example. Input data of the 10-unit
distributed random number, t [[0, 1], is generated. If the
random number t is greater than the ratio q, then the unit can move to the upper bound P^{v} ; otherwise, the unit moves to the lower bound P^{4} . ab
ab

The load demand of the system is divided into 24 dispatch intervals, shown in Table 4. The spinning reserve is required to be $\geq$ 5% of the load demand at every dispatch interval. The setting factors used in the VSHDE to solve the example system are as follows. The population size, N_p, is set to
5. The mutation operator, strategy, is set to 2. The
maximum generation is 500. The crossover factor, C_r, is set to 0.8. The scaling factor is updated as (19) and (20) in every ten iterations. The second mutation operator is used in the VSHDE. The two tolerances, 1_1 and 1_2, used in the migrating operation are both set to 0.1. These initial- setting factors for the HDE method are the same as that for the VSHDE, except that the HDE uses a scaling factor fixed at 0.3. The computational results are shown in Figs. 2 – 4. The fuel cost and the CPU time incurred by the HDE method are 1 343 243.2$ per day and 41 736 s, respectively. The fuel cost and CPU time incurred by the VSHDE method are 1 100 666.4$ per day, which is slightly lower than that of the HDE method, and 24 786 s, respectively. Fig. 5 represents the convergence property of the proposed VSHDE and HDE in the fuel cost of evaluation. It shows that the convergence property of the VSHDE method is superior to that of the HDE method.

Table 2 Input data of the 10-unit system for example 3

Unit	1	2	3	4	5
a_i	0.00043	0.00063	0.00039	0.00070	0.00079
b_i	21.60	21.05	20.81	23.90	21.62
c_i	958.20	1313.6	604.97	471.60	480.29
e_i	450	600	320	260	280
f_i	0.041	0.036	0.028	0.052	0.063
$P_{i\min}$	150	135	73	60	73
$P_{i\max}$	470	460	340	300	243
$S_{i\max}$	50	0	30	30	0
B_{ii}	0.000042	0.000069	0.000093	0.000093	0.000085
UR_i	80.00	80.00	80.00	50.00	50.00
DR_i	80.00	80.00	80.00	50.00	50.00
Unit	6	7	8	9	10
a_i	0.00056	0.00211	0.0048	0.10908	0.00951
b_i	17.87	16.51	23.23	19.58	22.54
c_i	601.75	502.70	639.40	455.60	692.40
e_i	310	300	340	270	380
f_i	0.048	0.086	0.082	0.098	0.094
$P_{i\min}$	57	20	47	20	55
$P_{i\max}$	160	130	120	80	55
$S_{i\max}$	0	50	50	0	0
B_{ii}	0.000053	0.000092	0.000065	0.000042	0.000070
UR_i	50.00	30.00	30.00	30.00	30.00
DR_i	50.00	30.00	30.00	30.00	30.00

Example 4: This DED application system is further expanded to demonstrate the applicability of the proposed VSHDE method to a large-scale system. The DED system of Example 3 is doubled to obtain a 20-unit DED system. The load demands of the 24 dispatch intervals of the system are also doubled. In this expanded DED system, units 2, 5, 6, 9, 12, 15, 16 and 19 have the prohibited operating zones. These zones result in four disjoint feasible sub-regions for each of units 2, 5, 6, 12, 15 and 16 and

Table 3 Prohibited zones of units for example 3
three for units 9 and 19. Hence, those zones result in a non-convex decision space, which consists of 36 864 convex sub-spaces for every dispatch interval of the expanded system.
Table 4 Load demand for 24 h for example 3

Hour	Load, MW	Hour	Load, MW	Hour	Load, MW
1	1036	9	1924	17	1480
2	1110	10	2072	18	1628
3	1258	11	2146	19	1776
4	1406	12	2179	20	2072
5	1480	13	2072	21	1924

