Congestion Relief of Contingent Power Network with Evolutionary Optimization Algorithm

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Abstrak

   Makalah ini menyajikan teknik optimasi evolusi diferensial sebagai sebuah metode untuk menyelesaikan masalah optimalisasi biaya manajemen kongesti dalam kontigensi jaringan. Dalam sistem yang terderegulasi, kongesti jalur transmisi selain merupakan penyebab masalah ketidakstabilan listrik juga dapat menambah biaya kelistrikan. Mempertahankan ketersediaan aliran daya pada tingkat kongesti tertentu adalah cukup penting jika ditinjau dari sudut pandang stabilitas sistem kelistrikan maupun ekonomi. Dengan menerapkan indeks kepekaan kongesti yang diusulkan dalam tulisan ini, algoritma yang dirancang dapat digunakan untuk memilih jalur yang terkongesti dalam jaringan listrik, kemudian digunakan untuk mencari batas batas kongesti yang selanjutnya digunakan menjadwalkan ulang pembangkitan dengan biaya minimum dalam suatu pembiayaan manajemen kongesti tanpa adanya pemutusan beban maupun penambahan pemasangan peralatan jaringan listrik yang fleksible (FACTS). Pada makalah ini terlihat bahwa metode yang diterapkan dapat memberikan kondisi pengoperasian listrik yang lebih baik dengan memperbaiki tegangan bus dan rugi rugi jaringan. Efisiensi dari metode yang diusulkan telah diujicobakan pada sistem IEEE 30 bus dengan hasil yang baik.

Kata kunci: evolisi differensial, indeks kepekaan kongesti, kontingensi jaringan listrik, optimasi, penjadwalan ulang.

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, diffrential 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 alleiavate 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:

$$\text{minimize F} = \sum_{n=1}^{Ng} C_T \quad \text{\$/Hr} \tag{1}$$

$$C_T = AP_{gi}^2 + BP_{gi} + C \tag{2}$$

Where, Ng =Number of generators; A , B , C = Cost Co-efficients of generators; P_{gi} = generation of ith generator in MW

Objective function for loss Optimisation method:

$$\text{Minimize} \quad F = V_i \sum_{j=1}^{n} V_j (G_{ij} Cos\theta_{ij} + B_{ij} Sin\theta_{ij} \tag{3}$$

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:

$$\text{Minimize} \quad F = \sum_{n=1}^{Ng} (C_T + C_p . \Delta P_{l\max}) - \sum_{n=1}^{Ng} C_T \tag{4}$$

Here, C_T =generation cost with congestion management; C_p =penalty for congestion limit violation; $\Delta P_{l\max}$ =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:

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{n} V_j (G_{ij} Cos\theta_{ij} + B_{ij} Sin\theta_{ij}) = 0 \tag{5}$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{n} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) = 0 \tag{6}$$

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:

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max} \tag{7}$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max} \tag{8}$$

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

3. Voltage constraint:

$$V_i^{\min} \leq V_i \leq V_i^{\max} \tag{9}$$

$V_i^{\min}, V_i^{\max}$ are lower and upper limit of V_i

4. Transmission constraint:

$$P_{ij\min} \leq P_{ij} \leq P_{ij\max} \tag{10}$$

$P_{ij\min}, P_{ij\max}$ 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

$$\text{Sensitivity index} = \Delta p_{i-j} / \Delta p_i \tag{11}$$

(where Δp_{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 Δp_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 Diffrential 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, nonderrivative 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.

$$P = [Y_1^G \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Y_{Np}^G] \tag{12}$$

$$Y_i^G = [X_{1i}^G, X_{2i}^G, \ldots\ldots\ldots\ldots, X_{Di}^G] \tag{13}$$

where $i = 1, 2, \ldots \ldots N_p$

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

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).

$$Y_{i,j}^0 = Y_j^{min} + \eta_j (Y_j^{max} - Y_j^{min}) \tag{14}$$

where, $i = 1, 2, .., N_p$ and $j = 1, 2, ..., D$

And, Y_j^{min} and Y_j^{max} are respectively, the lower and upper bound of the jth decision parameter and n_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).

