Congestion Relief of Contingent Power Network with Evolutionary Optimization Algorithm

Sandip Chanda¹, Abhinandan De²
¹Department of Electrical Engineering Techno India, Salt Lake, India
²Department of Electrical Engineering BESU Shibpur, India
e-mail: ¹sandipee1978@gmail.com, ²abhinandan.de@gmail.com

Abstract

This paper presents a differential evolution optimization technique based methodology for congestion management cost optimization of contingent power networks. In Deregulated systems, line congestion apart from causing stability problems can increase the cost of electricity. Restraining line flow to a particular level of congestion is quite imperative from stability as well as economy point of view. Employing ‘Congestion Sensitivity Index’ proposed in this paper, the algorithm proposed can be adopted for selecting the congested lines in a power networks and then to search for a congestion constrained optimal generation schedule at the cost of a minimum ‘congestion management charge’ without any load curtailment and installation of FACTS devices. It has been depicted that the methodology on application can provide better operating conditions in terms of improvement of bus voltage and loss profile of the system. The efficiency of the proposed methodology has been tested on an IEEE 30 bus benchmark system and the results look promising.

Keywords: congestion sensitivity index, contingent power networks, optimization, differential evolution, rescheduling

1. Introduction

Due to restructuring and deregulation, the electric utility industries are undergoing rapid changes and are being pushed to operate at optimum stress condition. Thus in a deregulated electricity market transmission line congestion has become almost inevitable where insufficient transmission capacity lines have to accommodate for all the requests of transmission service within the region, specially during contingencies like transmission line or generator outage. Line congestion of this kind may in effect be able to lead for cascading failures of the system [1]. Hence congestion management is a challenging task for independent System Operator (ISO) for maintaining stability, security and reliability. An ISO may adopt different congestion management methods proposed by researchers over the years. Methods depicted in [2]-[7] adopted loss optimization, generation rescheduling or reactive power redispatching to reduce the congestion but could not sustain a specified level of maximum line flow. Penalty based
Security constrained optimal power flow (SCOPFs) have been proposed in [8] and [9] where rescheduling cost have been minimized without ascertaining maximum allowable line flow or level of congestion. Moreover, the penalty method applied has to trace and calculate penalties for all the lines, therefore time complexity of the algorithms may be high with respect to the domain of application. [10] And [11] proposed voltage stability constrained Optimal Power Flow (OPF) to alleviate congestion, but the proposed generation schedule could not maintain a particular level of congestion during contingencies. Apart from rescheduling of generation, the line congestion can also be managed by employing FACTs devices and HVDC as cited in [12] - [13]. But the excess cost associated with these devices may prohibit their use in many existing systems. In [14]- [16] load curtailment based congestion management has been proposed, but the value of lost load (VOLL) may restrict its practical implementation Dynamic control of congestion as reported in [17] may be too expensive and also require precise monitoring.

In view of all these works, this paper presents an OPF solution, which attempts to reschedule the generators in such a way that the individual line flows are brought down to a desired level, not exceeding their loadability limits. The effectiveness of the proposed algorithm has been demonstrated on the modified IEEE 30 bus system under contingencies. The results indicate that the method proposed in this paper is efficient in limiting line congestion without any load curtailment and installation of FACTS devices. The proposed method also provides better management of operating conditions of the system.

2. Theory

To establish the applicability of the proposed algorithm in the present power market scenario, two more conventional optimization methods namely Cost Optimization and Loss Optimization have been considered.

2.1. Problem Statement

Objective function for conventional cost optimization:

\[ \text{minimize } F = \sum_{n=1}^{N_g} C_T \times $/Hr \]

\[ C_T = A P_{gi}^2 + B P_{gi} + C \]

Where, \( N_g \) = Number of generators; \( A, B, C \) = Cost Co-efficients of generators; \( P_{gi} \) = generation of \( i^{th} \) generator in MW

Objective function for loss Optimisation method:

\[ \text{Minimize } F = V_i \sum_{j=1}^{n} V_j \left( G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \right) \]

Where, \( V_i \) - voltage magnitude of the bus \( i \), \( V_j \) = voltage magnitude of the bus \( j \), \( G_{ij} \) - Conductance of transmission line from bus \( i \) to \( j \), \( B_{ij} \) - Susceptance of transmission line from bus \( i \) to \( j \); \( n \) - no of buses

Objective function for the proposed penalty based congestion management cost optimization:

\[ \text{Minimize } F = \sum_{n=1}^{N_g} \left( C_T + C_p \Delta P_{l_{\text{max}}} \right) - \sum_{n=1}^{N_g} C_T \]

