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Evolutionary programming based economic dispatch with prohibited operating zones

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SUMMARY

This paper presents an efficient and simple approach for solving the Economic Dispatch (ED) problem for units with prohibited operating zones. The operating region of the units with prohibited zones is broken into isolated feasible sub-regions which results in multiple decision spaces for the economic dispatch problem. The optimal solution will lie in one of the feasible decision spaces and can be found using the conventional λ–δ iterative method in each of the feasible decision spaces. But, this elaborate search procedure is time consuming and not acceptable for on-line application. In this paper, a simple and novel approach is proposed. In this approach, the optimal solution and the corresponding optimum system lambda are determined using an efficient Fast Computation Evolutionary Programming Algorithm (FCEPA) without considering the prohibited operating zones. Then, a small set of advantageous decision spaces is formed by combining the feasible sub-regions of the fuel cost curve intervening the prohibited zones in the neighbourhood of the optimal system lambda. A penalty cost for each advantageous decision space is judiciously computed using the participation factor. The most advantageous decision space is found out by comparing the penalty cost of the decision spaces. The optimal solution in the most advantageous decision space is obtained using the FCEPA. The proposed algorithm is tested on a number of sample systems with units possessing prohibited zones. The study results reveal that the proposed approach is computationally efficient and would be a competent method for solving the economic dispatch problem for units with prohibited operating zones.

Key words: *evolutionary programming, economic dispatch problem, prohibited operating zones, FCEPA, decision space.*

1. INTRODUCTION

Many methods have been proposed in the literature [1-5] to solve Economic Dispatch (ED) problem for units with prohibited operating zones. This paper presents a new algorithm based on Evolutionary Programming (EP) for determining the optimal loading of generators having prohibited operating zones. The fuel cost curve of units with prohibited zones are broken into several isolated feasible sub-regions. These isolated feasible sub-regions form multiple decision spaces. A decision space may be feasible or infeasible with respect to system demand and the optimal solution of the dispatch problem will reside in one of the feasible decision spaces [1, 2].

Fan and McDonald [2] presented a method that determines a small set of advantageous decision spaces and selects the most advantageous decision space among them. The optimal solution in the most advantageous decision space is obtained by performing the conventional λ–δ iterative search. In Ref. [5], ED problem with prohibited operating zones is solved using Standard Evolutionary Programming Algorithm (SEPA) taking the generator outputs as decision variables and fuel cost as fitness function. If the optimal generation schedules lie in the prohibited zone, then they are re-dispatched to the nearest boundary of the prohibited zone. Major drawbacks of this algorithm are a very slow and inconsistent convergence, a large number of iterations, a large number of decision variables and indeterministic stopping criteria, etc. To overcome the above difficulties a new approach based on EP and participation factor is proposed in this paper.

In this proposed approach, the ED problem is solved using Fast Computation Evolutionary Programming Algorithm (FCEPA) with system lambda as a decision variable and a power mismatch as fitness function without considering prohibited zones. A small set of advantageous decision spaces is formed by combining the feasible sub-regions of the fuel cost curve intervening the prohibited zones in the neighbourhood of the optimum system lambda. A simple and novel method which is based on the well-known participation factor [6] is used to estimate a penalty cost for each selected feasible advantageous decision space and the most advantageous decision space is chosen by a penalty cost comparison. The optimal solution of the dispatch problem which lies in the most advantageous decision space is computed using the FCEPA. This method is simple and faster and requires only two executions of EP based ED to get the solution.

2. PROBLEM FORMULATION

The ED problem for some units with prohibited zones can be stated as:

$$min\ F_T = \sum_{j \in \Omega} F_j(P_j) \tag{1}$$

Subject to:

i) Power-balance constraint (referred to as a power mismatch):

$$\sum_{j \in \Omega} P_j - P_D - P_L = 0 \tag{2}$$

ii) Spinning Reserve (SR) constraints:

$$\sum_j S_j \geq S_R \tag{3}$$

where:

$$S_j = min\{(P_{j,max} - P_j), S_{j,max}\}, \forall\ j \in (\Omega - \omega), \tag{4}$$

$$S_j = 0,\ \forall\ j \in \omega \tag{5}$$

iii) Generation limit constraint:

$$P_{j,min} \leq P_j \leq P_{j,max}, \forall\ j \in (\Omega - \omega) \tag{6}$$

The additional constraints for units with prohibited operating zones are:

$$\begin{aligned} & P_{j,min} \leq P_j \leq P^l_{j,1} \quad or: \\ & P^u_{j,k-1} \leq P_j \leq P^l_{j,k},\ k = 2,3,\dots,n_j \quad or: \\ & P^u_{j,n_j} \leq P_j \leq P_{j,max} \quad ; \forall\ j \in \omega \end{aligned} \tag{7}$$

