IMPACT OF PROHIBITED OPERATING ZONES OF GENERATING UNITS ON LOCATIONAL MARGINAL PRICES

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Abstract – This paper discusses the electricity market price simulation by considering transmission congestion and prohibited operating zones of units. Units with prohibited zones are prevented from operating in certain trajectories between their minimum and maximum heat rate capacities. Accordingly cost curve of these units are non-convex. The non-convexity could cause numerical difficulties when applying conventional methods for generation dispatch such as iteration methods. In this paper, a solution method is proposed for the generation dispatch problem by considering prohibited zones. The effect of prohibited zones on transmission congestion and locational marginal prices (LMPs) is discussed. It is shown that prohibited zones could aggravate transmission constraints and result in higher LMPS at critical buses. Furthermore prohibited zones could affect the competitive cost of operating power systems and lead to more conservative preventive actions such as load shedding to enhance the security of power systems. An example of 8-bus system demonstrates the prohibited zones and their effect on LMP and system operation.

Keywords: Power system operation, prohibited operating Zone, forbidden zone, locational marginal price (LMP), transmission congestion, generation dispatch.

1 INTRODUCTION

Because of the physical limitations of generation units (e.g., mechanical stress and vibrations of shaft bearings, thermal stress of boilers, and operating constraints of auxiliary equipment in power plants), the generating units may not be able to operate in specific operating zones. For instance, mechanical vibrations could cause cumulative metal fatigue in turbine blades and lead to premature turbine blade failures. Prohibited operating zones where generating units are forbidden to operate would represent the operating limits of generating units for practical reasons. The prohibited zones could represent gaps on generation cost curves and cause discontinuity on curves. Figure 1 depicts cost curve of a unit with prohibited zones.

This paper discusses the solution of economic dispatch (ED) problem with prohibited zones. Conventionally, the ED problem is solved by assuming that all units are utilized continuously between P_{min} and P_{max}. There are many approaches for solving convex ED problem including iterative method, linear programming (LP).

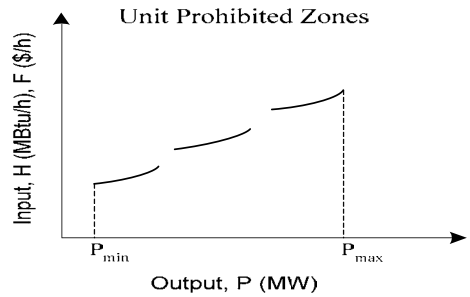

Figure 1: Cost curve for a unit with prohibited zones

If conventional ED methods are applied to a problem with prohibited zones, the optimal solution might require certain units to operate in prohibited zones. In such situations, those units would operate in their nearest feasible points for economic dispatch. This adjustment of economical point could result in a less optimal solution. Another option is to perform a conventional iterative search within each feasible region of individual units. However, this approach could be impractical for large power systems and would consume a lot of computation time. Dynamic programming is not a practical option in such circumstances because of computation time.

A limited number of technical studies were proposed to discuss ED with prohibited zones. Lee and Breipohl [1] solved the problem by dividing the non-convex decision space into classified subsets. The dispatch problem without prohibited zones was solved by Lagrangian relaxation. If the solution was infeasible or situated in prohibited zones the subset will be classified and optimal decision based on least cost will be made among all feasible solution with classified subsets.

Orero and Irving [2] investigated the application of genetic algorithms (GA) to solve the ED with prohibited zone problem. They proposed two different implementations: A standard GA and a deterministic crowding GA. Their solution technique makes a direct search and does not directly rely on the incremental cost function. Accordingly, the non-convex behavior of cost curve does not cause much difficulty in ED calculation.

El-Gallad and El.Hawary [3] introduced the particle swarm optimizer (PSO) for solving the non-convex ED problem. The proposed method was a parallel population-based search method and the ED results were compared with those of conventional method and the Hopfield neural network method.

Fan and McDonald [4] defined a set of decision spaces for ED. Each decision was made by analyzing the desired optimal solution, neglecting prohibited zones, and estimating a factor for each space to identify the suitable space. The optimal solution identifies the most suitable space via the $\lambda - \delta$ iterative method.

Su and Chiou [5] introduced a Hopfield neural network method for solving ED by considering prohibited zones. The proposed method employed a linear input-output model for neurons to solve the ED problem quickly. Applying the proposed model to prohibited zones, allowed the authors to achieve the optimal solution for the non-convex ED problem.

Yalcinoz and Altun [6] applied an improved Hopfield neural network method to solve the ED problem with prohibited zones. They formulated a new mapping process and described a computational method for calculating weights and biases to handle inequality constraints.

