Bid responsive generation rescheduling for congestion management in electricity market

Md Sarwar\textsuperscript{1} \quad | \quad Anwar Shahzad Siddiqui\textsuperscript{1} \quad | \quad Zainul Abdin Jaffery\textsuperscript{1} \quad | \quad D. P. Kothari\textsuperscript{2}

\textsuperscript{1}Department of Electrical Engineering, Jamia Millia Islamia, New Delhi, India
\textsuperscript{2}S.B. Jain Institute of Technology, Management & Research, Nagpur, India

Abstract
Electricity market economics is one of the vital factors which play a key role in achieving the efficient operation of the power system. Economic operation along with secure & reliable operation is must for ensuring optimum utilization of the resources in order to maximize social welfare. This article presents a method for achieving economic operation of electricity market in case of congestion occurring in the system. The generator sensitivity (GS) method alone can manage the system congestion, however it does not consider the economic benefits which can be achieved by considering the bids submitted by the generators and as a result it leads to situation of market power. To avoid such scenario, bid sensitivity factor (BSF) is proposed to select the generators to participate and regulate their real power generation for alleviating congestion from the system optimally. The BSF takes into account the GS as well as bids of the generators. In this paper, the effectiveness of the proposed method in eliminating market power is realized by changing the bids of the generators. The proposed method is tested on IEEE 30-bus system and IEEE 118-bus system. The obtained results show an encouraging pattern for managing the congestion more optimally and economically.

KEYWORDS
bid sensitivity factor, congestion management, generation rescheduling, generator sensitivity, market power

1 \quad INTRODUCTION

Due to ill condition and inefficient operation of vertically integrated power sector during mid-80s countries were forced to restructure their power sector in order to achieve efficient and reliable operation. In early 90s some countries successfully restructured there power sector. As a result many other countries were also encouraged to restructure their power sector. This was a major game changer which resulted in change of operation dynamics of power sector. All these developments in power sector led to the concept of electricity market, which introduces competition among its different players. Although the competition was introduced only in generation and distribution side, the transmission system was kept under the control of one entity which was solely responsible for its transparent, reliable, and secure operation. Hence the new power market structure resulted in reduced cost of electricity. However, in new liberalized
electricity market the participants would try to trade power so as to achieve maximum profit. This may lead to a situation in which the transmission networks are unable to accommodate all the committed power schedules due to violation of any of its transfer limits such as voltage limits, stability limit, thermal limit, and so on, resulting in congestion and unstable operation of power system. This condition has a direct impact on the economic aspects of the deregulated electrical market as it may result in increased electricity cost. Therefore, occurrence of the congestion in the power system network must be avoided or it must be alleviated quickly in order to ensure smooth and secure functioning of power system.

The management of congestion over the transmission network is one of the fundamental problems faced by the system operator as it involves both technical and economic aspects of the system. It allows the electricity market participants to utilize the transmission network at its maximum capacity. Henceforth, an effective congestion management scheme is necessary. There exists several congestion management schemes which are generation rescheduling, load curtailment, implementation of FACTS devices, distributed generations and energy storage devices, and so on. The implementation of such schemes suitable for different competitive market structures are discussed in References 8-10.

Among all, generation rescheduling-based congestion management is one of the most widely used methods around the world. This method along with load curtailment is in use since long time. The method is not only adopted in deregulated market structure, but was also used in vertically integrated system. In fact, it is considered to be one of the promising methods to achieve effective congestion management. But, still it lacks in an efficient model on the basis of rescheduling cost. So far, many research works are reported to address this issue.

The management of congestion by rescheduling real power generation is presented by Yesuratnam and Thukaram. The authors introduced relative electrical distance (RED) to find the rescheduling power amount. But, the generators having equal RED values contribute equal power to the congested line. It results in non-optimized rescheduling cost due to the generators having dissimilar cost functions. A sensitivity based method for generation rescheduling is proposed by Dutta and Singh. Generator sensitivity (GS) factor is utilized to select the participating generators in rescheduling process. The GS factor is calculated for the change in real power flow through the line to the change in real power output of generators. But the effect of change in bid values on the selection of the participating generators and rescheduling cost is not presented in the proposed algorithm. Pandya et al modified the method of selection of participating generator by considering both real and reactive power sensitivity factors. The participating generators adjust its output according to their GS values and accordingly rescheduling cost is obtained. Nonetheless, this method also gives non-optimized rescheduling cost as it fails to address the effect of change in bid values. More optimized rescheduling cost is obtained in References 14,15 by adopting the similar approach presented in References 12,13 with some modification in the optimization algorithm. The parameters of the particle swarm optimization (PSO) algorithm are modified to obtain the amount of rescheduling power. But both methods fail to address the issue of market power often arises due to congestion. It allows certain generators to maximize their profit. The issue is somehow addressed by Suganthi et al in References 16,17. Improved GS factor (IGSF) is introduced to reflect the effect of bid values in the selection of participating generators. The method helps in achieving minimized rescheduling cost and eliminating market power to some extent. Nevertheless, the IGSF values fail to select the generators with much lower bid value and comparable GS value, as compared to other participating generators, which can be effective in managing congestion. Henceforth, the rescheduling cost calculated is not optimal.