An effective upper generation limit $P^{eff1}{}_{j,max}$ for each unit $j \in (\Omega - \omega)$ is first calculated to satisfy the spinning reserve constraints for the units without prohibited zones as explained in Ref. [1] and Eq. (6) becomes:

$$P_{j,min} \leq P_j \leq P^{eff1}_{j,max},\ \forall\ j \in (\Omega - \omega) \tag{8}$$

iv) Ramp-rate constraint:

The ramp rate constraint restricts the lower and upper limit to the effective lower limit and upper limit given by:

$$P^{eff\,2}_{j,min} = max\{P_{j,min}, P_{j0} + DR_j\}, \forall\ j \in \Omega \tag{9}$$

$$P^{eff2}_{j,max} = \begin{cases} min\{P^{eff1}_{j,max},\ P_{j0} + UR_j\}, \forall\ j \in (\Omega - \omega) \\ min\{P_{j,max},\ P_{j0} + UR_j\},\ \forall\ j \in \omega \end{cases} \tag{10}$$

Now, we have:

$$P^{eff2}_{j,min} \leq P_j \leq P^{eff2}_{j,max},\ \forall\ j \in \Omega \tag{11}$$

The constraints in Eq. (7) imply that if a unit has n_j prohibited zones its operating region will be broken into $n_j + 1$ isolated feasible sub-regions, resulting in multiple decision spaces for the ED problem. The number of total disjoint decision spaces is given by:

$$N = \prod_{j \in \omega} (n_j + 1) \tag{12}$$

The optimal solution will reside in one of the feasible decision spaces.

3. PROPOSED APPROACH

The proposed approach is based on the fact that the optimal solution with prohibited zones is most likely to lie in one of the feasible decision spaces, which are in the neighbourhood of the optimal solution obtained without considering the prohibited zones.

An overview of the various steps of the proposed approach are outlined below.

Step I Solve the economic dispatch problem without considering the prohibited zones using FCEPA and obtain the optimum system lambda and generation schedule.

Step II Assemble the disjoint advantageous decision spaces by combining the feasible sub-regions of the fuel cost curves in the neighbourhood of the optimum system lambda. Retain only the feasible advantageous decision spaces.

Step III Find out the most advantageous decision space from the feasible advantageous decision spaces by comparing the penalty cost of the decision spaces.

Step IV Obtain the optimal solution in the most advantageous decision space using FCEPA.

The steps I to IV are explained in detail in the following sections.

Step I. Solution of ED problem using FCEPA

The co-ordination equations for the ED problem without considering the prohibited operating zones are:

$$\frac{dF_j}{dP_j} + \lambda \frac{\partial P_L}{\partial P_j} = \lambda, \quad \forall\ j \in \Omega \tag{13}$$

$$\sum_{j \in \Omega} P_j - P_D - P_L = 0 \tag{14}$$

and the inequality constraint:

$$P_{j,min}^{eff2} \le P_j \le P_{j,max}^{eff2}, \quad \forall\ j \in \Omega \tag{15}$$

the transmission loss is expressed as:

$$P_L = \sum_{i \in \Omega} \sum_{j \in \Omega} P_i B_{ij} P_j \tag{16}$$

The solution for the ED problem can be obtained by solving the set of Eqs. (13) to (15) which may be stated as:

Determine the decision variable λ, to minimise the power mismatch to zero satisfying Eqs. (13) and (15). Alternatively, the problem may be viewed as an optimisation problem with an objective to minimize the power mismatch to zero subject to the equality and inequality constraints in Eqs. (13) and (15) respectively with λ as a decision variable. The problem stated above is solved using EP taking system lambda as a decision variable and a power mismatch as the fitness function.

Algorithmic steps

Step 1: Initialisation of a single parent λ_p.

A single parent is deterministically generated as:

$$\lambda_p = \frac{\lambda_1 + \lambda_2 + \cdots\cdots\cdots + \lambda_{ng}}{ng} \tag{17}$$

where:

$$\lambda_j = \frac{dF_j(P_j)}{dP_j} \cdot \frac{1}{\left(1 - \frac{dP_L}{dP_j}\right)}, \quad \forall\ j \in \Omega$$

$$P_j = \frac{P_{j,max}}{\sum P_{j,max}} \cdot P_D, \quad \forall\ j \in \Omega \tag{18}$$

The system demand is distributed among the units in proportion to their capacity as stated in Eq. (18) for fixing the initial generation schedule.