Zang and Wang [7] introduced an approach for solving the ED problem in power markets. The Newton interpolation method was adopted to solve the ED problem. Some special conditions of bidding curve and generation cost was considered in ED problem.

In this paper, a numerical approach is proposed for adjusting cost curves with prohibited zones. Accordingly the ED problem would be solved by conventional methods. Effect of prohibited zones on transmission congestion and LMP is illustrated. We show that prohibited zones could aggravate transmission congestion and change LMPs.

2 PROHIBITED OPERATING ZONES

We consider the minimum cost solution as the objective of ED in which the total generation cost is minimized over certain periods while satisfying certain operating constraints such as generating unit capacity, system demand, and operating reserve requirements.

For units without prohibited zones, the generation dispatch is calculated using the following optimization problem:

$$Min \quad \sum_{i=1}^{N} F(P_i) = \sum_{i=1}^{N} \left(a_i + b_i P_i + c_i P_i^2 \right) \qquad (1)$$

$st.$

$$\sum_{i=1}^{N} P_i = P_d + P_L$$

$$\sum_{i=1}^{N} S_i \geq S_R$$

$$P_{i,\min} \leq P_i \leq P_{i,\max} \qquad i = 1,\ldots,N$$

where,

i : Index of unit

P_i : Generation of unit i

a_i, b_i, c_i : Cost coefficient of unit i

N : Number of units

$F(P_i)$: Cost of generation P_i

S_i : Unit spinning reserve

S_R : System required spinning reserve

P_L : Transmission losses in MW

P_d : System load demand

However, when prohibited zones are present, the following additional constraints must be added:

$$\begin{cases} P_{i,min} \leq P_i \leq P_{i,1}^{d} \\ \vdots \\ P_{i,j-1}^{u} \leq P_i \leq P_{i,j}^{d} \\ \vdots \\ P_{i,M_i}^{u} \leq P_i \leq P_{i,max} \end{cases} \qquad j=2,\ldots,M_i \qquad (2)$$

where,

$P_{i,j}^{d}$: Lower limit of j^{th} prohibited zone of unit i

$P_{i,j}^{u}$: Upper limit of j^{th} prohibited zone of unit i

M_i : Number of prohibited zones of unit i

It is noted in (2) that unit i will have (M_i+1) disjoint operating sub-regions if it has M_i prohibited zones. Since the unit with prohibited zones can be only operated in one of the disjoint operating sub-regions, the ED problem is associated with many decision sub-spaces. The number of decision sub-spaces resulting from prohibited zones is enumerated as:

$$N_D = \prod_{i=1}^{N} (M_i + 1) \qquad (3)$$

where N_D is the number of decision sub-spaces. If there are many units with prohibited zones in the system, the number of decision sub-spaces and the computation time for ED could increase accordingly.

In this paper, we model the prohibited zone by an equivalent incremental cost section which facilitates the unit i dispatch at its most economical and feasible region. The equivalent incremental cost section will bridge the gap between lower and upper limits of prohibited zone on the cost curve so that the ED problem could be solved by conventional methods.

3 PROPOSED ED MODEL FOR PROHIBITED ZONE

In this section, we propose an approach for solving ED by considering prohibited zones. Based on equal incremental cost criterion, committed units in a power system are dispatched based on their incremental costs. The solution state for minimum operation cost is obtained when the unit incremental costs are the same.

Figure 2 depicts a cost curve with prohibited zone where unit cannot operate between P_{ij}^{d} and P_{ij}^{u}. To model prohibited zone, we introduce a representative incremental cost λ_{ij} which is associated with the j^{th} prohibited zone of unit i as follow:

$$\lambda_{ij} = \left.\frac{dF_i}{dP}\right|_{P_i = P_{ij}^E}, \; P_{ij}^E \in \left[P_{ij}^d, P_{ij}^u\right] \quad (4)$$

where F_i is the cost function and P_{ij}^E is the economical dispatch of unit i corresponding to incremental cost λ_{ij}. First, it is assumed that the unit could operate within its j[th] zone and ignore prohibited zone limit. If the j[th] zone is a prohibited zone, we define λ_{ij} such that if the system's incremental cost exceeds λ_{ij}, then it would be more economical to dispatch the unit at or above P_{ij}^u. Similarly, it would be more economical to operate the unit at or below P_{ij}^d, if the system incremental cost is less than λ_{ij}. For the system incremental cost equal to λ_{ij}, it would be equally economical to operate the unit at either P_{ij}^d or P_{ij}^u. Accordingly, the objective is to calculate the equivalent λ_{ij} when the system incremental cost is between λ_{ij}^d and λ_{ij}^u (λ_{ij}^d and λ_{ij}^u are corresponding incremental cost for lower and upper limit of prohibited zone *j*).