$$Y_i^{'G} = Y_a^G + S(Y_b^G - Y_c^G) \tag{15}$$

where, $i = 1, 2, .., N_p$ where, Y_a, Y_b, Y_c are randomly chosen vectors $\in \{1, 2, ..., N_p\}$ 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].

$$X_{i,j}^{''G} = X_{i,j}^{'G} \text{ if } \eta_j' \leq C_r \text{ or } j = q \tag{16}$$
$$= X_{i,j}^G \text{ Otherwise} \tag{17}$$

where $i = 1, 2, ..., N_p$ and $j = 1, 2, ..., D$

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

$$Y_i^{G+1} = Y_i^{"G} \, if \, f(Y_i^{"G}) \le f \, (Y_i^{G}) \tag{18}$$

$$= Y_i^{G} \quad otherwise \tag{19}$$

The selection process is repeated for each pair of target/ trail 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 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 methology 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

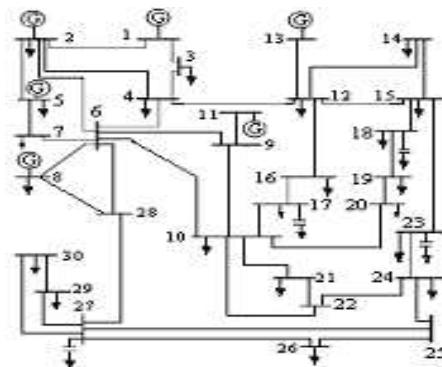| Variables	Adopted system
Branches	41
Generators	6
Total Demand(MW)	283.6

Figure 1. Single line Diagram of IEEE 30 Bus System

Table 3a. Cost co-efficients of generators

Bus no	Real Power output limit in MW		Cost Co-efficient		
	Max	Min	A (US$/MW^2)	B (US$/MW)	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^{-6}
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 limitedand violation of which may motivate ISO to reschedule the generators for safe operation of the power system.
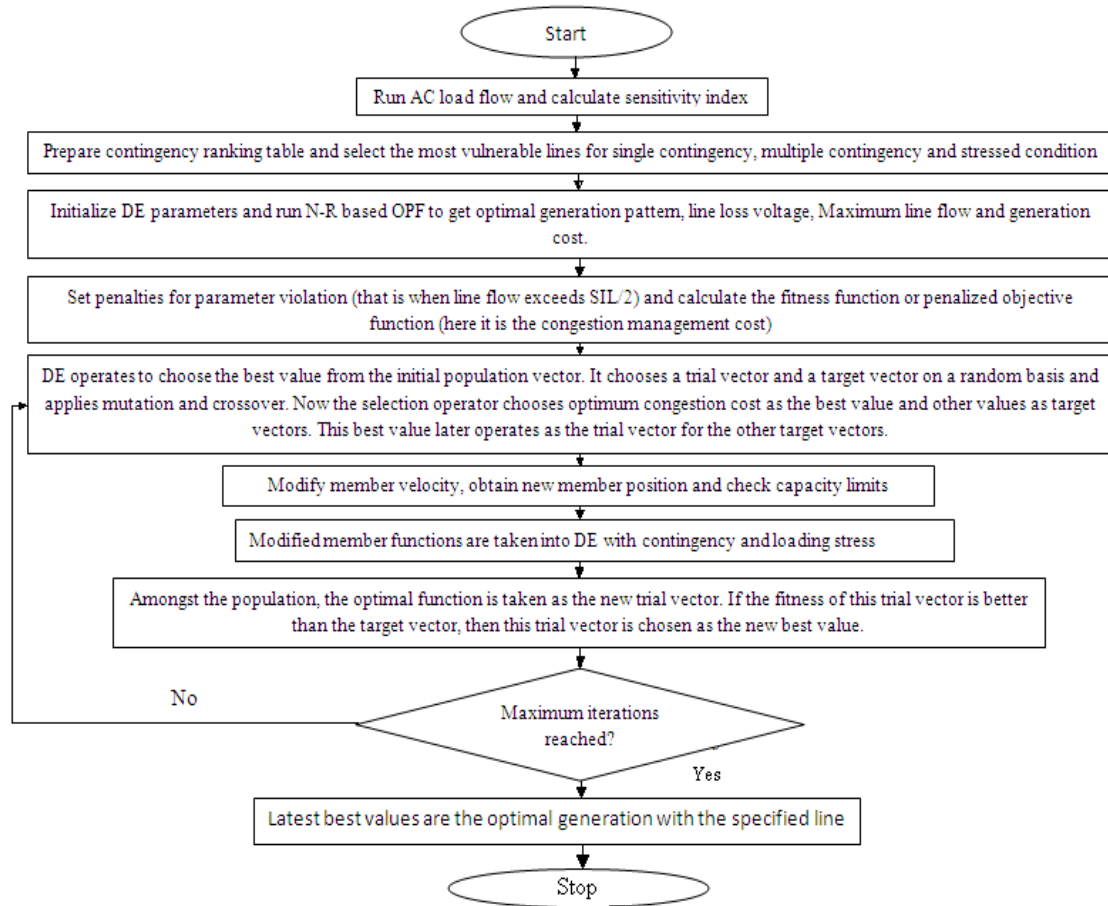
Figure 2. Flow chart of the proposed methodology