Here, \( C_T \) = generation cost with congestion management; \( C_p \) = penalty for congestion limit violation; \( \Delta P_{l_{\text{max}}} \) = Maximum Line flow – Maximum Limit Of line flow
The constraints are common for all the above objective functions and are as follows:

1. Equality or power balance constraints:

\[ P_{Gi} - P_{Di} - V \sum_{j=1}^{n} V_j (G_j \cos \theta_j + B_j \sin \theta_j) = 0 \]  
\[ Q_{Gi} - Q_{Di} - V \sum_{j=1}^{n} V_j (G_j \sin \theta_j - B_j \cos \theta_j) = 0 \]  

\( P_{Gi} \) - Active power injected in bus \( i \); \( P_{Di} \) - Active power demand on bus \( i \); \( Q_{Gi} \) - Reactive power injected in bus \( i \); \( Q_{Di} \) - Reactive power demand on bus \( i \)

2. Inequality or generator output constraints:

\[ P_{Gi}^\text{min} \leq P_{Gi} \leq P_{Gi}^\text{max} \]  
\[ Q_{Gi}^\text{min} \leq Q_{Gi} \leq Q_{Gi}^\text{max} \]  

\( P_{Gi}^\text{min}, Q_{Gi}^\text{min} \) - Lower limit of active and reactive power of generator \( i \) respectively; \( P_{Gi}^\text{max}, Q_{Gi}^\text{max} \) - upper limit of active and reactive power of the generators

3. Voltage constraint:

\[ V_i^\text{min} \leq V_i \leq V_i^\text{max} \]  
\( V_i^\text{min}, V_i^\text{max} \) are lower and upper limit of \( V_i \)

4. Transmission constraint:

\[ P_{ij}^\text{min} \leq P_{ij} \leq P_{ij}^\text{max} \]  
\( P_{ij}^\text{min}, P_{ij}^\text{max} \) are the minimum and maximum line flow limits of \( P_{ij} \)

2.2. The Congestion Sensitivity Index

For the selection of proper congestion zone, a line flow sensitivity index has been proposed in this paper and the Congestion Sensitivity index has been formulated as below

\[ \text{Sensitivity index} = \frac{\Delta P_{i-j}}{\Delta P_i} \]  

(\( \Delta P_{i-j} \) represents the difference in line flow in MW of the line between bus ‘\( i \)’ and bus ‘\( j \)’ before and after tripping another line connected to bus ‘\( i \)’ and \( \Delta P_i \) represents the difference in power between total power injected to bus ‘\( i \)’ and the power flow in line ‘\( i-j \)’ after tripping another line connected to bus ‘\( i \)’). The values of sensitivity indices are arranged in descending order for the most congested lines of IEEE 30 bus system as shown Table 1.

2.3. Overview of Differential Evolution

As the Objective function with the constraints is highly nonlinear as described in section 2.1, it utilizes Differential evolution (DE) for its stochastic, nondervative based search method to obtain a global solution without premature convergence [18]. DE solves real valued problems based on the principles of natural evolution using a population \( P \) of \( N_p \) floating point-encoded individuals that evolve over \( G \) generations to reach an optimal solution.

\[ P = \{ Y^g_{1}, \ldots, Y^g_{N_p} \} \]  
\[ Y^g_{i} = \{ X^g_{i_1}, X^g_{i_2}, \ldots, X^g_{i_D} \} \]
Table 1. Ranking of lines in terms of congestion sensitivity indices

| Lines tripped  | Congestion Sensitivity Index |
|---------------|-----------------------------|
| 10-21         | 33.9469                     |
| 1-2           | 33.2681                     |
| 27-30         | 18.5378                     |
| 27-29         | 16.1798                     |
| 4-6           | 15.4039                     |
| 10-22         | 11.1308                     |
| 1-3           | 03.5545                     |
| 12-14         | 02.5550                     |
| 2-4           | 01.1500                     |
| 10-17         | 01.0890                     |
| 2-5           | 0.42000                     |
| 9-11          | 0.00016                     |

where \( i = 1, 2, \ldots, N_p \)

### 2.3.1. Initialization

The first step in the DE optimization process is to create an initial population of candidate solutions by assigning random values to each decision parameter of each individual of the population. Such values must lie inside the feasible bounds of the decision variable and can be generated by Eq. (2).

\[
Y_{i,j}^m = Y_{j_{\min}} + \eta_j \left( Y_{j_{\max}} - Y_{j_{\min}} \right)
\]

where, \( i = 1, 2, \ldots, N_p \) and \( j = 1, 2, \ldots, D \)

And, \( Y_{j_{\min}} \) and \( Y_{j_{\max}} \) are respectively, the lower and upper bound of the \( j^{th} \) decision parameter and \( \eta_j \) is a uniformly distributed random number within \([0, 1]\) generated anew for each value of \( j \).