The generation schedule and the power mismatch f_p (fitness value) corresponding to λ_p are obtained from Eqs. (13) and (14).

Step 2: Generation of offsprings.

A set of N_p effective offsprings is generated as stated below.

The i^{th} offspring is generated as:

$$\lambda_i = \lambda_p + N_i(0, \sigma_p^2)$$

where $N_i(0,\sigma_p^2)$ is the normal random number generated from the normal distribution curve with a standard deviation σ_p.

Retain λ_i in the set only if:

i) f_p is positive and $N_i(0, \sigma_p^2)$ is negative,

ii) f_p is negative and $N_i(0, \sigma_p^2)$ is positive,

and abort the offsprings in all other cases.

An offspring is effective and useful only if its fitness function converges with respect to its parent's fitness function value or else the offspring is ineffective. In the above two cases, the fitness function, namely the power mismatch corresponding to the offspring f_i, converges with respect to its parent's fitness function value f_p while in all other cases its fitness function diverges. The above selective process is used to generate N_p offsprings λ_i, $i=1, 2, ..., N_p$ from the single parent.

Selection of normal distribution curve

It may be recalled that in conventional gradient optimisation methods, the step size to move along the negative gradient direction is fixed arbitrarily to start-with and reduced progressively during subsequent iterations to achieve faster and non-oscillatory convergence. On similar grounds the normal distribution curve may be generated by fixing an arbitrary width (maximum range of $\Delta\lambda$) as displayed in Figure 1 and the width may be reduced successively during subsequent offspring generations to get faster and non-oscillatory convergence.

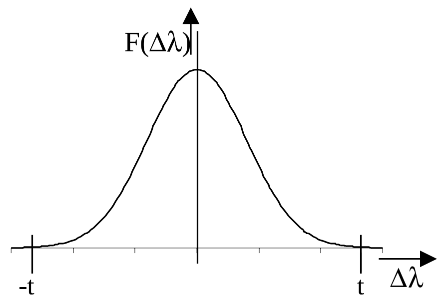

Fig. 1 Search range

Selection of σ_p for normal distribution curve

The maximum permissible range of the initial variation in the decision variable λ_p is fixed judiciously based on experience. The maximum range of the random variation in λ may be taken as $\Delta\lambda = \pm\ t$ where $t = \alpha \cdot (\lambda_{max} - \lambda_{min})$, α being an arbitrary constant in the range 0 to 1. The normal distribution curve is constructed such that the probability of occurrence of $\Delta\lambda \ge t$ is zero.

Mathematically:

$$\frac{1}{\sqrt{2\pi} \cdot \sigma_p} \int_t^{\infty} e^{-\frac{1}{2}\left(\frac{\Delta\lambda - \mu}{\sigma_p}\right)^2} = 0 \tag{19}$$

The above equation is solved to compute σ_p by setting the RHS value to a small value as:

$$\frac{1}{\sqrt{2\pi}\cdot\sigma_p}\int_t^{\infty} e^{-\frac{1}{2}\left(\frac{\Delta\lambda-\mu}{\sigma_p}\right)^2} = 0.00003 \tag{20}$$

The solution of the above equation is obtained by using the standard normal tables [7]. The width of $\Delta\lambda$ is progressively decreased during successive generation of offsprings.

Step 3: The generation schedule and power mismatch corresponding to offsprings λ_i, $i=1, 2, ..., N_p$ are computed by solving Eqs. (13) and (14).

Step 4: The best offspring having the minimum fitness function value is selected from the population N_p and the convergence is checked. If the convergence criterion is satisfied, then the optimum is reached. Otherwise steps 2 and 3 are repeated by taking this offspring as the parent.

Step II. Formation of advantageous decision spaces

The prohibited operating zones of units leads to multiple decision spaces for the economic dispatch problem. The operating range of a decision space can be defined as:

$$\left[\sum_{j=\Omega} P_j^{l,\Re i}, \sum_{j=\Omega} P_j^{u,\Re i} - S_R\right] \tag{21}$$

A decision space is feasible with respect to system demand, P_D and spinning reserve, S_R if Eq. (22) is satisfied:

$$\sum_{j=\Omega} P_j^{l,\Re i} \le P_D \le \sum_{j=\Omega} P_j^{u,\Re i} - S_R \tag{22}$$

The decision spaces formed by considering feasible sub-regions in the neighbourhood of the optimal solution obtained without considering the prohibited zones are called the advantageous decision spaces. The formation of advantageous decision spaces is explained by considering the incremental cost curves of the three-unit system as shown in Figure 2.