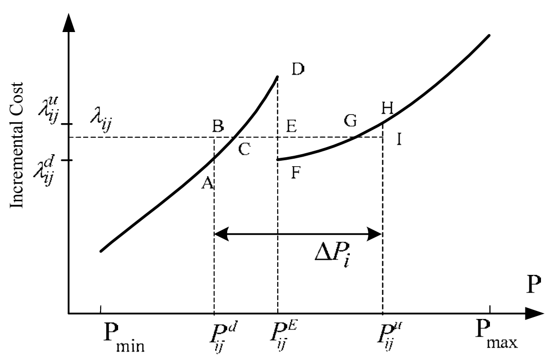

Figure 2: Cost curve with prohibited zone

In order to calculate the equivalent incremental cost, we assume that unit i is generating P_{ij}^d MW. Based on Figure 2, when generation level changes from P_{ij}^d to P_{ij}^u, the additional generation cost will change as follow:

$$\Delta F_i = F_i(P_{ij}^u) - F_i(P_{ij}^d) \quad (5)$$

The additional generation cost is the difference between cost of generating P_{ij}^u and P_{ij}^d MW. It is also represented by the area between cost curve and horizontal axes (P) which is equal to:

$$\Delta F_i = \Delta P_i \times \lambda_{ij} + \Delta 1 - \Delta 2 \quad (6)$$

Where $\Delta 1$ is sum of the surrounded areas CDE and GHI, and $\Delta 2$ is the sum of ABC and EFG. When output of one unit changes other units need to balance energy in the system. Since unit i output is increased by ΔP_i, the output of other units will be decreased by ΔP_i to satisfy the balance between generation and demand. Accordingly, the total system cost changes as:

$$\Delta F_s = \Delta P_i \times \lambda_{ij} \quad (7)$$

Accordingly, the total change in the system cost is:

$$\Delta F = \Delta F_i - \Delta F_s = \Delta 1 - \Delta 2 \quad (8)$$

From (8), when $\Delta 1 = \Delta 2$, the additional cost of supplying the load is zero. As a result, if we find λ_{ij} based on the equal area criterion. In Figure 2:

$$\Delta 1 = \left[F(P_{ij}^E) - F(P_{ij}^d)\right] - \lambda_{ij}(P_{ij}^E - P_{ij}^d) \quad (9)$$

$$\Delta 2 = \lambda_{ij}(P_{ij}^u - P_{ij}^E) - \left[F(P_{ij}^u) - F(P_{ij}^E)\right] \quad (10)$$

If we let $\Delta 1$ to be equal to $\Delta 2$, then

$$\lambda_{ij} = \frac{F(P_{ij}^u) - F(P_{ij}^d)}{P_{ij}^u - P_{ij}^d} \quad (11)$$

In Figure 3, λ_{ij} is equal to the average cost associated with prohibited zone and the conventional method can be applied to solve ED with unit prohibited zone.

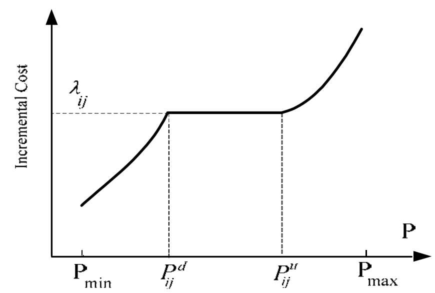

Figure 3: Modified cost curve with prohibited zone

4 EFFECT OF PROHIBITED ZONE ON LMP

LMP is the marginal cost of supplying the next increment of load at a specific bus or power system location with respect to system limits [8]. When the there is no congestion, price is same on all buses throughout the system which is the marginal cost of meeting the last incremental demand. However, when there is congestion the locational price signal could be different from MCP. Because the available low cost supply cannot be delivered to the demand sites.

Different factors affect system congestion and LMP consequently. In this study we illustrate the effect of prohibited zone on congestion. In case of prohibited zone, there is more limitation to utilize the generating unit. Assume that for a given load the optimum generation of unit is into the prohibited zone. Since unit cannot operate at this point, the unit output will jump to upper or lower limit of prohibited zone. This causes change in the output of other units to balance the generation and demand. As a result, system will move from optimum solution. These changes in system operation act like a noise, and cause congestion, especially when system works near the critical point.