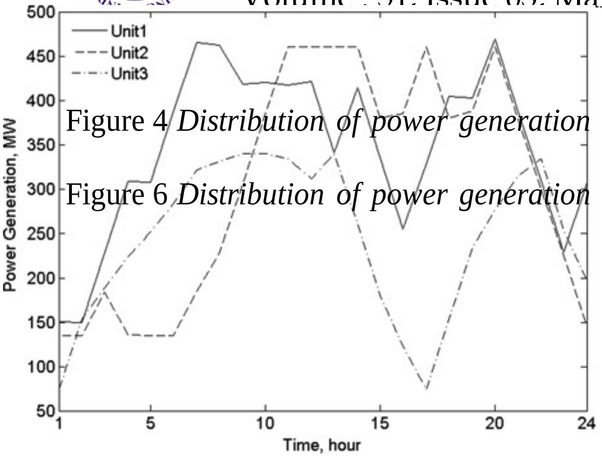
Unit	Zone 1, MW	Zone 2, MW	Zone 3, MW
2	[185, 225]	[305, 335]	[420, 450]
5	[90, 100]	[153, 168]	[195, 210]
6	[77, 85]	[122, 132]	[143, 153]
9	[30, 40]	[55, 65]	

Figure 2 *Distribution of power generation of unit 1 to unit3 in Example 3*

Figure 5 *Convergence characteristics for two algorithms in Example 3*

Figure 3 *Distribution of power generation of unit 4 to unit6 in Example 3*

To solve the expanded system, the spinning reserve dispatch is required to be 5% of the load demand at every dispatch interval. The setting factors used in the VSHDE method to solve the example system are as follows. The population size, N_p, is set to 5. The mutation operator, strategy, is set to 2. The maximum generation is 1000. The crossover factor, C_r, is set to 0.8. The scaling factor is updated as (19) and (20) in every ten iterations. The second mutation operator is used in the VSHDE. The two tolerances, 1_1 and 1_2, used in the migrating operation are both set to 0.1. These initial-setting factors for the HDE method are the same as those for the VSHDE, except that the HDE uses a scaling factor fixed at 0.3. The computational results are shown in Figs. 6 – 10. The fuel cost and CPU time incurred by the HDE method are 2 410 332.3$ per day and 201 945 s, respectively. The fuel cost and CPU time incurred by the VSHDE method are 2 143 500.6$ per day, which is slightly lower than that of the HDE method, and 84 048 s, respectively. Fig. 11 represents the convergence property of the proposed



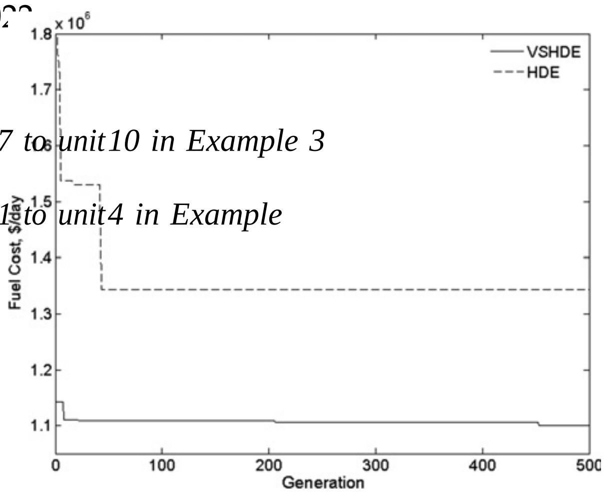
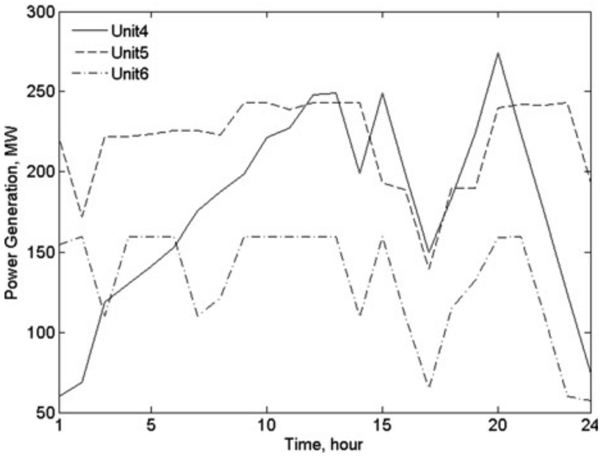
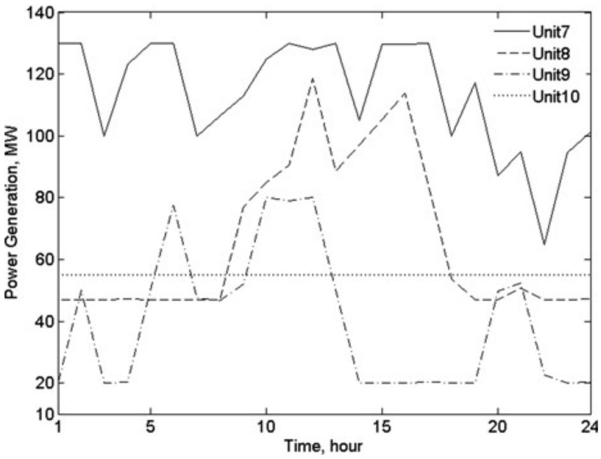