The main objective of this work is to present an efficient rescheduling-based congestion management method. The proposed technique aims to achieve (i) optimal rescheduling cost and (ii) market power elimination. It combines the technical and economic aspects both to select and reschedule the participating generators for efficient congestion alleviation. This is accomplished by adopting a novel approach which combines the effect of GS to the flow of active power and the rescheduling bid values. It could be revealed from the literature, that all the generators are not sensitive to the flow of power through congested line. Also, the generators which are sensitive to flow of power through congested line with high bid values results in high rescheduling cost and hence are not preferred. Thus to achieve minimum rescheduling cost, generators with low bid values are preferred even if they are less sensitive to flow of power on congested lines yet effective enough in alleviating congestion. The issue is taken care by the bid sensitivity factor (BSF) proposed in this paper. The GS factor is calculated first which is utilized to calculate the BSF. Based on the BSF values the generators are selected to reschedule their generation for managing congestion at minimum rescheduling cost. Furthermore, the effectiveness of the proposed method in eliminating market power is also analyzed.
2 | GENERATOR SENSITIVITY

The generators in power system are impacted by flow of power through transmission lines and they respond accordingly to the changes occurring in transmission network. However, some are more sensitive and some are less sensitive to these changes in transmission network. To find the effect of these changes on generators, a term GS factor is introduced which relates the change in active power flow through line with change in active power output of the corresponding generator and is given as:

$$G_{Spq}^i = \frac{\Delta P_{pq}}{\Delta P_{gi}}$$

(1)

where, $G_{Spq}^i$ is the GS value of generator-$i$, $\Delta P_{pq}$ is change in flow of active power in line connecting bus-$p$ and bus-$q$ and $\Delta P_{gi}$ is the change in generation of active power of generator-$i$.

Neglecting the coupling between P-V, Equation (1) is written as

$$G_{Si} = \frac{\partial P_{pq}}{\partial \theta_p} \cdot \frac{\partial \theta_p}{\partial P_{gi}} + \frac{\partial P_{pq}}{\partial \theta_q} \cdot \frac{\partial \theta_q}{\partial P_{gi}}$$

(2)

The equation of power flow through a transmission line is given as

$$P_{pq} = -V_p^2 G_{pq} + V_p V_q G_{pq} \cos(\theta_p - \theta_q) + V_p V_q B_{pq} \sin(\theta_p - \theta_q)$$

(3)

where, $V_p$ and $\theta_p$ represents voltage magnitude and phase angle at bus-$p$ respectively, $G_{pq}$ and $B_{pq}$ are conductance and susceptance of line connected between bus-$p$ and bus-$q$ respectively.

Differentiating Equation (3) with respect to $\theta_p$ and $\theta_q$ we get,

$$\frac{\partial P_{pq}}{\partial \theta_p} = -V_p V_q G_{pq} \sin(\theta_p - \theta_q) + V_p V_q B_{pq} \cos(\theta_p - \theta_q)$$

(4)

$$\frac{\partial P_{pq}}{\partial \theta_q} = V_p V_q G_{pq} \sin(\theta_p - \theta_q) - V_p V_q B_{pq} \cos(\theta_p - \theta_q) = -\frac{\partial P_{pq}}{\partial \theta_p}$$

(5)

The injected active power at any bus-$s$ of the system is expressed as

$$P_s = |V_s| \sum_{k=1}^{n} ((G_{sk} \cos(\theta_s - \theta_k) + B_{sk} \sin(\theta_s - \theta_k)) |V_k|)$$

(6)

$$= |V_s|^2 G_{ss} + |V_s| \sum_{k=1}^{n} ((G_{sk} \cos(\theta_s - \theta_k) + B_{sk} \sin(\theta_s - \theta_k)) |V_k|)$$

Differentiating Equation (7) with respect to $\theta_s$ and $\theta_k$ we get,

$$\frac{\partial P_s}{\partial \theta_k} = |V_s| |V_k|(G_{sk} \sin(\theta_s - \theta_k) - B_{sk} \cos(\theta_s - \theta_k))$$

(8)

$$\frac{\partial P_s}{\partial \theta_s} = |V_s| \sum_{k=1}^{n} ((-G_{sk} \sin(\theta_s - \theta_k) + B_{sk} \cos(\theta_s - \theta_k)) |V_k|)$$