### 2.3.2. Mutation

The mutation operator creates mutant vectors by perturbing a randomly selected vector \( Y_a \) with the difference of two other randomly selected vectors \( Y_b \) and \( Y_c \) according Eq. (15).

\[
Y_{i,j}^G = Y_{i,j}^m + \left( Y_{i,j}^m - Y_{i,j}^m \right)
\]

where, \( i = 1, 2, \ldots, N_p \) where, \( Y_a, Y_b, Y_c \) are randomly chosen vectors \( \{1, 2, \ldots, N_p\} \) and \( a \neq b \neq c \neq i \) is the scaling constant. For certain problems, it is considered \( a = i \).

### 2.3.3. Crossover

The crossover operator creates the trial vectors, which are used in the selection process. The crossover operation maintains diversity in the population, preventing local minima convergence. The crossover constant \( c_r \) must be in the range of \([0, 1]\).

\[
X_{i,j}^G = \begin{cases} X_{i,j}^m & \text{if } \eta_j \leq c_r \text{ or } j = q \\ X_{i,j}^m & \text{Otherwise} \end{cases}
\]

where \( i = 1, 2, \ldots, N_p \) and \( j = 1, 2, \ldots, D \)

\( q \) is a randomly chosen index \( \in \{1, 2, \ldots, D\} \) that guarantees that the trial vector gets at least one parameter from the mutant vector. \( \eta_j \) is a uniformly distributed random number within \([0, 1]\) generated a new for each value of \( j \). Here \( X_{i,j}^m \) is the parent (target) vector, \( X_{i,j}^G \) is the mutant vector and \( X_{i,j}^{G} \) is the trial vector.
2.3.4. Selection

The selection operator chooses the vectors that are going to compose the population in the next generation. This operator compares the fitness of the trial vector and fitness of the corresponding target vector, and selects the one that performs better as mentioned in Eq. (5).

\[
Y_{i+1}^{G} = Y_i^{G} \text{if } f(Y_{i+1}^{G}) \leq f(Y_i^{G})
\]

\[
= Y_i^{G} \text{ otherwise}
\]

The selection process is repeated for each pair of target/trial vector until the population for the next generation is complete.

3. Simulation and Results

The feasibility and effectiveness of the proposed algorithm has been demonstrated in the modified IEEE 30 bus system shown in Figure 1. A summarised description of the adopted system is given in Table 2 and 3a. The proposed optimization algorithm (formulated in equation number 4) has been adopted for the developed methodology implementation in differential evolution environment (the parameter setting is given in Table 3b). The flow chart of the developed methodology has been depicted in Figure 2.

- Table 2. Description of IEEE 30 bus system

| Variables          | Adopted system |
|--------------------|----------------|
| Branches           | 41             |
| Generators         | 6              |
| Total Demand (MW)  | 283.6          |

- Table 3a. Cost co-efficients of generators

| Bus no | Max (MW) | Min (MW) | Cost Co-efficient A (US$/MW²) | Cost Co-efficient B (US$/MW) | Cost Co-efficient C (US$) |
|--------|----------|----------|-------------------------------|------------------------------|--------------------------|
| 1      | 50       | 200      | 0.00375                       | 2.00                         | 5000                     |
| 2      | 20       | 80       | 0.01750                       | 1.75                         | 1000                     |
| 5      | 15       | 50       | 0.06250                       | 1.00                         | 600                      |
| 8      | 10       | 35       | 0.00834                       | 3.25                         | 300                      |
| 11     | 10       | 30       | 0.02500                       | 3.00                         | 350                      |
| 13     | 12       | 40       | 0.02500                       | 3.00                         | 400                      |

- Table 3b. Parameter setting of differential evolution

| Optimisation Parameter                  | Adopted setting |
|----------------------------------------|-----------------|
| Value to Reach (VTR)                   | 10              |
| Number Of Population (NP)              | 20              |
| Maximum Number Of Iterations (Itermax) | 500             |
| DE Stepsize, Crossover Probability Constant | 0.8           |

3.1. Determination of line flow limit

It is evident from the ranking Table 1, the outage of the transmission lines having high congestion sensitivity index, the flow limit of the other lines may exceed the thermal limit and may initiate cascading failure. Thus the maximum level of congestion has to be limited and violation of which may motivate ISO to reschedule the generators for safe operation of the power system.
Though the proposed algorithm is capable of limiting the line flow at any arbitrary value, in the present work, the line flow limit has been assumed to be 50% of the SIL. Table 4, 5 and 6 presents the contribution of generators with the two conventional and the proposed congestion management cost optimization technique during contingency. The contingent state have however been selected from the contingency ranking Table 4.

