Optimal Congestion Management by Load Curtailment in Electricity Market

*J.Senthil Kumar¹, C.Kumar², S.Balavignesh¹, A. Dheepanchakkravarthy¹

¹,²Department of Electrical and Electronics Engineering, ¹Bannari Amman Institute of Technology, ²M.Kumarasamy College of Engineering, ¹Sathyamangalam, India, ²Karur, India
¹*senthilkumarj@bitsathy.ac.in
* Corresponding Author

Abstract. A novel bi-level framework is developed for congestion management in electric power market by load curtailment and generator rescheduling. Interruptible load auction schemes are performed to detect the load buses which require corrective measures to relieve congestion. The proposed congestion management problem is solved in two different levels. The objective functions formulated as non-linear equation is solved using swarm intelligence techniques. In first level, the load curtailment problem is solved, while in second level the generator rescheduling problem is solved. Generator rescheduling through swarm based optimization techniques minimizes the curtailment of contracted power in a deregulated market. A comparative study has been carried out on the swarm intelligence techniques such as Cauchy Gaussian infused PSO (CGI-PSO) and Particle Swarm Optimization with Time Varying Acceleration Coefficient (PSO-TVAC) to solve the proposed problem. The formulated methodology is simulated on standard IEEE 30 bus system and verified through Indian utility-69 bus system.

Keywords: Cauchy and gaussian distribution; Load Curtailment (LC); Particle Swarm Optimization (PSO); transmission congestion management.

1 Introduction

The congestion in a transmission line is detected when the power flow through the line exceeds the thermal limit of the lines. In a deregulated environment, the variation in generated power and unbalanced load condition leads to transmission congestion. This overload may threaten network security and consistency; which affects the electricity price in different regions of the electricity market.

The Independent System Operator (ISO) plays a major role in maintaining the reliability of the deregulated environment and ensuring continuous power supply to all consumers. In recent years, different optimization techniques are invoked to relieve congestion in transmission lines. The literature review for different possible congestion management technique is given in literature [1, 2]. The process of congestion management and the modes of transaction differ from countryside to countryside. Similarly the congestion management technique varies in accordance with the type of electricity market involved in the system [3] and the cost spent to relieve congestion [4]. A detailed analysis has been carried out in [5] using security-constrained price-based unit commitment for coordinated congestion management process. The congestion management is further analyzed with the operation of FACTS devices and load power curtailment [6].

The optimal congestion management is performed through evolutionary algorithms. PSO based Optimal Power Flow is formulated to solve congestion management problem in pool market [7]. The congestion in pool market is relieved by optimal rescheduling generators using multi objective PSO technique [8]. The modified PSO is introduced to optimize the congestion management technique
in [9] which effectively minimizes the cost of dispatching generation cost. The economic load dispatch problem is solved using Gaussian function in the PSO algorithm [10]. The PSO algorithm is also improved by combining with Cauchy mutation which is discussed in [11, 12]. Based on these available techniques, it is proposed to combine the Cauchy and Gaussian probability distribution technique along with PSO algorithm to solve the Congestion Management problem.

In [13] the concept of Transmission Congestion Distribution Factor (TCDF) is incorporated along with PSO technique to identify and relieve congestion in transmission system. The relative electrical distance approach is followed for rescheduling the generation using TCDF which is then compared with cluster based approach [14, 15]. Indices representing the effective and possible load curtailment alleviating congestion are proposed for congestion management in [16, 17]. Power exchange collects the interruptible price offer from buyer and provides transmission scheduling plan to operate under congestion. In view of power exchange operation, the schedule is fixated by transmission rights and flow gate rights [18, 19]. In also some cases, the contingency-constraints are incorporated with the objective function of congestion management [20]. The major part of the present work is to relieve the congestion occurred due to bilateral and multilateral transaction by the curtailment of contracted load power in the deregulated market. In this paper, the non-linear functions are solved using the swarm based techniques for optimal rescheduling of active power of generators. The formulated methodology is studied in IEEE-30 bus and verified through Indian utility-69 bus systems.