Neglecting the P-V coupling, the active power change at system buses with change in voltage phase angles is expressed as:

$$[\Delta P]_{n \times 1} = [H]_{n \times n}[\Delta \theta]_{n \times 1}$$

(10)
where,

\[
[H]_{n \times n} = \begin{bmatrix}
\frac{\partial P_1}{\partial \theta_1} & \frac{\partial P_1}{\partial \theta_2} & \cdots & \frac{\partial P_1}{\partial \theta_n} \\
\frac{\partial P_2}{\partial \theta_1} & \frac{\partial P_2}{\partial \theta_2} & \cdots & \frac{\partial P_2}{\partial \theta_n} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{\partial P_n}{\partial \theta_1} & \frac{\partial P_n}{\partial \theta_2} & \cdots & \frac{\partial P_n}{\partial \theta_n}
\end{bmatrix}
\] (11)

Therefore,

\[
[\Delta \theta] = [H]^{-1}[\Delta P]
\] (12)

If \([M] = [H]^{-1}\) (13)

Then,

\[
[\Delta \theta] = [M][\Delta P]
\] (14)

The matrix \([M]\) can be modified with respect to reference bus-1 as:

\[
[\Delta \theta]_{n \times 1} = \begin{bmatrix} 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ [M^{-1}]_{n \times n} \end{bmatrix} [\Delta P]_{n \times 1}
\] (15)

The values of terms \(\partial \theta_{p_i}/\partial P_{g_i}\) and \(\partial \theta_{q_i}/\partial P_{g_i}\) of Equation (2) are obtained from the modified \([M]\) to calculate the GS values of each generator.

3 | SELECTION OF PARTICIPATING GENERATORS

GS factor can alone be utilized to mitigate the congestion, but the increment or decrement of bids of generators does not have any impact on the amount of rescheduling power of the participating generators. When the generators with high GS values increase their rescheduling bids, there will be a loss of revenue. Such issue is addressed by proposing another sensitive factor known as BSF in this paper. BSF is made sensitive to the change in rescheduling bids. It is defined as the ratio of generation rescheduling bid cost to the square root of magnitude of GS factor and is given as:

\[
BSF_i = \begin{cases} 
+ \frac{RC_i}{\sqrt{|GS_i|}} & \text{if } GS_i > 0 \\
- \frac{RC_i}{\sqrt{|GS_i|}} & \text{if } GS_i < 0
\end{cases}
\] (16)

where
- BSF\(_i\) is the bid sensitivity factor of generator-\(i\).
- RC\(_i\) is the rescheduling bid submitted by generator-\(i\).

BSF is formulated to include both the technical as well as economic aspects. The GS value gives an indication of the sensitivity of a particular generator to the power flow on a congested line while the bids of the generators help in achieving the economy of the rescheduling process. This is accomplished by selecting the generators with low BSF values to manage congestion at minimum rescheduling cost. The selected generators can either upscale or downscale their generation for managing congestion depending upon the sign of BSF values. The negative values of BSF show that the generation of the corresponding generator has to be increased and vice versa.

4 | PROBLEM FORMULATION

With deregulation of power sector, the problem of managing congestion has somewhat become more complex as compared to that in vertically integrated utility. Existence of competition in electricity market further makes it more difficult
to manage congestion. The present work considers a congestion management scheme in pool market structure wherein generators submits bid to serve the load. The problem of congestion management is formulated as a non-linear optimal power flow problem with an objective of cost minimization for active power rescheduling by the generators and is given as.

\[
\text{Minimize } \sum_{i=1}^{n_g} RC_i \Delta P_{gi}
\]  

subject to following constraints.

1. Equality constraint of power balance

\[
\sum_{i=1}^{n_g} \Delta P_{gi} = 0
\]

\[\text{FIGURE 1} \quad \text{Flowchart of the proposed algorithm}\]
2. Inequality constraint of operating limit

\[ \Delta P_{gi}^{\text{min}} \leq \Delta P_{gi} \leq \Delta P_{gi}^{\text{max}}, \quad i = 1, 2, \ldots, n_g \]  

(19)

where,

\[ \Delta P_{gi}^{\text{min}} = P_{gi} - P_{gi}^{\text{min}} \]

\[ \Delta P_{gi}^{\text{max}} = P_{gi}^{\text{max}} - P_{gi} \]

3. Inequality constraint of line flow

\[ F_L \leq F_{L}^{\text{max}}, \quad L = 1, 2, \ldots, n_L \]  

(20)

where,

\[ \Delta P_{gi} \] is the adjustment of active power by generator-\(i\),
\[ \Delta P_{gi}^{\text{min}} \] and \[ \Delta P_{gi}^{\text{max}} \] are minimum and maximum adjustment limit of active power generation of generator-\(i\) respectively,
\[ F_L \] is the power flow in line-\(L\) allowing all the contracts,
\[ F_{L}^{\text{max}} \] is the maximum limit of power flow in line-\(L\),
\[ n_L \] is the total number of lines.