Table 4. Contribution of generators during contingency with conventional cost optimisation

| Lines tripped   | P1 (MW/hr) | P2 (MW/hr) | P3 (MW/hr) | P4 (MW/hr) | P5 (MW/hr) | P6 (MW/hr) |
|----------------|------------|------------|------------|------------|------------|------------|
| 10-21          | 16.61      | 28.30      | 98.51      | 37.89      | 68.69      | 35.71      |
| 1-2            | 7.06       | 37.16      | 98.38      | 36.35      | 72.09      | 34.08      |
| 27-30          | 16.62      | 28.24      | 98.47      | 37.34      | 71.24      | 33.89      |
| 10-21 and 1-2  | 7.15       | 37.46      | 98.49      | 37.55      | 69.21      | 35.64      |
| 4-6 and 27-30  | 15.56      | 26.44      | 99.30      | 38.82      | 67.91      | 37.66      |
| 4-6 and 10-22  | 15.46      | 26.28      | 99.25      | 38.46      | 67.47      | 38.39      |

Table 5. Contribution of generators during contingency with conventional power loss optimisation method

| Lines tripped   | P1 (MW/hr) | P2 (MW/hr) | P3 (MW/hr) | P4 (MW/hr) | P5 (MW/hr) | P6 (MW/hr) |
|----------------|------------|------------|------------|------------|------------|------------|
| 10-21          | 171.26     | 48.95      | 21.51      | 21.95      | 12.14      | 11.33      |
| 1-2            | 151.18     | 59.20      | 24.05      | 33.95      | 16.38      | 14.89      |
| 27-30          | 177.31     | 48.97      | 21.51      | 21.99      | 12.19      | 11.28      |
| 10-21 and 1-2  | 151.31     | 59.25      | 24.07      | 34.06      | 16.36      | 14.98      |
| 4-6 and 27-30  | 174.11     | 48.68      | 21.69      | 26.23      | 13.36      | 10.17      |
| 4-6 and 10-22  | 173.95     | 48.64      | 21.67      | 26.08      | 13.31      | 10.16      |
Table 6. Individual contribution of generators during contingency with proposed method

| Lines tripped | P1(MW/hr) | P2(MW/hr) | P3(MW/hr) | P4(MW/hr) | P5(MW/hr) | P6(MW/hr) |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 10-21        | 112.59    | 68.27     | 26.01     | 44.82     | 19.88     | 18.06     |
| 1-2          | 71.71     | 74.07     | 28.06     | 63.34     | 26.23     | 25.90     |
| 27-30        | 112.65    | 68.53     | 26.00     | 44.52     | 19.96     | 18.11     |
| 10-21 and 1-2| 71.72     | 73.54     | 28.39     | 64.21     | 26.22     | 25.59     |
| 4-6 and 27-30| 101.94    | 68.12     | 26.08     | 54.80     | 21.96     | 16.76     |
| 4-6 and 10-22| 101.61    | 67.08     | 26.48     | 54.87     | 20.76     | 18.41     |

Figure 3. Generation cost maximum line flow with conventional and proposed method

Figure 4. Bus voltage profile and congestion management cost

3.2. Operational Issues
Apart from congestion management, for the effective implementation of the proposed algorithm, some operational issues are needed to be considered.

3.2.1. Reduction in total generation cost and line congestion with the proposed algorithm
The proposed algorithm aims to minimize congestion management cost hence the total generation cost may get higher than the conventional cost optimization technique. But the most promising part of this algorithm is that it can offer lower generation cost with respect to loss optimization technique as shown in Figure 3. In addition, as shown in the same figure the algorithm is capable of limiting line congestion. It can be noted that the loss optimization method offers lesser line flow or congestion but considering the total generation cost the proposed method must be preferred ahead of this method for congestion management.