2 OVERVIEW OF PSO SCHEMES

PSO is a Meta heuristic algorithm which performs searching through global spacing to identify best particle and position. The particles change its position corresponding to velocity which depends upon the experience of neighborhood particles in an N-dimensional space [21, 22]. While the search is initiated, the particles fix their personal best position, Pbest = (Pbest_i1, Pbest_i2, ..., Pbest_in) and their global best position, Gbest = (Gbest_i1, Gbest_i2, ..., Gbest_in) to vary their velocity. The particles searching through each iteration moves at velocity, \( V^i_k \), and updates the particle position \( X^i_k \).

2.1. Standard PSO (SPSO)

SPSO is precisely defined in [18].

\[
V^{i+1}_k = wV^i_k + C_{r1}\cdot (Pbest^i_k - X^i_k) + C_{r2}\cdot (Gbest^i_k - X^i_k) \tag{1}
\]

\[
X^{i+1}_k = X^i_k + V^{i+1}_k \tag{2}
\]

2.2. Cauchy Gaussian Infused PSO (CGI-PSO)

The core idea of CGI-PSO is similar to SPSO. The velocity updation alone modified by Cauchy (Cd) and Gaussian (Gd) distribution function. The Cauchy function generates the random numbers in the interval [0, 1] for Social part and Gaussian function generates the interval for cognitive part. The velocity updation is performed using,

\[
V^{i+1}_k = C\cdot \left[ wV^i_k + C_{1}\cdot Gd()\cdot (Pbest^i_k - X^i_k) + C_{2}\cdot Cd()\cdot (Gbest^i_k - X^i_k) \right] \tag{3}
\]

2.3. PSO with Time Varying Acceleration Coefficient (PSO-TVAC)

The velocity updation of PSO-TVAC is expressed as [9-20].
As mentioned in section II, the proposed objective is solved using SPSO, CGI-PSO and PSO-TVAC.

3 PROBLEM FORMULATION

During bilateral and multilateral transaction in competitive power market, load curtailment is performed for eliminating congestion. For the proposed model of load curtailment, an auction model is introduced. Where, offer price ($\beta$) are submitted by the participating customers.

Once congestion is observed after the transaction, customers are selected for incrementing and decrementing loads based on the lower and higher offer price bid submitted by the participants respectively.

Method 1: Load curtailment for congestion management

**Objective function**

The number of load buses for curtailment (NLC) is minimized by ISO using,

$$\text{NLC} = \sum_{i=1}^{n_d} B_i$$

(5)

Where $B$ is a binary decision variable (0 or 1) representing the selection of loads. If $B=0$, load bus is not selected or otherwise ($B=1$) for the buses identified for load curtailment among the total load buses $n_d$.

The minimization of power interruption denoted by PI is expressed as,

$$\text{PI} = \sum_{i_1=1}^{\text{NLC}_{\text{dec}}} \Delta P_{i_1} + \sum_{i_2=1}^{\text{NLC}_{\text{inc}}} \Delta P_{i_2}$$

(6)

First term in the equation (6), represents the power interruption by load curtailment for decreasing the load at buses $\text{NLC}_{\text{dec}}$. Second term represents the power interruption by load curtailment for increasing their load at buses $\text{NLC}_{\text{inc}}$ to meet the power balance equation. Here, $\Delta P_{i_1}$ and $\Delta P_{i_2}$ represent the deviation in real power load for decreasing and increasing the load respectively.

Method 2: Generation rescheduling for congestion management

The congestion level in transmission line is minimized by generator rescheduling with optimal fuel cost. The objective is solved by considering power system constraints.

**Objective Function**

The cost minimization objective function is formulated for generator rescheduling as,

$$C = \min \left( \sum_{i=1}^{n_g} C_i(P_{gi}) + C(P_{gs}) \right) \$/\text{hr}$$

(7)

Where,

$$C_i(P_{gi}) = a_{gi}P_{gi}^2 + b_{gi}P_{gi} + c_{gi} \$/\text{hr}$$

(8)
\[ C(P_{gx}^{IPP}) = a_{IPP}(P_{gx}^{IPP})^2 + b_{IPP}(P_{gx}^{IPP}) + c_{IPP} \text{$/hr$} (9) \]

Subject to:

Equality constraint

The power balance constraint for node \( i \) is given as,

\[ (P_g + P_{gx}^{IPP}) - (P_d + P_{dy}^{buyer}) = \sum_{j=1}^{n} |V_j||V_j| \cos(\delta_i - \delta_j - \theta_j) \] (10)

\[{Q_{gi}} - {Q_{di}} = \sum_{j=1}^{n} |V_j||V_j| \sin(\delta_i - \delta_j - \theta_j) \] (11)

\[ \sum_{i=1}^{n} P_{gi} + P_{gx}^{IPP} = \sum_{i=1}^{n} P_{di} + P_{dy}^{buyer} \] (12)

Inequality Constraints:

Real and reactive power generation limit in each generator bus is given as

\[ P_{gi}^{\text{min}} \leq P_{gi} \leq P_{gi}^{\text{max}} \] (13)

\[ Q_{gi}^{\text{min}} \leq Q_{gi} \leq Q_{gi}^{\text{max}} \] (14)

Voltage limit and line flow limit in each bus and transmission line is given as

\[ V_i^{\text{min}} \leq V_i \leq V_i^{\text{max}} \] (15)

\[ S_{ij} \leq S_{ij}^{\text{max}} \] (16)

Here,

\( g \)-Generator buses,

\( d \)-Load buses,

\( P_{gi} \)- Generated real power in bus \( i \),

\( P_{di} \)- Load power in bus \( i \),

\( P_{gx}^{IPP} \)- Power generated by IPP at bus \( x \),

\( P_{dy}^{buyer} \)- Load at buyer bus \( y \),

\( Y_{ij} \) and \( \theta_{ij} \) - magnitude and angle of bus admittance matrix,

\( V_i \)- Voltage in bus \( i \),

\( V_i^{\text{min}} \) and \( V_i^{\text{max}} \)- minimum and maximum voltage at bus \( i \),

\( S_{ij} \)- Power flow in transmission line \( i-j \),

\( S_{ij}^{\text{max}} \)- Maximum allowable transmission line \( i-j \).
4 RESULTS WITH DISCUSSION

The formulated methodology is studied on a IEEE-30 bus [23, 24] and 69 bus - Indian utility system [25]. The simulation study is carried out for the systems in its base case. When an IPP is interested in providing additional load for buyer bus, the systems are slightly modified to perform bilateral and multilateral transaction. Optimal generation capacity is identified for the modified system by using SPSO, CGI-PSO and PSO-TVAC.

In IEEE 30 bus system, an IPP with a generation capacity of 35 MW is connected for bilateral transaction at bus number 24 and 45MW is connected for multilateral transaction at bus number 6. In Indian utility 69 bus system, an IPP with a generation capacity of 890 MW is connected for bilateral transaction at bus number 20 and 950MW is connected for multilateral transaction at bus number 65. The size of particles is selected by varying it from 10 to 100 in steps of 10. Finally, the best particle size is found to be 100. The optimal solution is obtained from 20 trial runs.

4.1 Method 1: Load curtailment for congestion management

4.1.1 IEEE 30 bus system

The IEEE 30 bus transmission system is selected to simulate the proposed methodology. The generator buses are located at 2, 5, 8, 11 and 13 buses.

The modified system for bilateral and multilateral transaction with connected IPP consists of 7 generators and 23 PQ buses with 41 transmission lines. The customers with the lowest offer price of 20 $/MWh and with the highest offer price of 25 $/MWh is preferred for load curtailment. The identified interruptible load contract to clear congestion in both bilateral and multilateral transaction is given in Table 1.

The customer at bus 12 (L-12) with the minimum offer price of 20 $/MWh and at bus 23 (L-23) with maximum offer price of 25 $/MWh is selected from Table.1 for bilateral transaction. For multilateral transaction the load curtailment is performed by reducing 10MW in bus 29 (L-29) and bus 30 (L-30) with incrementing the same in bus 7 (L-7) and bus 9 (L-9). In both transactions power interruption completely gets reduced to zero.