The formulated congestion management problem is solved by PSO algorithm\(^{18}\) rather than utilizing classical optimization algorithms such as linear programming, lambda iteration, gradient method, and so on.\(^{19}\) This is due to the dependency of the classical methods on the convexity assumed for the objective function. As a result, the solution of these methods may diverge or get trapped in local minima due to discontinuities of the objective function. Also, the quality of the solution gets affected due to the choice of initial starting point. Further, PSO has also proved its dominance over other artificial intelligence methods in solving various optimal power flow problems.\(^{20}\) The steps involved in the proposed method are described in Figure 1.

5 | RESULTS AND DISCUSSIONS

The proposed method is tested for its performance in managing congestion effectively on IEEE 30-bus system and IEEE 118-bus system.\(^{14}\) The GS and BSF values are calculated first using Equations (2) and (16) respectively. These values are utilized to select the generators in rescheduling their power output for managing congestion. The rescheduling cost given by Equation (17) is minimized. To show the effectiveness of the proposed method, the results are compared with the methods reported by Dutta and Singh,\(^{12}\) Boonyaritdachochai et al,\(^{14}\) and Suganthi et al.\(^{16}\)

The optimization of rescheduling cost due to congestion is carried out with PSO in MATLAB environment. The various PSO parameters considered for simulation is shown in Table 1. The maximum iteration count and particle size are taken as 500 and 70 respectively.

5.1 | IEEE 30-bus system

The regulating bids submitted by different generators of IEEE 30-bus system are given in Appendix A, Table A1. The power flow analysis is performed and the result for the congested line is shown in Table 2. It is found that line-1 is congested
as the power flow is above its maximum limit. Consequently, GS values and BSF corresponding to congested line-1 are calculated and tabulated in Table 3. It is observed that all the generators have comparable GS values, which is true for such a small system being tightly coupled. It can also be observed that the variations in BSF values of all the generators are very small. The BSF values of all the generators being small and comparable with each other necessitate that all the generators must participate and reschedule their output to manage congestion. However, the amount of rescheduling power obtained for each generator is different considering BSF values as compared to the GS value alone. The GS value of the generator connected at bus-2 is most negative while the GS value of the generator at bus-13 is least negative. But both the generators have comparable BSF values. The increase of real power generation of any of these two generators will have least effect on the rescheduling cost of the system. Similarly, the variation in GS values of the generators connected at bus-8 and bus-11 are very small. The variation in amount of real power rescheduling of these generators to mitigate congestion is also small. Nevertheless, the difference in BSF values of these generators is large, generator at bus-8 having highest BSF value, and the generator at bus-11 having the lowest BSF value among all the generators of the system. Hence, the adjustment in amount of real power generation of any of these two generators will have a major impact on the rescheduling cost of the system.

The generation rescheduling results are shown in Table 4. It shows that the generator at bus-2 and bus-13 being most and least sensitive to the flow of power on congested line, increase its real power generation to 19.7 MW and 6.8 MW respectively to relieve congestion based on GS method. Similarly, the generator at bus-8 and bus-11 increase its real power generation to 6.0 and 6.5 MW respectively. The difference in real power generation of these generators is small due to small difference in their GS values. The GS method gives 1447.5 $/h as the cost of rescheduling of real power generation for managing congestion. However with consideration of bid values of generators, the BSF values of the generator at bus-8 and bus-11 are 23.2589 and 17.6069, respectively. The large difference in BSF values of these generators is primarily due to their submitted bid costs. Although with comparable GS values, the BSF value of bus-11 generator is low due to its low bid cost as compared to bus-8 generator. So, the amount of real power adjustment by the generator at bus-11 is more as compared to the generator at bus-8. Similarly, the real power generation of bus-5 generator increases due to its low BSF
Table 5: Power flow results for IEEE 30-Bus system after generation rescheduling

| Line no. | From bus | To bus | Power flow (pu) | Line limit (pu) |
|---------|---------|--------|----------------|----------------|
| 1       | 1       | 2      | 0.96           | 1.00           |

Figure 2: Power flow in lines of IEEE 30-bus system

Table 6: Effect of change of bids on generation rescheduling for IEEE 30-bus system

| Generator no. | Active power rescheduling (MW) after change of bid |
|---------------|----------------------------------------------------|
|               | Without rescheduling | With rescheduling |
| $\Delta P_1$  | $-53.2$ | $-53.3$ |
| $\Delta P_2$  | $+18.5$ | $+20.4$ |
| $\Delta P_3$  | $+15.6$ | $+12.8$ |
| $\Delta P_4$  | $+3.3$ | $+3.5$ |
| $\Delta P_{11}$ | $+7.1$ | $+7.5$ |
| $\Delta P_{13}$ | $+4.3$ | $+4.6$ |
| Total $\Delta P$ | $102.0$ | $102.1$ |
| Cost ($/h$)    | $1525.5$ | $1516.2$ |

value and vice-versa for the bus-2 generator. Nevertheless, these adjustments in generation must alleviate congestion from the system. The line-1 which is earlier congested now operates well within its limit as given in Table 5. Also, power flow through other lines of IEEE 30-bus system is also under their respective maximum limit. Thus a congestion free system is successfully achieved as illustrated in Figure 2. The cost of achieving congestion free system with the proposed method is obtained as 1595.2 $/h$. Hence, a saving of 147.7 $/h$ in rescheduling cost is obtained with the proposed method and therefore congestion is relieved more optimally.