Mathematically, LMP is the dual variable or Lagrangian multiplier for the equality constraint (node balance equation) in the constrained economic dispatch problem [8].

5 CASE STUDY

To illustrate the impact of prohibited zones on power system security and bus LMPs, we apply the proposed approach to an 8-bus system. The network configuration is given in Figure 4 with unit information in Table 1.

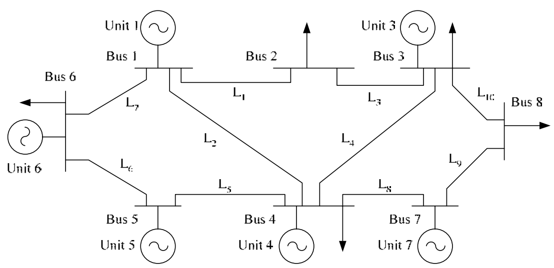

Figure 4: Network configuration of 8-bus system

Based on Table 1, the most expensive incremental cost is that of unit 6. Units 1, 3, 4, 5 and 7 have prohibited zones as listed in Table 2. It shows lower and upper generating limits of prohibited zones. Table 3 shows transmission parameters.

To demonstrate the effect of prohibited zones on power system security and market prices, we analyze the following scenarios:

- **Case 1:** Effect of unit prohibited zone on LMP
- **Case 2:** Effect of unit prohibited zone on system operation

Bus No	Units cost coefficients			P_{min}	P_{max}
	c ($/MW.H^2)	b ($/MW.H)	a ($/H)		
1	.0037	9.8	100	20	100
2	-	-	-	-	-
3	.0041	17.02	145	10	70
4	.0039	10	112	10	90
5	.004	10.1	110	10	100
6	.0045	25.1	180	10	50
7	.0035	9.3	100	20	200
8	-	-	-	-	-

Table 1: Generating units information

Unit No	Number of prohibited zones	Prohibited Zones
1	1	[60,70]
3	2	[15,25], [45,55]
4	2	[30,45], [70,85]
5	1	[75,85]
7	2	[50,60], [110,125]

Table 2: Unit prohibited zones

Line No	From bus	To bus	X (p.u.)	Line Limit (MW)
1	1	2	0.03	37
2	1	4	0.03	200
3	2	3	0.011	200
4	3	4	0.03	60
5	4	5	0.03	22
6	5	6	0.02	200
7	6	1	0.025	75
8	7	4	0.015	200
9	7	8	0.022	200
10	8	3	0.018	37

Table 3: Line parameters

Case 1: Effect of prohibited zones on LMP

Figure 5 depicts the most economical load flow solution without prohibited zones. In this case lines are not congested and ED calculates the system cost. Basically, when there is no congestion, ED will allocate the required load demand between the generation units such that the cost of generation is minimized. So, an efficient generating dispatch could be utilized based on equal incremental cost criteria. This issue can be seen in Figure 5. The expensive units 3 and 6 are not utilized, and there is no limitation to supply the load by cheaper units.

LMP will be same for all buses, as 10.4 $/MWh. These results show that unit 5 would have been operated within its prohibited zone (between 75 and 85 MW), had we considered those zones in ED.

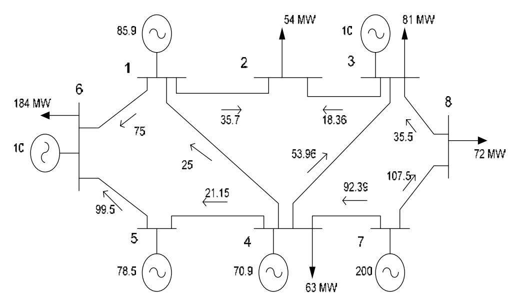

Figure 5: Generation dispatch without prohibited zones (Case 1)

Now for the same generating system we consider the effect of prohibited zones. As it is discussed in this paper, in a power system transmission congestion could prevent an economical generating dispatch. When a transmission line becomes congested, there is no additional power that can be transferred from injection point to sink point. It causes more expensive units may have to be utilized for load balance. In a competitive market, such an occurrence would cause different LMP. Here, we show that operating out of the prohibited zone aggravates congestion and LMP consequently.

Based on equation (11), the associated incremental cost for prohibited zone of unit 5 is 10.7 $/MWh. Since the system incremental cost is less than 10.7, unit output will jump to lower limit of prohibited zone. So, by considering the prohibited zone effect, the 78.5 MW generation of unit 5 in Figure 5 decreases to 75 MW at the lower limit of the unit prohibited zone. Figure 6 shows that unit 6 is also dispatched for supplying the load at bus 6 since line flows on L_7 (between buses 1 and 6) and L_6 (between buses 4 and 5) have reached their upper limits. This is an expensive unit which will increase the cost of supplying the load in the system. Table 4 indicates that LMPs at buses 5 and 6 are much higher since flows on lines L_6 and L_7 are constrained. It can be seen that unit prohibited zone aggravates congestion and increases LMP.