Table 1: Load curtailment in modified IEEE 30 bus system with transactions

| Parameters                  | Bilateral Transaction | Multilateral Transaction |
|-----------------------------|-----------------------|--------------------------|
| Customer location           | 9                     | 22                       | 28                       |
| Congested lines             | 24-25                 | 6-28                     |
| Line limit (MVA)            | 16                    | 32                       |
| Active power flow (MW)      | 16.5862               | 40.7571                  |
| NLCdec(Bus no)              | 12                    | 29                       | 30                       |
| $\Delta P_{i1}$ (MW)        | -9.13                 | -9                       | -1                       |
| NLCinc(Bus no)              | 23                    | 7                        | 9                        |
| $\Delta P_{i2}$ (MW)        | +9.13                 | +7                       | +3                       |
| Power Interruption, PI      | 0                     | 0                        |

4.1.2 69 bus - Indian utility system

The 69 bus - Indian utility system data is taken for a region in southern part of India [22]. The selected system comprises of 1 slack bus, 13 generator bus and 56 load buses. The modified system for
bilateral and multilateral transaction with connected IPP consists of 14 generators and 55 PQ buses with 99 transmission lines.

The customers with the lowest offer price of 20 $/MWh and with the highest offer price of 25 $/MWh is preferred for load curtailment. The customer at bus 26 (L-26) with the minimum offer price of 20 $/MWh and at bus 51 (L-51) with maximum offer price of 25 $/MWh is selected from Table 3 for bilateral transaction. The identified interruptible load contract to clear congestion in both bilateral and multilateral transaction is shown in Table 2. The load curtailment is performed in bus 26 (L-26) and bus 51 (L-51) by reducing 84.102 MW in bus 26 (L-26) and incrementing the same in bus 51 (L-51) to remove congestion. For multilateral transaction the load curtailment is performed by reducing 33 MW in bus 5 (L-5) with incrementing the same in bus 28 (L-28), bus 68 (L-68) and bus 69 (L-69).

**Table 2: Details of load curtailment in modified Indian utility 69 bus system with transactions**

| Parameters          | Bilateral Transaction | Multilateral Transaction |
|---------------------|-----------------------|--------------------------|
| Customer location   | 4                     | 4                        | 67                       |
| Congested lines     | 20-22                 | 1-5                      |
| Line limit (MVA)    | 150                   | 90                       |
| Active power flow (MW) | 151.285             | 93.096                   |
| $P_{\Delta}$ dec (Bus no) | 26                | 5                        |
| $P_{\Delta}$ inc (Bus no) | 51               | 28, 68, 69              |
| Power Interruption, PI | 0                   | 0                        |

4.2  Method 2: Generation rescheduling for congestion management

The severity of congestion is reduced by active power rescheduling with load curtailment using proposed optimization techniques. The influence of the SPSO, CGI-PSO and PSO-TVAC is studied.

4.2.1 IEEE 30 bus system

The selected customer location for bilateral transaction is at bus number 9 (L-9) and for multilateral transaction at bus number 22 (L-22), 28 (L-28). The congested power flow in transmission lines for both bilateral and multilateral transaction is compared with different algorithms and the results are tabulated in Table 3. The result indicates that the amount of power congested using PSO-TVAC is 0.125 MW in bilateral transaction and its 7.2557 MW in multilateral transaction, which is very much reduced than that of SPSO and CGI-PSO method in both transactions. It also provides the comparisons between different techniques in bilateral and multilateral transactions for load curtailment.

As the congested power is reduced by using PSO-TVAC method, the quantity of power curtailment in PSO-TVAC is also reduced than that of CGI-PSO and SPSO. The results clearly show that the PSO-TVAC method is preferred over CGI-PSO and SPSO to clear the congestion by active power rescheduling and load curtailment.
Table 3: Comparison of interruptible load contract for modified IEEE 30 bus system after rescheduling

| Parameter                  | Bilateral       | Multilateral   |
|----------------------------|-----------------|----------------|
| Technique                  | SPSO            | CGI-PSO        | PSO-TVAC       | SPSO            | CGI-PSO        | PSO-TVAC       |
| Congested lines            | 24-25           | 24-25          | 24-25          | 6-28            | 6-28           | 6-28           |
| Line limit (MVA)           | 16              | 16             | 16             | 32              | 32             | 32             |
| Active power flow (MW)     | 16.193          | 16.183         | 16.125         | 39.9319         | 39.7861        | 39.2557        |
| NLC_{dec}(Bus no)          | 30              | 30             | 30             | 30              | 30             | 30             |
| \Delta P_i (MW)            | -1.2            | -1.1           | -0.6           | -8.7            | -8.6           | -8.5           |
| NLC_{inc}(Bus no)          | 23              | 23             | 23             | 7               | 7              | 7              |
| \Delta P_i (MW)            | +1.2            | +1.1           | +0.6           | +8.7            | +8.6           | +8.5           |
| Power Interruption, PI     | 0               | 0              | 0              | 0               | 0              | 0              |