In electricity market, the generators try to maximize its profit. The generators can grasp the network congestion as an opportunity and exploit the condition to maximize its profit. This is referred as market power and it always results in non-optimal congestion management. The performance of the proposed method in eliminating market power and to give optimal congestion management is analyzed by varying the bid cost of a generator. The bid of bus-5 generator is increased from 17 $/MWh$ to 22 $/MWh$. With the change of the bid, the BSF value for this generator now increases to 23.82454 from 18.4099. This necessitates bus-5 generator to reduce its real power generation. Accordingly, all generators reschedule their generation in order to achieve optimal management of congestion and the results are shown in Table 6. The previously obtained rescheduling power of 15.6 MW of bus-5 generator is now reduced to 12.8 MW. It results in reduction of profit margin of bus-5 generator by 61.6 $/h$. Thus, it helps in eliminating the market condition utilized by the generators to maximize their profit. Subsequently, all other selected generators reschedule their real power output with the change of
FIGURE 3  Effect of change of bid on power generation rescheduling for IEEE 30-bus system

![Figure 3](image_url)

FIGURE 4  Comparison of generation rescheduling cost for IEEE 30-bus system

![Figure 4](image_url)

The effectiveness of the proposed method is analyzed by comparing the derived results with the methods presented in literature by Dutta and Singh,12 Boonyaritdachochai et al.,14 and Suganthi et al.16 The results of the different reported methods are shown in Table 7. In order to compare the results, the amount of rescheduling power reported in literature12,14,16 are listed here and the rescheduling cost is obtained with the regulating bids considered in this paper. It is very clear from Table 7 that the proposed technique provides minimum rescheduling cost in comparison with reported methods. The rescheduling cost achieved by the proposed technique is 1447.5 $/h as compared to 1584.6 $/h, 1463.8 $/h, and 1638.9 $/h obtained by Dutta and Singh,12 Boonyaritdachochai et al.,14 and Suganthi et al.16 It is to be noted from Table 7 that even though the total amount of real power rescheduling obtained by the proposed technique for congestion alleviation is more than the reported methods; the rescheduling cost achieved by the proposed method is less in comparison with other
### TABLE 7 Result comparison of IEEE 30-bus system

| Amount of generation rescheduling | Results obtained by proposed method (MW) | Results reported by (MW) |
|----------------------------------|------------------------------------------|--------------------------|
|                                  |                                           | Dutta and Singh¹²         |
|                                  |                                           | Boonyaritdachochai et al¹⁴ |
|                                  |                                           | Suganthi et al¹⁶          |
| ΔP₁                             | -53.2                                    | -59                      |
|                                  |                                           | -49.3                    |
|                                  |                                           | -2.23                    |
| ΔP₂                             | +18.5                                    | +19.9                    |
|                                  |                                           | +17.5                    |
|                                  |                                           | +25.61                   |
| ΔP₅                             | +15.6                                    | +13                      |
|                                  |                                           | +14.0                    |
|                                  |                                           | -27.65                   |
| ΔP₈                             | +3.3                                     | +6                       |
|                                  |                                           | +9.9                     |
|                                  |                                           | -16.68                   |
| ΔP₁₁                            | +7.1                                     | +6.5                     |
|                                  |                                           | +6.8                     |
|                                  |                                           | +15.99                   |
| ΔP₁₃                            | +4.3                                     | +7                       |
|                                  |                                           | +3.0                     |
|                                  |                                           | +4.96                    |
| Total ΔP                        | 102.0                                    | 111.4                    |
|                                  |                                           | 100.5                    |
|                                  |                                           | 93.12                    |
| Rescheduling cost ($/h)         | 1447.5                                    | 1584.6                   |
|                                  |                                           | 1463.8                   |
|                                  |                                           | 1638.9                   |

### TABLE 8 Power flow results for IEEE 118-bus system before generation rescheduling

| Line no. | From bus | To bus | Power flow (pu) | Line limit (pu) |
|----------|----------|--------|-----------------|-----------------|
| 145      | 89       | 90     | 1.37            | 1.00            |

### FIGURE 5 GS values for IEEE 118-bus system

methods. This is due to the fact that the proposed method considers both the GS and bid cost of a generator for generation rescheduling as compared to the reported methods.¹²,¹⁴,¹⁶