3.2.2. Improvement in Voltage Profile with reduced congestion management charge
Another important feature of the proposed algorithms is the improvement in voltage profiles. Figure 4 shows the comparison of voltage profiles in the three different methods. Improvement in voltage profile suggests an improvement in power transfer capability of the lines. Apart from improving the voltage profile, the algorithm offers a net saving in congestion management charge, defined as the difference between the total generation cost with congestion relief and without any congestion relief. ISO can recover these charges from the market participants according to their involvement in generating congestion. Figure 6 shows a
comparison between loss optimization technique and the proposed algorithm in respect of congestion management charge.

4. Conclusion

A DE based methodology has been proposed in this paper for congestion management in a contingent state of the system at an optimum cost of management but without any load curtailment or FACTS device installation. In the proposed method, on violation of a specified line flow, an additional penalty has been added to the objective function to direct the DE based search process to the most feasible optimal solution considering the constraints. Bus voltage profile has improved with respect to the conventional and loss optimization algorithms. The proposed method has been demonstrated to cause a reduction in congestion management cost which may appear as social welfare in deregulated power networks. The IEEE30 bus system is analyzed to establish the technique. The results show that the proposed algorithm develops a cost effective congestion management technique in a restructured contingent power system which can be used effectively used by ISO.

References

[1] K Selvi, T Meena, N Ramaraj. A generation Rescheduling Method to Alleviate Line Overloads using PSO. IE (I) Journal-EL. 2005.
[2] Yu Xiaodan, Jia Hongjie, Zhao Jing, Wei Wei, Li Yan, Zeng Yuan. Interface Control Based on Power Flow Tracing and Generator Re-redispatching. Automation of Electric Power Systems IEEE, 2008.
[3] G Baskar, MR Mohan. Contingency constrained economic load dispatch using improved particle swarm optimization for security enhancement. Electric Power System Research Elsevier, 2008.
[4] E Muneender, MD Vinod Kumar. Optimal Rescheduling of real and reactive powers of generators for zonal Congestion Management Based on FDR PSO. IEEE T&D Asia. 2009.
[5] Sujatha Balaraman, K Kamaraj. Congestion management in Deregulated power system using real coded genetic algorithm. International Journal of Engineering Science and Technology. 2010; 2(11): 6681-6690.
[6] Sujatha Balaraman, K Kamaraj. Application of Differential Evolution for Congestion management in power system. Modern Applied Science. 2010; 4(8).
[7] Zhao Jinli, Jia Hongjie, Yu Xiaodan. Voltage Stability Control Based on real power flow tracing. Proceedings of CSEE, IEEE. 2009.
[8] Xiaosong Zou, Xianjue Luo, Zhiwei Peng. Congestion Management Ensuring Voltage Stability under Multicontingency with preventive and Corrective Controls. IEEE. 2009.
[9] Hwa-Sik Choi, Seung II Moon. A new Operation of series compensating device under Line Flow Congestion using the Linearized Line Flow sensitivity. Power Engineering Society winter meeting IEEE. 2001.
[10] EM Yap, M Al-Dabbagh, PC Thum. UPFC Controller in Mitigating Line Congestion for Cost-Efficient Power Delivery. Power Engineering Conference IPEC, IEEE. 2006.
[11] Xiao-Ping Zhang, Liangzhong Yao. A Vision of Electricity network Congestion Management with FACTS and HVDC. DRPT2008. Nanjing China. 2008.
[12] Garg M Huang, Nirman Kumar, C Nair. An OPF based Algorithm to Evaluate Load Curtailment Incorporating Voltage Stability Margin Criteria. Power Engineering Society Winter Meeting, IEEE. 2002.
[13] Fei HE, Yihong WANG, Ka Wing CHAN, Yutong ZHANG, Shengwei MEI. Optimal Load Shedding Strategy Based on Particle Swarm Optimisation. 8th international conference on Advances in Power System Control operation and Management (APSCOM), 2009.
[14] RN Nayak, YK Sehgal, Subir Sen. EHV Transmission Line Capacity Enhancement through Increase in Surge Impedance Loading Level. Power India Conference. 2006.
[15] KP Basu. Power transfer Capability of Transmission Line Limited by voltage Stability: Simple Analytical Expressions. IEEE Power Engineering Review. 2000
[16] J Ma, YH Song, Q Lu, S Mei. Framework for dynamic congestion Management in open power markets. IEEE Proc.Gener.Transm. Distrib. 2002; 149(2).
[17] K Vaisakhi, LR Srinivas. Differential evolution approach for optimal power flow solution. Journal of theoretical and applied information technology. 2005-2008.