4.2.2 69 bus - Indian utility system

The selected customer location for bilateral transaction is at bus number 4 (L-4) and for multilateral transaction at bus number 4 (L-4) and bus number 67 (L-67).

Table 4: Comparison of interruptible load contract for modified Indian utility 69 bus system after rescheduling

| Parameter                  | Bilateral       | Multilateral   |
|----------------------------|-----------------|----------------|
| Technique                  | SPSO            | CGI-PSO        | PSO-TVAC       | SPSO            | CGI-PSO        | PSO-TVAC       |
| Congested lines            | 20-22           | 20-22          | 20-22          | 1-5             | 1-5           | 1-5           |
| Line limit (MVA)           | 150             | 150            | 150            | 90              | 90            | 90            |
| Active power flow (MW)     | 151.121         | 151.086        | 150.997        | 92.612          | 92.601        | 92.168         |
| NLC_{dec}(Bus no)          | 7               | 22             | 22             | 5               | 5             | 5             |
| \Delta P_i (MW)            | -20             | -7             | -6.5           | -28             | -27.7         | -24           |
| NLC_{inc}(Bus no)          | 3               | 3              | 3              | 68              | 68            | 68            |
| \Delta P_i (MW)            | +15             | +7             | +6.5           | +28             | +27.7         | +24           |
| Power Interruption, PI     | 0               | 0              | 0              | 0               | 0             | 0             |

The congested power flow in transmission lines for both bilateral and multilateral transaction is compared with different algorithms and the results are tabulated in Table 4. The result indicates that the amount of power congested using PSO-TVAC is 0.997 MW in bilateral transaction and its 2.168 MW in multilateral transaction, which is very much reduced than that of SPSO and CGI-PSO method in both transactions. As the congested power is reduced by using PSO-TVAC method, the quantity of power
curtailment in PSO-TVAC is also reduced than that of CGI-PSO and SPSO. The results clearly show that the PSO-TVAC method is preferred over CGI-PSO and SPSO to clear the congestion by generator rescheduling and load curtailment.

Fig. 2 shows the plot of both transactions with the quantity of power curtailment to relieve the congestion for both methods. It is evident from the plot that the quantity of power curtailment is reduced drastically from method 1 to method 2.

![Fig. 2 Quantity of load curtailment for Indian utility 69 bus system](image)

5 CONCLUSION

The proposed method successfully relieves the congestion in bilateral and multilateral transaction with the connected IPP. From the results obtained, it is evident that the severity of congestion is very much reduced by performing generation rescheduling with load curtailment using optimization techniques. It is also proven that the proposed PSO-TVAC technique has improved the performance in reducing the severity of congestion than that of SPSO and CGI-PSO technique. The results obtained in IEEE 30 bus and verified through 69 bus - Indian utility system are found to be free from complex mathematical formulation. The simulated results conclude that the formulated methodology performs as an active tool for congestion management in different transactions.

ACKNOWLEDGEMENT

The authors sincerely acknowledge the support provided by their respective college management and principal for successful completion of this research work.

REFERENCES

1. RD Christie, BF Wollenberg, I Wangensteen, “Transmission Management in the Deregulated Environment”, IEEE transactions on Power Systems, 88(2), pp.170-195, 2000.
2. A Kumar, SC Srivastava, SN Singh, “Congestion Management in Competitive Power Market: A bibliographical survey”, Electric Power Systems Research, 76, pp.153-164, 2005.
3. KL Lo, YS Yuen, LA Snider, “Congestion Management in Deregulated Electricity Markets”, International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, London, UK, pp. 47-52, 2000.
4. H Singh, S Hao, A Papalexopoulos, “Transmission Congestion Management in competitive Electricity Market”, IEEE transactions on Power Systems, 13(2), pp. 672-680, 1998.
5. HY Yamina, SM Shahidepour, “Congestion management coordination in the deregulated power market”, Electric Power Systems Research, 65(2), pp. 119-127, 2003.