### 5.2 IEEE 118-bus system

The performance of the proposed method is also analyzed by implementing on IEEE 118-bus system.¹⁴ The real power regulating bids submitted by generators of IEEE 118-bus is given in Appendix A, Table A2. The power flow solution performed on the system provides that line-145 connected between bus-89 and bus-90 is congested as shown in Table 8. Subsequently, GS values are obtained for each generators of the system and are illustrated in Figure 5. It is observed that only few of the generators of the system have high GS values which are given in Table 9. Table 9 also shows the obtained BSF values of these generators and can be observed that all these generators including slack bus are selected to participate in congestion management process due to their high values of GS and BSF. The negative and positive value of both GS and BSF of a generator corresponds to its increment and decrement in real power output respectively. The GS value of bus-85 and bus-87 generators is almost equal. Any of these two generators along with other participating generators can
Table 9: Generator sensitivity values of IEEE 118-bus system for congested line 89-90

| Generator no. | GS values | BSF values  |
|---------------|-----------|-------------|
| 85            | +0.0501   | +75.9732    |
| 87            | +0.0507   | +84.4236    |
| 89            | +0.0745   | +80.6288    |
| 90            | −0.7012   | −21.4957    |
| 91            | −0.4279   | −29.0457    |

Table 10: Rescheduling results for IEEE 118-bus system

| Generator no. | Active power rescheduling (MW) |
|---------------|---------------------------------|
|               | BSF method | GS method  |
| ΔP1           | −3.5        | −4.4       |
| ΔP85          | −6.9        | −4.3       |
| ΔP87          | −4.3        | −6.1       |
| ΔP89          | −67.5       | −69.9      |
| ΔP90          | +63.5       | +63.2      |
| ΔP91          | +17.9       | +20.7      |
| Total ΔP      | 163.6       | 168.6      |
| Cost ($/h)    | 3205.6      | 3306.1     |

Table 11: Power flow results for IEEE 118-bus system after generation rescheduling

| Line no. | From bus | To bus | Power flow (pu) | Line limit (pu) |
|----------|----------|--------|-----------------|-----------------|
| 145      | 89       | 90     | 0.92            | 1.00            |

adjust more power as compared to other for relieving congestion successfully. Since the GS value of bus-87 generator is slightly more than bus-85 generator; it reschedules more real power output irrespective of its rescheduling bids. But the differences in BSF values of these two generators are large due to high bid value of generator at bus-87 as compared to generator at bus-85. Henceforth, the greater adjustment of real power output by generator at bus-87 as compared to generator at bus-85 results in non-optimal rescheduling cost of the system.

The generation rescheduling results obtained from GS method and BSF method are shown in Table 10. The generators at bus-85 and bus-87 reschedule 4.3 and 6.1 MW respectively based on GS method. However, due to low BSF value of bus-85 generator as compared to bus-87 generator, it must reschedule more power in comparison with bus-87 generator for effective congestion management which can be observed from Table 10. Bus-85 generator reschedules 2.6 MW more than bus-87 generator which helps in minimizing the rescheduling cost. Similarly, bus-89 generator also reduces its real power output due to its low BSF value as compared to bus-87 generator. Accordingly, the generators at bus-90 and bus-91, due to their very low negative BSF values, also adjust their real power generation to manage congestion. With these adjustments in real power generations, it is found that the line-145, which is earlier congested, now operates well within its limit as shown in Table 11. Also, the power flow through other lines of IEEE 118-bus system is under their respective maximum limit as shown in Figure 6. The congestion is successfully alleviated from the network resulting in a rescheduling cost of $3205.6/h. Hence, a saving of $100.5/h in rescheduling cost is achieved with the proposed method resulting in more optimized rescheduling cost and efficient congestion management.

The effectiveness of the proposed method in elimination of market power and optimal management of congestion is also examined by changing the bid cost of bus-85 generator. The bid of generator at bus-85 is increased to 22$/MWh from 17$/MWh and the effect on system rescheduling cost before and after change of bid is analyzed. With the increase in bid of bus-85 generator, its BSF value also increases. The BSF values changes to 98.3182 from 75.9732 and now is more than the BSF values of generator at bus-87 and bus-89. This necessitates the generator at bus-85 to reduce its real power generation resulting generators at bus-87 and bus-89 to upscale their real power output as compared to bus-85 generator in order to achieve a congestion free network. The amount of rescheduling power and rescheduling cost obtained due to
The efficacy of the proposed method is further analyzed by comparing the derived results with the methods presented in literature by Dutta and Singh, Boonyaritdachochai et al., and Suganthi et al. The results of the different reported methods are shown in Table 13. Here also, to compare the results, the amount of rescheduling power reported in literature are listed and the rescheduling cost is obtained with the regulating bids considered in this paper. The comparison of the reported results demonstrates that the rescheduling cost obtained by the proposed technique is minimum among all methods. It gives only $3205.6 per hour of rescheduling cost which is very less as compared to the reported methods. It is also identified from Table 13 that along with the rescheduling cost, the total amount of real power rescheduling necessary for congestion alleviation, obtained by the proposed method is very less in comparison with reported methods. Thus, optimum congestion management is achieved by the proposed method.