Though the proposed algorithm is capable of limiting the line flow at any arbitrary value, in the present work, the line flow limitr 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	Contribution of the generators					
	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	Contribution of the generators					
	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

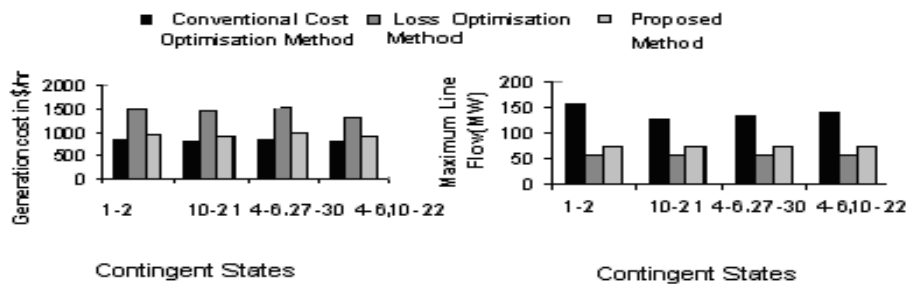| Lines tripped	Contribution of the generators					
	P1(MW/hr)	P2(MW/hr)	P3(MW/hr)	P4(MW/hr)	P5(MW/hr	P6(MW/hr
10-21	112.59	68.27	26.01	44.82	19.88	18.06
1-2	71.71	74.07	28.06	63.34	26.23	25.90
27-30	112.65	68.53	26.00	44.52	19.96	18.11
10-21 and 1-2	71.72	73.54	28.39	64.21	26.22	25.59
4-6 and 27-30	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
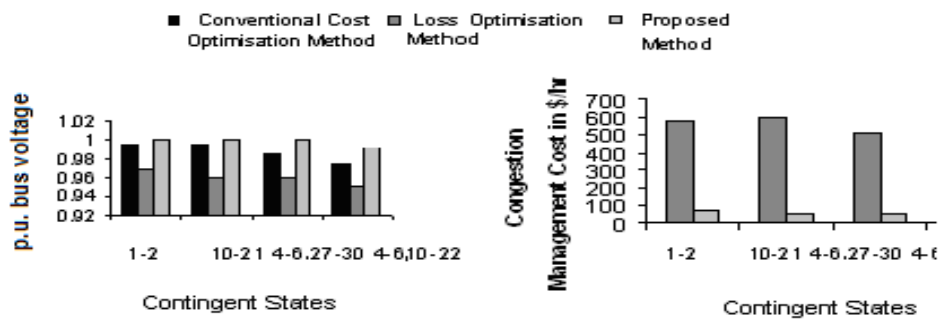

Figure 4. Bus voltage profile and congestion management cost

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.

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