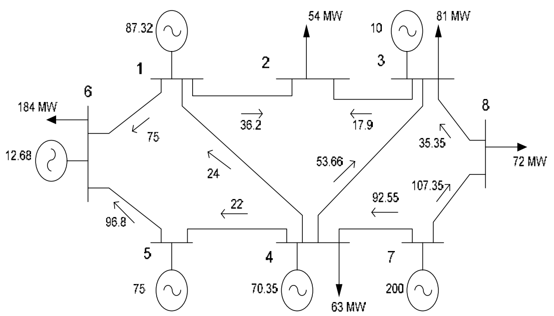

Figure 6: Generation dispatch with prohibited zones (Case 1)

Bus No	1	2	3	4	5	6	7	8
LMP ($/MWh)	10.4	10.4	10.4	10.4	25.2	25.2	10.4	10.4

Table 4: LMP on buses with considering prohibited zones (Case 1)

Case 2: Effect of prohibited zones on system operation

In this case, we consider the same system but load has been changed. Figure 7 shows load distribution and load flow without considering prohibited zone effect. The dispatch results indicate that the congestion occurs on buses 2 and 3. As shown in Figure 7, flows on lines L_1 (between buses 1 and 2), L_4 (from bus 4 to 3) and L_{10} (between buses 8 and 3) are near their upper limits. Because of congestion on interconnection lines to buses 2 and 3, expensive unit 3 must be utilized to satisfy load balance on buses 2 and 3. This causes increasing price on buses 2 and 3. Table 5 indicates the LMP at buses 2 and 3 is higher at 17.1 $/MWh. Unit 3 is generating 19.85 MW which is within its prohibited zone (between 15 and 25).

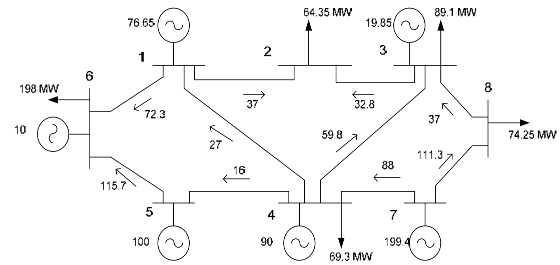

Figure 7: Generation dispatch without prohibited zones (Case 2)

Bus No	1	2	3	4	5	6	7	8
LMP ($/MWh)	10.4	17.2	17.2	10.4	10.4	10.4	10.4	10.4

Table 5: LMP on Buses without considering prohibited zones (Case 2)

Now for the same system we consider the impact of prohibited zones and solve ED problem. Unit 3 will be decreased by 4.85MW to its lower limit of prohibited zone (15MW). Since line flows to buses 2 and 3 are congested they cannot supply the remaining 4.85 MW. So there is problem to supply the load on bus 2 if we consider prohibited zone of unit 3. In this case we need to shed load at buses 2 and 3 as shown in Fig. 8. Table 6 shows the corresponding LMPs.

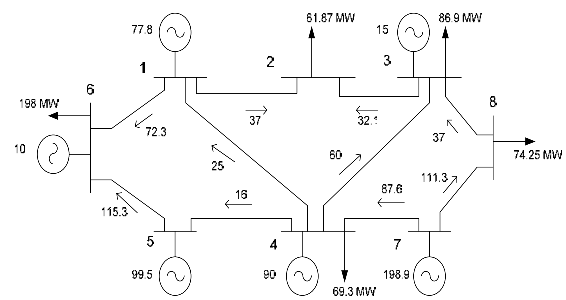

Figure 8: Generation dispatch with prohibited zones (Case 2)

Bus No	1	2	3	4	5	6	7	8
LMP ($/MWh)	10.4	17.2	17.2	10.4	10.4	10.4	10.4	10.4

Table 6: LMP on Buses with considering prohibited zones (Case 2)

6 CONCLUSION

Constrained economic dispatch problem is an important issue in power system study. This paper is focused on generating units with prohibited operating zones and their effect on system operation. A numerical approach is proposed to solve the problem by conventional methods. The proposed method has been tested and implemented with an 8-bus test system data. Results show the prohibited zone limit impacts system congestion and pricing.

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