### 5.2.1 Results comparison for IEEE 118-bus system

The change of bid of generator at bus-85 is shown in Table 12. The previously obtained value of 6.9 MW of rescheduling power of bus-85 generator is now reduced to 3.7 MW. It results in reduction of profit margin of bus-5 generator by $70.4 per hour. Thus, it helps in eliminating the market power condition utilized by the generators to maximize their profit. Subsequently, all generators reschedule all other selected generators reschedule their real power output with the change of bid of bus-85 generator as illustrated in Figure 7 to optimally alleviate congestion from the system. The cost of generation rescheduling is obtained as $3219.5 per hour. If the selected generators do not change their output with the change of bid of bus-85 generator, the rescheduling cost is obtained as $3240.1 per hour. Therefore, a saving in rescheduling cost is achieved by making the participating generators to adjust its real power output accordingly with increase and decrease in their bid values. Hence the objective of optimal rescheduling cost and congestion free system is achieved with the proposed method as presented in Figure 8.
**Figure 7** Effect of change of bid on power generation rescheduling for IEEE 118-bus system

**Figure 8** Comparison of generation rescheduling cost for IEEE 118-bus system

| Amount of generation rescheduling | Results obtained by proposed method (MW) | Results reported by (MW) |
|-----------------------------------|------------------------------------------|--------------------------|
|                                  |                                          | Dutta and Singh\textsuperscript{12} | Boonyaritdachochai et al\textsuperscript{14} | Suganthi et al\textsuperscript{16} |
| ΔP\textsubscript{1}              | −3.5                                     | −3.79                    | −4.4                                      | 0                              |
| ΔP\textsubscript{85}             | −6.9                                     | −16.3                    | −10.3                                     | +24.41                        |
| ΔP\textsubscript{87}             | −4.3                                     | −9.0                     | −22.0                                     | +75.43                        |
| ΔP\textsubscript{89}             | −67.5                                    | −55.0                    | −58.5                                     | −24.12                        |
| ΔP\textsubscript{90}             | 63.5                                     | 81.9                     | +69.4                                     | −40.14                        |
| ΔP\textsubscript{91}             | 17.9                                     | 16.4                     | +24.7                                     | −10.2                         |
| ΔP\textsubscript{92}             | Not participated                         | −17.0                    | Not participated                           | −25.6                         |
| ΔP\textsubscript{99}             | Not participated                         | Not participated         | Not participated                           | Not participated |
| Total ΔP                         | 163.6                                    | 199.4                    | 189.3                                     | 199.9                         |
| Rescheduling cost ($/h)          | 3205.6                                   | 3655.6                   | 3647.0                                    | 3551.1                        |

**6 | Conclusions**

A congestion management methodology with an objective of achieving economic system operation based on generation rescheduling was proposed. This methodology was mainly accomplished by proposing BSF. The generators reschedule their real power output for managing congestion by participating through BSF. Earlier methods reported in literature mainly considered GS to reschedule the real power output of generators, however it led to condition of market power. BSF eliminated market power as it included both the GS and bids submitted by the generators. The amount for rescheduling...
The generation rescheduling cost was evaluated by BSF. The proposed algorithm was tested on IEEE 30-bus system and IEEE 118-bus system. In comparison to methods proposed earlier this methodology led to a remarkable cost cut for rescheduling of real power generation. Thus, the objective of optimal congestion management was achieved effectively. Also, the effectiveness of the proposed method in eliminating market power was successfully realized by changing the bids of the generators. The proposed work can be extended to include the reactive power rescheduling along with real power rescheduling for congestion management.

PEER REVIEW INFORMATION

Engineering Reports thanks the anonymous reviewers for their contribution to the peer review of this work.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Md Sarwar https://orcid.org/0000-0002-5187-5865