6. SC Srivastava, P Kumar, “Optimal Power Dispatch in Deregulated Market considering Congestion Management”, International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, London, UK, pp.53-59, 2000.

7. D Shirmohammadi, B Wollenberg, A Vojdani, P Sandrin, M Pereira, F Rahimi, T Schneider, B Stott, “Transmission Dispatch and Congestion Management in the Emerging Energy Market Structure”, IEEE transactions on Power Systems, 13(4), pp.1466-1474, 1998.

8. ZX Chen, LZ Zhang, J Shu, “Congestion management based on particle swarm optimization”, International Power Engineering Conference, Singapore, pp. 1019-1023, 2005.

9. S Dutta, SP Singh, “Optimal rescheduling of generators for congestion management based on particle swarm optimization”, IEEE transaction on power systems, 23(4), pp.1560-1569, 2008.

10. P Boonyaritdachochai, C Boonchuay, W Ongsakul, “Optimal congestion management in an electricity market using particle swarm optimization with time-varying acceleration coefficients”, Computers and Mathematics with Applications, 60(4), pp. 1068-1077, 2010.

11. LS Coelho, CS Lee, “Solving economic load dispatch problems in power systems using chaotic and Gaussian particle swarm optimization approaches”, Electrical power and energy systems, 30(5), pp. 297-307, 2008.

12. Manojkumar P, Veena P and Jayabharath R, “Sustainable development of universal electronic control unit for fuel saving in automobiles to protect the environment pollution”, J electr. Eng., 2019, 19.

13. H Wang, C Li, Y Liu, S Zeng, “A hybrid particle swarm algorithm with Cauchy mutation”, IEEE Swarm Intelligence Symposium, Honolulu, HI, pp. 356-360, 2007.

14. T Niimura, S Niioka, R Yokoyama, “Transmission Loading relief solution for congestion management”, Electrical Power Systems Research, 67(2), pp. 73-78, 2003.

15. Dheepanchakkravarthy, A., Jawahar, M.R., Venkatraman, K., Selvan, M.P. and Moorthi, S "Performance evaluation of FPGA-based predictive current controller for FLDSTATCOM in electric distribution system”, IET Generation, Transmission and Distribution ,13(19), pp. 4400 – 4409, 2019.

16. T Niimura, Y Niu, “Transmission Congestion Relief by Economic Load Management”, IEEE Power Engineering Society Summer Meeting, Chicago, IL, USA, pp. 1645-1649, 2002.

17. R Mendez, H Rudnick, “Congestion Management and Transmission Rights in Centralized Electric Markets”, IEEE Transactions on Power Systems, 19(2), pp.889-896, 2004.

18. HY Yamina, SM Shahidepour, “Congestion management coordination in the deregulated power market”, Electric Power Systems Research, 65(2), pp. 119-127, 2003.

19. DP Manjure, EB Makram, “Optimal load curtailment as a bi-criteria program”, Electric Power Systems Research, 66(2), pp. 155-161, 2003.

20. LA Tuan, K Bhattacharya, J Daalder, “Transmission Congestion Management in bilateral markets: An interruptible load auction solution”, Electric Power Systems Research, 74(3), pp.379-389, 2005.

21. J Kennedy, R Eberhart “Particle swarm optimization”, International Conference on Neural Networks, Perth, WA, Australia, pp. 1942-1948, 1995.

22. M Mandala, CP Gupta, “Congestion management under Hybrid Electricity Market using Self-organizing Hierarchical Particle Swarm Optimization”, International Journal of Computer Applications, 82(17), pp.39-45, 2013.
23. B Divya, R Devarapalli, "Estimation of sensitive node for IEEE-30 bus system by load variation," International Conference on Green Computing Communication and Electrical Engineering, Coimbatore, pp. 1-4, 2014.
24. Report from University of Washington.
25. Tamil Nadu Electricity Board (TNEB), “Tamil Nadu Electricity Board Statistics at a Glance 2003–2004”, 2004.