Figure 4 *Distribution of power generation of unit 7 to unit10 in Example 3*

Figure 6 *Distribution of power generation of unit 1 to unit4 in Example*





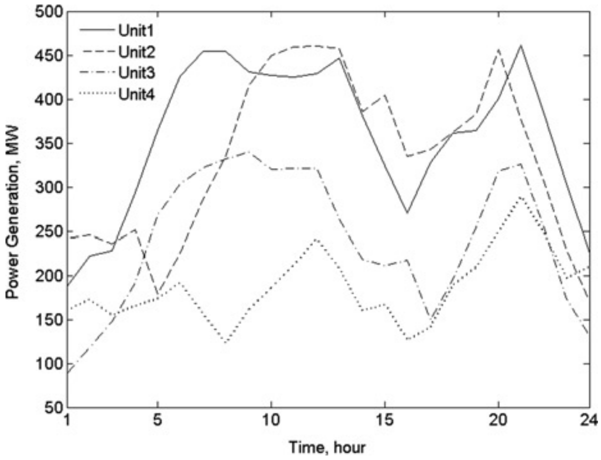


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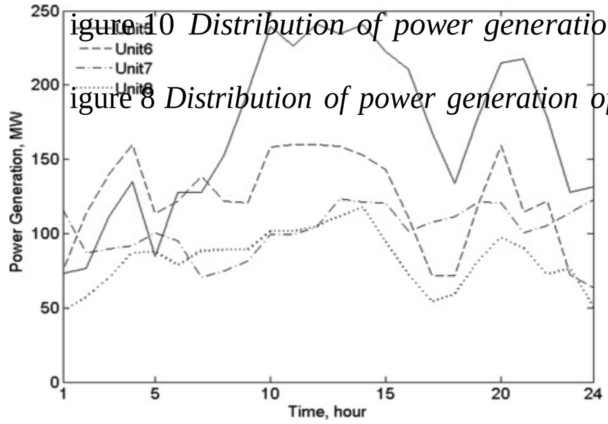
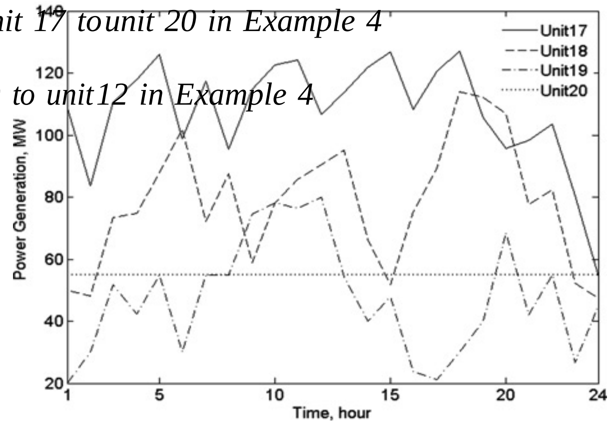
Figure 7 *Distribution of power generation of unit 5 to unit8 in Example 4*