The intersection of the λ_{opt} line obtained without considering prohibited zones and the incremental cost curves of the units gives the optimum schedule. The optimum schedule of units 1 and 2 falls in the prohibited zone while that of unit 3 lies in the feasible sub-region, $R_{3,2}$.

A search range for the system λ is defined in the vicinity of λ_{opt}. If the optimal schedule of a unit falls in the prohibited zone then its generation schedule can be re-dispatched to its adjacent feasible sub-region such that the incremental cost remains in the search range. This can be mathematically described as:

$$\lambda_{s,min} \le \lambda_s \le \lambda_{s,max} \tag{23}$$

with:

$$\lambda_{s,min} = \min_{j\in\omega'}\left\{L_j \frac{dF_j}{dP_j}\bigg|_{P_j = P_{j,k}^l}\right\} \tag{24}$$

and:

$$\lambda_{s,max} = \max_{j\in\omega'}\left\{L_j \frac{dF_j}{dP_j}\bigg|_{P_j = P_{j,k}^u}\right\} \tag{25}$$

where k is the active prohibited zone of j-th unit.

For units 1 and 2 the generation can be re-dispatched to the feasible sub-region $R_{1,1}$ or $R_{1,2}$ and $R_{2,1}$ or $R_{2,2}$ respectively, while for unit 3 its generation may be re-dispatched to any of the two neighbouring feasible sub-regions $R_{3,1}$ and $R_{3,3}$ or may remain in the feasible sub-region $R_{3,2}$ itself.

Thus, the number of advantageous decision spaces M will have the range:

$$2^{\omega'} \le M \le 2^{\omega'}\cdot 3^{(\omega-\omega')} \tag{26}$$

Among the N number of decision spaces, only the M advantageous decision spaces are selected. There are twelve advantageous decision spaces for the three-unit system as given in Table 1. The units without prohibited zones will have only one region between its minimum and maximum limits and will be included in all advantageous decision spaces. The advantageous decision spaces which satisfy the Eq. (22) are the feasible advantageous decision spaces.

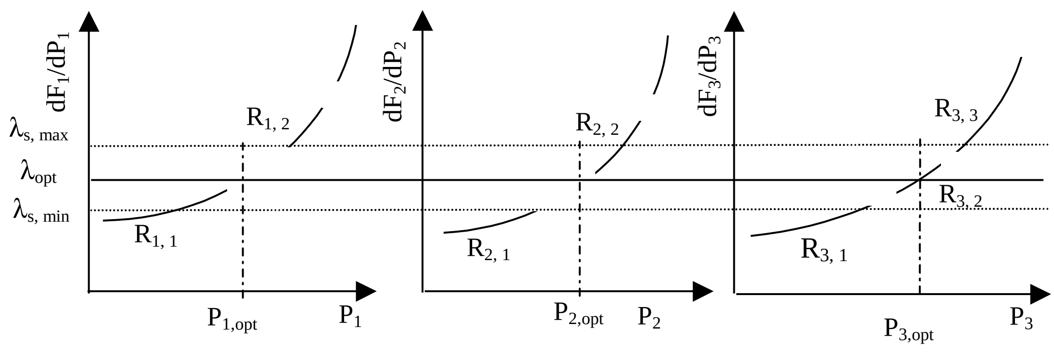

Fig. 2 Incremental cost curves

Table 1 Advantageous decision spaces

Sub-region	Advantageous decision spaces											
	$\Re 1$	$\Re 2$	$\Re 3$	$\Re 4$	$\Re 5$	$\Re 6$	$\Re 7$	$\Re 8$	$\Re 9$	$\Re 10$	$\Re 11$	$\Re 12$
Unit 1	$R_{1,1}$	$R_{1,1}$	$R_{1,1}$	$R_{1,1}$	$R_{1,1}$	$R_{1,1}$	$R_{1,2}$	$R_{1,2}$	$R_{1,2}$	$R_{1,2}$	$R_{1,2}$	$R_{1,2}$
Unit 2	$R_{2,1}$	$R_{2,1}$	$R_{2,1}$	$R_{2,2}$	$R_{2,2}$	$R_{2,2}$	$R_{2,1}$	$R_{2,1}$	$R_{2,1}$	$R_{2,2}$	$R_{2,2}$	$R_{2,2}$
Unit 3	$R_{3,1}$	$R_{3,2}$	$R_{3,3}$	$R_{3,1}$	$R_{3,2}$	$R_{3,3}$	$R_{3,1}$	$R_{3,2}$	$R_{3,3}$	$R_{3,1}$	$R_{3,2}$	$R_{3,3}$

Step III. Selection of most advantageous decision space

Cost penalties of advantageous decision spaces:

A penalty cost is computed for each feasible advantageous decision space using a simple procedure based on participation factor and the most advantageous decision space is selected by penalty cost comparison. The penalty cost of a feasible advantageous decision space is the increment of the generation cost from that of the optimal dispatch obtained without considering the prohibited zones.