REFERENCES

1. Houndjéga M, Muriithi CM, Wekesa CW. Active power rescheduling for congestion management based on generator sensitivity factor using ant lion optimization algorithm. *Int J Eng Res Technol*. 2018;11(10):1565-1582.
2. Srivastava J, Yadav NK, Sharma AK. A novel hybrid algorithm for rescheduling-based congestion management scheme in power system. *Electr Eng*. 2020;102:1993-2010.
3. Reddy SS. Multi-objective based congestion management using generation rescheduling and load shedding. *IEEE Trans Power Syst*. 2017;32(2):852-863.
4. Zaeim-Kohan F, Razmi H, Doagou-Mojarrad H. Multi-objective transmission congestion management considering demand response programs and generation rescheduling. *Appl Soft Comput*. 2018;70:169-181.
5. Yousefi A, Nguyen TT, Zareipour H, Malik OP. Congestion management using demand response and FACTS devices. *Elecrr Power Energy Syst*. 2012;37(1):78-85.
6. Nguyen TT, Mohammad F. Optimal placement of TCSC for congestion management and power loss reduction using multi-objective genetic algorithm. *Sustainability*. 2020;12(7):1-15.
7. Dehnavi E, Aminifar F, Afsharnia S. Congestion management through distributed generations and energy storage systems. *Int Trans Electr Energy Syst*. 2020, 29(6):1-12.
8. Christie RD, Wollenberg BF. Transmission management in the deregulated environment. *Proc IEEE*. 2000;88(2):170-195. https://doi.org/10.1109/5.823997.
9. Pillay A, Prabakhar Karthikeyan S, Kothari DP. Congestion management in power systems—a review. *Elecrr Power Energy Syst*. 2015;70:83-90.
10. Yusoff NI, Zin AAM, Khairuddin AB. Congestion management in power system: a review. Paper presented at: Proc. of 3rd International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET); 2017:22-27. https://doi.org/10.1109/PGSRET.2017.8251795.
11. Yesuratnam G, Thukaram D. Congestion management in open access based on relative electrical distances using voltage stability criteria. *Elecrr Power Syst Res*. 2007;77(12):1608-1618.
12. Dutta S, Singh SP. Optimal rescheduling of generators for congestion management based on particle swarm optimization. *IEEE Trans Power Syst*. 2008;23(4):1560-1569.
13. Pandya KS, Joshi SK. Sensitivity and particle swarm optimization based congestion management. *Elecrr Power Compon Syst*. 2013;41(4):465-484.
14. Boonyaritdachochai P, Boonchuay C, Onsgakul W. Optimal congestion management in an electricity market using particle swarm optimization with time-varying acceleration coefficients. *Comput Math Appl*. 2010;60(4):1068-1077.
15. Sarwar M, Siddiqui AS. An efficient particle swarm optimizer for congestion management in deregulated electricity market. *J Electr Syst Inform Technol*. 2015;2:269-282.
16. Suganthi ST, Devaraj D, Thilagar SH, Ramar K. Optimal generator rescheduling with distributed slack bus model for congestion management using improved teaching learning based optimization algorithm. *Sadhana*. 2018;43(181):1-11.
17. Saravanabalaji S, Krishnanthevar R, Thilagar SH, Durairaj D. A novel approach for congestion management using improved differential evolution algorithm. *Int Trans Electr Energy Syst*. 2018;28(10):1-19.
18. Balaraman S, Kamaraj N. Transmission congestion management using particle swarm optimization. *J Electr Systems*. 2011;7(1):54-70.
19. Semshchikov E, Negnevitsky M. Congestion management optimization in electric transmission system. Paper presented at: Proc of Australasian Universities Power Engineering Conference (AUPEC); 2018:1-5. https://doi.org/10.1109/AUPEC.2018.8757932.

20. Singh B, Mahanty R, Singh SP. Social welfare maximization for congestion management in multiutility market using improved PSO incorporating transmission loss cost allocation. *Int Trans Electr Energy Syst*. 2018;28(9):1-22.

**How to cite this article:** Sarwar M, Siddiqui AS, Jaffery ZA, Kothari DP. Bid responsive generation rescheduling for congestion management in electricity market. *Engineering Reports*. 2021;3:e12331. https://doi.org/10.1002/eng2.12331

### APPENDIX A.

**Table A1** Rescheduling bids submitted by different generators of IEEE 30-bus system

| Generator no. | Bids ($/MWh) |
|---------------|--------------|
| 1             | 11           |
| 2             | 19           |
| 5             | 17           |
| 8             | 20           |
| 11            | 15           |
| 13            | 17           |

**Table A2** Rescheduling bids submitted by different generators of IEEE 118-bus system

| Generator no. | Bids ($/MWh) | Generator no. | Bids ($/MWh) | Generator no. | Bids ($/MWh) |
|---------------|--------------|---------------|--------------|---------------|--------------|
| 1             | 11           | 42            | 14           | 80            | 18           |
| 4             | 25           | 46            | 10           | 85            | 17           |
| 6             | 19           | 49            | 20           | 87            | 19           |
| 8             | 16           | 54            | 21           | 89            | 22           |
| 10            | 21           | 55            | 13           | 90            | 18           |
| 12            | 12           | 56            | 18           | 91            | 19           |
| 15            | 13           | 59            | 16           | 92            | 10           |
| 18            | 14           | 61            | 15           | 99            | 21           |
| 19            | 17           | 62            | 17           | 100           | 30           |
| 24            | 19           | 65            | 19           | 103           | 15           |
| 25            | 70           | 66            | 25           | 104           | 14           |
| 26            | 15           | 69            | 60           | 105           | 11           |
| 27            | 17           | 70            | 15           | 107           | 20           |
| 31            | 19           | 72            | 14           | 110           | 21           |
| 32            | 20           | 73            | 17           | 111           | 22           |
| 34            | 15           | 74            | 9            | 112           | 23           |
| 36            | 10           | 76            | 6            | 113           | 19           |
| 40            | 18           | 77            | 20           | 116           | 25           |