igure 10 *Distribution of power generation of unit 17 to unit 20 in Example 4*

igure 8 *Distribution of power generation of unit 9 to unit12 in Example 4*



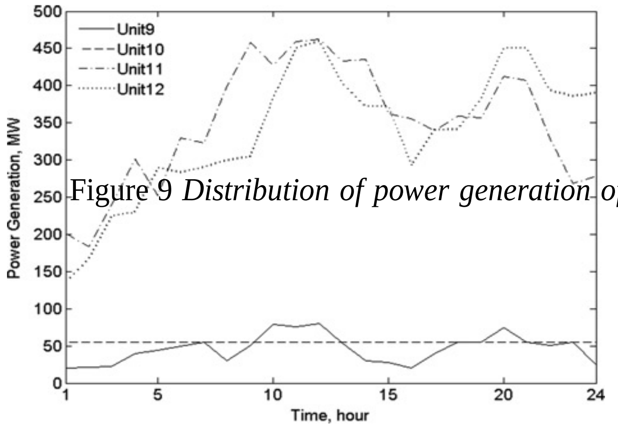
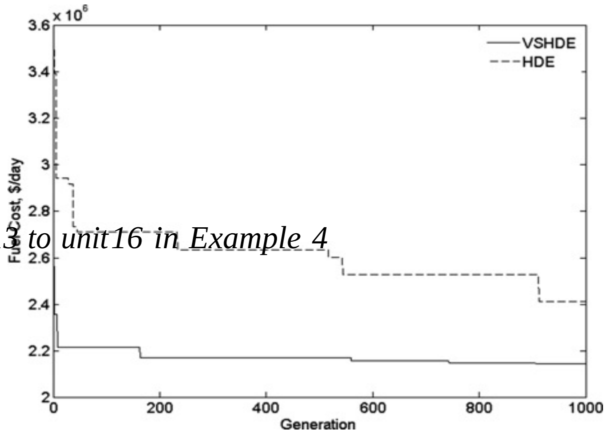


Figure 9 *Distribution of power generation of unit 13 to unit16 in Example 4*



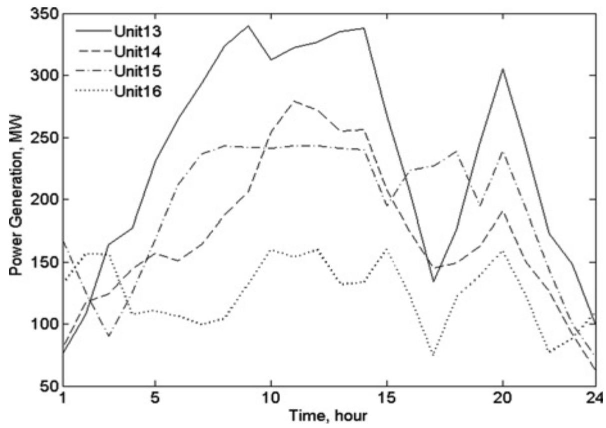


Figure 11 *Convergence characteristics for two algorithms in example 4*

VSHDE and HDE in the fuel cost of evaluation. It shows that the convergence property of the VSHDE method is superior to that of the HDE method.

5 Conclusions

Two heuristic methods including the VSHDE and HDE for solving the two test problems and two DED systems including the 10-unit and 20-unit systems, have been described. The HDE method has been presented as a method using N_p parallel processors of the two-membered evolution strategy ((1 1)-ES), where N_p is the number of individuals in the solution space. Thus, the one-fifth success rule of the ESs is embedded into the original HDE method, producing the VSHDE method, to adjust the scaling factor to accelerate the search for the global solution. The variable scaling factor is used to overcome the drawback of fixed and random scaling factor used in an HDE. The computational result obtained from solving two test problems and two DED systems, including the 10-uint and 20-unit systems, are investigated. The computational results of the first two test problems show that global convergence property of the VSHDE method is better than that of the HDE. The computational results of example 3 show the performance of the VSHDE method to be better than that obtained by the HDE. From example 4, it is observed that the VSHDE method is especially suitable for application to large-scale DED systems.

6 Acknowledgment

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