If a unit, e.g. the j^{th} unit has its optimal generation dispatch in a prohibited zone k, having its upper boundary generation $P^u_{j,k}$ and lower boundary generation $P^1_{j,k}$, then the feasible sub-region of the j^{th} unit in an advantageous decision space will be either the feasible sub-region above $P^u_{j,k}$ or below $P^1_{j,k}$. Since the j^{th} unit optimum schedule is in prohibited zone k, it is to be re-dispatched either to $P^u_{j,k}$ or $P^1_{j,k}$. The re-dispatch involves a change in generation. The net change in generation in a decision space $\Re i$ due to re-dispatch is computed as:

$$\Delta P_{net}^{\Re i} = \sum_{j \in \omega'} \left(P_{j,opt} - \rho_j^{\Re i} P_{j,k}^{l} - \left(1 - \rho_j^{\Re i} \right) P_{j,k}^{u} \right) \quad (27)$$

where:

$$\rho_j^{\Re i} = \begin{cases} 1 & \text{If generation is redispatched to } P_{j,k}^{l} \\ 0 & \text{If generation is redispatched to } P_{j,k}^{u} \end{cases}$$

The net change in the generation in a decision space may be positive or negative. The net change in generation, $\Delta P_{net}^{\Re i}$ is re-dispatched to all the units according to Eq. (28) subject to the operating restrictions due to prohibited zones as well as upper and lower limits of the units:

$$\Delta P_j = PF_j \cdot \Delta P_{net}^{\Re i} \quad \forall\, j \in \Omega \quad (28)$$

This re-dispatched feasible generation schedule in the decision space $\Re i$ differs from the optimum schedule obtained without considering the prohibited zones. The difference between the fuel cost of the optimal solution and the re-dispatched feasible solution is defined as penalty cost.

The penalty cost for the $\Re i^{th}$ feasible advantageous decision space is computed as:

$$PC^{\Re i} = \sum_{j \in \Omega} F\left(P_{j,opt} + \Delta P_j \right) - \sum_{j \in \Omega} F\left(P_{j,opt} \right) \quad (29)$$

The most advantageous decision space is the one that gives the minimum penalty cost.

Step IV. Optimal solution in the most advantageous decision space is obtained using FCEPA as explained in Step I.

4. EXAMPLES AND DISCUSSION

The effectiveness of the proposed approach is demonstrated by solving a few examples of dispatch problems.

Example 1

A system with five on-line units represented by the following input-output cost function is considered:

$$F_j(P_j) = 1x10^{-6} P_j^3 + 0.001 P_j^2 + 8 P_j + 350 \,\$/h; \; j = 1,2,3,4,5$$

and the operating limits:

$$120 \; MW \le P_j \le 450 \; MW; \quad j = 1, 2, 3, 4, 5.$$

Units 1, 2 and 3 have prohibited zones and units 4 and 5 do not. The prohibited zones are given in Table 2. The transmission loss penalty factor is assumed to be a unity for all units. The system demand is *1,175 MW*.

Table 2 Prohibited zones of the units

Unit	Zone 1 [MW]	Zone 2 [MW]
1	[240, 275]	[315, 375]
2	[210, 270]	[300, 390]
3	[200, 250]	[290, 370]

As per Eq. (12), there are 27 decision spaces for the dispatch problem. The optimal generation schedule without considering prohibited zones is determined by using the FCEPA and is found to be:

$$P_{j,opt} = 235 \; MW, \quad j = 1, 2, 3, 4, 5$$

and the corresponding optimum system lambda is:

$$\lambda_{opt} = 8.63567 \; \$/MWh.$$

Apparently, unit 1 is in the first feasible sub-region, while units 2 and 3 are in prohibited zones. Unit 1 has one adjacent feasible sub-region [275 MW, 315 MW]. Based on Eqs. (23) to (25), the search range of system λ is found to be [*8.52 \$/MWh, 8.7587 \$/MWh*]. The incremental cost, *8.7769 \$/MWh* corresponding to the upper bound of the first prohibited zone of unit 1 does not fall in the search range. Thus, a set of four advantageous decision spaces, $\Re 1$, $\Re 2$, $\Re 3$ and $\Re 4$ is defined, as shown in Table 3. All the four advantageous decision spaces are feasible with respect to a system demand.

Table 3 Advantageous decision spaces

Sub-region	Advantageous decision spaces			
	$\Re 1$	$\Re 2$	$\Re 3$	$\Re 4$
Unit 1	[120, 240]	[120, 240]	[120, 240]	[120, 240]
Unit 2	[120, 210]	[120, 210]	[270, 300]	[270, 300]
Unit 3	[120, 200]	[250, 290]	[120, 200]	[250, 290]
Unit 4	[120, 450]	[120, 450]	[120, 450]	[120, 450]
Unit 5	[120, 450]	[120, 450]	[120, 450]	[120, 450]
Operating range of the decision space	[600, 1550]	[730, 1640]	[750, 1640]	[880, 1730]

The penalty cost for $\Re 1$ is calculated as follows:

The net change in generation due to prohibited operating zones of units 2 and 3 is obtained as follows:

$$\Delta P_{net}^{\Re 1} = (P_{2,opt} - P^{l}_{2,1}) + (P_{3,opt} - P^{l}_{3,1}) =$$
$$= (235.0 - 210) + (235 - 200) = 60\ MW$$

This net change in generation is re-dispatched to all the units based on participation factors as:

$$\Delta P_1 = 5\ MW,$$
$$\Delta P_2 = 0\ MW,$$
$$\Delta P_3 = 0\ MW,$$
$$\Delta P_4 = 27.5\ MW,$$
$$\Delta P_5 = 27.5\ MW.$$

According to Eq. (29) penalty cost is:

$$PC^{\Re 1} = 11496.77905 - 11491.01953 =$$
$$= 5.75952\ (\$/h).$$

The optimal schedule and penalty cost for each feasible advantageous decision space are given in Table 4. Space $\Re 2$ is the most advantageous decision space as its penalty cost is minimum. The optimal solution in this most advantageous decision space is obtained using the FCEPA. Table 5 presents the results obtained by the λ–δ iterative method [2], SEPA with unit generations as decision variables [5] and the proposed method.

Table 4 Optimal schedule and penalty cost

Unit generation [MW]	Optimal schedule without prohibited zones	Optimal schedule for decision spaces			
		$\Re 1$	$\Re 2$	$\Re 3$	$\Re 4$
P_1	235.0	240.0	238.33	235.0	218.33
P_2	235.0	210.0	210.00	270.0	270.0
P_3	235.0	200.0	250.00	200.0	250.0
P_4	235.0	262.5	238.33	235.0	218.33
P_5	235.0	262.5	238.33	235.0	218.33
$\lambda_{optimum}$ [\$/MWh]	8.63567	8.73172	8.64707	8.63567	8.57968
Fuel cost [\$/h]	11491.02	11496.77	11492.50	11495.19	11494.95
Penalty cost [\$/h]	–	5.75952	1.49463	4.17749	3.92627

Table 5 Comparison of the generation schedule for 5-unit system

Unit generation [MW]	λ-δ iterative method [2]	SEPA with unit generation as variable [5]	Proposed method
P_1	238.33	240.0	238.33
P_2	210.0	210.0	210.00
P_3	250.0	250.0	250.00
P_4	238.33	223.07	238.33
P_5	238.33	251.93	238.33
Fuel cost [\$/h]	11492.51	11493.23	11492.5
Computation time in ms	–	2750	5.4

From Table 5 it can be seen that the optimal schedule obtained with the proposed method is exactly the same as that of results given in Ref. [2]. It can be observed that the optimum schedule obtained with the proposed method is different from that given in Ref. [5]. But the optimal fuel cost is almost the same. The computation time (IBM PC, *1 GHz*) for the proposed method and SEPA is given in the last row of Table 5. It can be noted that on average there is *99%* reduction in computation time when compared to the method proposed in Ref. [5]. This shows the computational efficiency of the proposed method. The results reveal that the proposed algorithm is very fast and reliable compared to the method proposed in Ref. [5].

Example 2

A practical example used by Lee and Breipohl in Ref. [1] is considered. The system has 15 on-line units that supply a system demand of *2,650 MW* with a system spinning reserve requirement of *200 MW*. No regulating margin is required. The prohibited zones are given in Table 6. Among the on-line units, four of them (units 2, 5, 6 and 12) have prohibited operating zones that form 192 decision spaces for the dispatch problem.

Table 6 Prohibited zones of the units

Unit	Zone 1 [MW]	Zone 2 [MW]	Zone 3 [MW]
2	[185, 225]	[305, 335]	[420, 450]
5	[180, 200]	[260, 335]	[390, 420]
6	[230, 255]	[365, 395]	[430, 455]
12	[30, 55]	[65, 75]	–

The optimal solution without considering the prohibited zones is given in Table 7. It can be seen that unit 5 alone falls in prohibited zone, [*260 MW*, *335 MW*]. According to Eqs. (23) to (25), the search range of system λ is found to be [*10.5066 \$/MWh*, *10.53735 \$/MWh*]. The adjacent feasible sub-regions of the other three units are given in Table 8.

Table 8 shows the incremental costs of the adjacent feasible sub-regions does not fall in the search range of λ. Thus, there are only two advantageous decision spaces. The feasible sub-region, [*200 MW*, *260 MW*], below the active prohibited zone of unit 5 is in decision space $\Re 1$ and the feasible sub-region, [*335 MW*, *390 MW*], above the prohibited zone is in $\Re 2$. Both spaces

$\Re 1$ and $\Re 2$ are feasible with respect to the system demand and the system spinning reserve requirement. The penalty cost and optimal solution for each of the feasible advantageous decision spaces are given in Table 7 from which it can be noted that space $\Re 2$ is the most advantageous decision space.

Table 7 Optimal schedule and penalty cost

Unit generation [MW]	Optimal schedule without prohibited zones	Optimal schedule in the advantageous decision spaces	
		$\Re 1$	$\Re 2$
P_1	455.00	455.0	450.0
P_2	455.00	455.0	450.0
P_3	130.00	130.0	130.0
P_4	130.00	130.0	130.0
P_5	317.83	260.0	335.0
P_6	460.00	460.0	455.0
P_7	465.00	465.0	465.0
P_8	60.00	60.0	60.0
P_9	25.00	25.0	25.0
P_{10}	20.00	70.0	20.0
P_{11}	20.00	20.0	20.0
P_{12}	57.16	65.0	55.0
P_{13}	25.00	25.0	25.0
P_{14}	15.00	15.0	15.0
P_{15}	15.00	15.0	15.0
$\lambda_{optimum}$ [$/MWh]	10.5303	10.8884	10.3391
Fuel cost [$/h]	32542.41	32558.35	32544.97
Penalty Cost [$/h]	–	15.9350	2.5670

Table 8 Adjacent feasible sub-regions

Unit	Lower sub-region		Upper sub-region	
	MW	$\lambda_{i,max}$ [$/MWh]	MW	$\lambda_{i,min}$ [$/MWh]
2	[355, 420]	10.3737	–	–
6	[395, 430]	10.3589	–	–
12	[20, 30]	10.2308	[75, 80]	10.7269

The optimal solution in the most advantageous decision space is obtained using the FCEPA. Table 9 presents the results obtained by the $\lambda-\delta$ iterative method [2], SEPA with unit generations as decision variables [5] and the proposed method. The optimal dispatch in space $\Re 2$ is almost closer to that obtained in Ref. [5] and exactly matches the results given in Ref. [2].

The performance of the proposed method is tested on the above two sample systems, as well as on several others that were not shown in this paper. The analysis shows that the proposed method is reliable and uses a simple procedure to select the most advantageous decision space. It requires only two executions of the FCEPA, one for determining the optimal solution without considering the prohibited zones and the other for determining the optimal solution in the most advantageous decision space.

5. CONCLUSIONS

This paper presents an efficient and simple approach for solving the ED problem for units with prohibited operating zones. Initially, the optimal solution without considering the prohibited zones is obtained by using FCEPA. A small set of advantageous decision spaces is formed by combining the feasible sub-regions of the fuel cost curve intervening the prohibited zones in the neighbourhood of optimum system lambda. A simple and novel method which is based on the well known participation factor is used to estimate a penalty cost for each selected feasible advantageous decision space. The most advantageous decision space is chosen by penalty cost comparison. The optimal solution in the most advantageous decision space is obtained by using FCEPA. The effectiveness of the proposed approach has been tested on a number of sample systems. The proposed approach is relatively simple, reliable, efficient and suitable for on-line applications.

Table 9 Comparison of the generation schedule for 15-unit system

Unit generation [MW]	λ-δ iterative method [2]	SEPA with unit generation as variable [5]	Proposed method
P_1	450.0	446.98	450.0
P_2	450.0	451.50	450.0
P_3	130.0	130.00	130.0
P_4	130.0	130.00	130.0
P_5	335.0	335.02	335.0
P_6	455.0	456.11	455.0
P_7	465.0	464.91	465.0
P_8	60.0	60.00	60.0
P_9	25.0	25.00	25.0
P_{10}	20.0	20.00	20.0
P_{11}	20.0	20.01	20.0
P_{12}	55.0	55.46	55.0
P_{13}	25.0	25.00	25.0
P_{14}	15.0	15.01	15.0
P_{15}	15.0	15.00	15.0
Fuel cost [$/h]	32544.99	32545.20	32544.97
Computation time in ms	–	3000	9.4

6. APPENDIX

List of symbols

$F_j(P_j)$ = input/output cost function of the j^{th} unit
P_j = power output of the j^{th} generator
Ω = set of all dispatchable on-line units
P_D = system demand
P_L = transmission loss
S_j = j^{th} unit SR contribution
S_R = total SR requirement
$S_{j,max}$ = j^{th} unit maximum SR contribution
$P_{j,max}$ = j^{th} unit upper generation limit
$P_{j,min}$ = j^{th} unit lower generation limit
ω = set of units with prohibited operating zone(s)
k = index of prohibited zones of a unit
n_j = number of prohibited zones of the j^{th} unit
ng = number of dispatchable on-line units

$P^{l}_{j,k}$ = lower bound of the k^{th} prohibited zone of the j^{th} unit
$P^{u}_{j,k}$ = upper bound of the k^{th} prohibited zone of the j^{th} unit
n_j = total number of prohibited zones of unit j
P_{j0} = power generation of the j^{th} generator at previous hour
DR_j = ramp-rate limit of the j^{th} unit as generation decreases
UR_j = ramp-rate limit of the j^{th} unit as generation increases
B_{ij} = loss coefficient
μ = mean
λ = system lambda
λ_{max} = maximum value of the system lambda
λ_{min} = minimum value of the system lambda
ω' = set of units in active prohibited zones
L_j = transmission loss penalty factor of the j^{th} unit
$P_{j,opt}$ = optimum schedule of the j^{th} unit without considering prohibited zones
$P_j^{l,\Re i}$ = lower limit of the feasible sub-region of the j^{th} unit with respect to decision space $\Re i$
$P_j^{u,\Re i}$ = upper limit of the feasible sub-region of the j^{th} unit with respect to decision space $\Re$i
ΔP_j = change in generation at the j^{th} unit
PF_j = participation factor of the j^{th} unit
$PC^{\Re i}$ = penalty cost for decision space $\Re i$.

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EKONOMIČNO OTPREMANJE TEMELJENO NA EVOLUCIJSKOM PROGRAMIRANJU SA ZABRANJENIM OPERACIJSKIM ZONAMA

SAŽETAK

U radu se prikazuje jedan efikasan i jednostavan pristup za rješavanje problema ekonomičnog otpremanja (ED) u jedinicama sa zabranjenim operacijskim zonama. Operacijska regija jedinica sa zabranjenim zonama podjeljena je na odvojene pod-regije što rezultira postojanjem prostora višestrukog odlučivanja za problem ekonomskog otpremanja. Optimalno rješenje se nalazi u jednom od prostora odlučivanja i koristi konvencionalnu λ–δ iterativnu metodu u svakom od prostora odlučivanja. Međutim ovaj složeni postupak istraživanja zahtjeva mnogo vremena i nije prihvatljiv za on-line primjene. U ovom radu predlaže se jednostavan i nov pristup. Kod ovog pristupa optimalno rješenje i odgovarajući optimalni sustav lambda određuju se koristeći efikasni algoritam brzog kompjuterskog evolucijskog programiranja a da se ne uzimaju u obzir zabranjene zone. Zatim se formira mali skup povoljnih prostora odlučivanja tako što se kombiniraju pod-regije krivulja cijene goriva koja se pojavljuje u blizini optimalnog sustava lambda. Izračunava se točno cijena penala koristeći faktor sudjelovanja. Najpovoljniji prostor odlučivanja se određuje usporedbom cijena penala u prostorima odlučivanja. Optimalno rješenje je najpovoljniji prostor odlučivanja koji se dobiva primjenjujući FCEPA. Predloženi algoritam je testiran na određenom broju uzoraka sustava koji uključuju jedinice sa zabranjenim zonama. Rezultati proučavanja pokazuju da je predloženi pristup kompjuterski ekifasan i da predstavlja kompetentnu metodu za rješavanje problema ekonomičnog otpremanja u jedinicama sa zabranjenim operacijskim zonama.

***Ključne riječi**: evolucijsko programiranje, ekonomično otpremanje, zabranjene operacijske zone, FCEPA, prostor odlučivanja.*