

Alleviation of Line Congestion using Multiobjective Particle Swarm Optimization

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Abstract

This paper presents an effective method of congestion management. Congestions or overloads in transmission network are mitigated by generation rescheduling and/or load curtailment. Here, the two conflicting objectives 1) mitigation of overload and 2) minimization of cost of operation are optimized to provide pareto-optimal solutions. A multiobjective Particle Swarm Optimization (MOPSO) method is used to solve this complex nonlinear optimization problem. The proposed congestion constrained cost optimization algorithm, is capable of limiting line congestion with a minimum management charge without any load curtailment and it also provides better operating conditions in respect of voltage profile, total line loss and security for the system during contingency. For contingency selection and ranking, a Security Sensitivity Index (SSI) has also been proposed in this paper. The main advantage of this algorithm is that, it can also confine the level of congestion at any preferred value according to the affordable congestion management cost decided by market participants in deregulated environment. Though the proposed algorithm has been shown to be tested on IEEE 30 bus test system, the same has been found to be effective with system of higher number busses.

Keywords: contingency, congestion management, particle swarm optimization, generation rescheduling, security sensitivity index.

Introduction

The main objective of power system restructuring is to provide the customer more

choices in respect of supply reliability as well as costs [1]. But commercial pressures on obtaining greater returns from existing assets suggest an increasingly important role for congestion management because it can make a penalty for the market players [2]. The congestion management in deregulated power environment can be solved by load curtailment resulting in reduced reliability [3] and by using external devices such as FACTS or phase shifters increasing the cost of transmission [4]. Hence other alternative may be searched which can improve reliability without load curtailment or FACTS devices. Generator re-scheduling can be one of the alternative solutions of the problem [5] but conventional optimization algorithm, for re-scheduling, gives rise to line flow and hence congestion charge. In [6], a new systematic approach of re-scheduling transaction under congestion is proposed. But due to the non-linear nature of loss relationship, it is difficult to allocate the losses accurately to individual transaction. The congestion management cost has been reported to be minimized in [7]. Penalty based Security Constrained Optimal Power Flow (SCOPF) have been proposed in [8] and [9] where rescheduling cost have been minimized without ascertaining maximum allowable line flow or level of congestion and minimization of line loss. Moreover since the penalty method applied has to trace and calculate penalties for all the lines, the time complexity of the algorithms may be very high. Dynamic control of congestion as reported in [10] may be too expensive and also require precise monitoring. Sensitivity index with dc load flow assumptions has been proposed in [11] but it ignores voltage and reactive power effects as well as system nonlinearity and might also lead to unaccepted errors. [12] proposes load curtailment based congestion management but it can not sustain a particular the level of congestion. Congestion management in a bilateral based power market with load curtailment has been proposed in [13] but the value of load loss associated could not be recovered. To get an optimal solution of maintaining cost, congestion and congestion management cost, the requirement of an optimal power flow method can be considered which not only minimizes cost of generation and congestion but also tries to maintain a standard level of congestion according to the affordable congestion management charge offered by the power market participants without degrading the system operating condition.

In this paper, congestion constrained algorithm in PSO environment has been projected which not only reschedules the generation by keeping the line flow limited to a preferred value but also manages congestion according to the charges offered by the participants. In deregulated environment this limit of line flow is essential, as with that, ISO can operate with a higher power transfer capability [14]. In addition, the proposed algorithm can manage congestion without any load curtailment and it provides better security and reliability of the system. For security assessment and hence to determine the degree of vulnerability of the lines of the system, a Security Sensitivity Index (SSI) has also been proposed. The validity of the proposed algorithm has been demonstrated with standard IEEE 30 bus test system using Multiobjective Particle Swarm Optimization. The results reveal the capabilities of the proposed approach to generate true and well-distributed optimal solution of the dispatch problem in one run.

Theory

Security Sensitivity Index

Power system security is defined as its ability to maintain normal state even during contingency. Hence power system security assessment is required in the current power environment to implement proper security control in case of contingency. In security assessment, the likelihood and severity of security violation are the two main factors that determine the security level of a power system. Thus, an index has to be defined which assesses both during eventuality. The security level can be judged by an index proposed as Security Sensitivity Index (SSI). Mathematically, it can be expressed as follows:

$$SSI = \frac{P_{ij}^n - P_{ij}^{(n-1)}}{P_i^n - P_i^{(n-1)}} \quad (1)$$

It is quite evident that the higher the value of this index, the lower is the level of security of the line.

Overview of Particle Swarm Optimisation

PSO is a simple and efficient population based optimisation method proposed by Kennedy and Eberhart [15]. It is motivated by social behaviour of organism such as fish schooling and bird flocking. In PSO, potential solutions called particles fly around the multidimensional problem space. Population of particles is called swarm. Each particle in a swarm flies in the search space towards the optimum or quasi optimum solution based on its own experience, experience of nearby particles, and global best position among particles in the swarm.

Let us define search space S is n -dimension and the swarm consists of N particles. At time t , each particle i has its position defined by $X_t^i = \{x_1^i, x_2^i, \dots, x_n^i\}$ and a velocity defined by $V_t^i = \{v_1^i, v_2^i, \dots, v_n^i\}$ in the variable space S . Position and velocity of each particle changes with time. Velocity and position of each particle in the next generation (time step) can be calculated as

$$V_{t+1}^i = w \times V_t^i + c_1 \times rand() \times (P_t^i - X_t^i) + c_2 \times Rand() \times (P_t^{i,g} - X_t^i) \quad (2)$$

$$X_{t+1}^i = X_t^i + V_{t+1}^i ; i = 1, \dots, N \quad (3)$$

Where, N = number of particles in the swarm; n = number of elements in the particle; w = inertia weight of the particle; t = generation number; c_1, c_2 = acceleration constant; $rand(), Rand()$ = uniform random values in the range $[0,1]$; $P_t^{i,g}$ = global best position of the particle in the population; P_t^i = best position of the particle i so far. The inertia weight w is an important factor for the PSO's convergence. It is used to control the impact of previous history of velocities on the current velocity. A large inertia weight factor facilitates global exploration (searching of new area) where small weight factor facilitates local exploration. Therefore, it is wise to choose large weight factor for initial iterations and gradually reduce weight factor in successive iterations

[16]. This can be done by using

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} \times iter \quad (4)$$

Where w_{\max} and w_{\min} are maximum and minimum weight, respectively, $iter$ is iteration number, and $iter_{\max}$ is the maximum iteration allowed.

With no restriction on the maximum velocity (V_{\max}) of the particles, velocity may move towards infinity. If V_{\max} is very low, particles may not explore sufficiently and if V_{\max} is very high, it may oscillates about optimal solution. Velocity clamping effect has been introduced to avoid the phenomenon of 'swarm explosion'. in the proposed method, velocity is controlled with in a band as

$$V_{\max,t} = V_{\max} - \frac{V_{\max} - V_{\min}}{iter_{\max}} \times iter \quad (5)$$

Where $V_{\max,t}$ is the maximum velocity at generation t, and V_{\max} and V_{\min} are initial and final velocity, respectively. Acceleration constant c_1 is called cognitive parameters pulls each particle towards local best position whereas constant c_2 is called social parameter pulls the particle towards global best position. Usually c_1 equals to c_2 and ranges from 0 to 4.

Problem Formulation

The proposed methodology rests on proper formulation of the objective functions along with all the constraints. The methodology has been primarily used with conventional cost optimisation and then it has been applied with the proposed congestion constrained cost optimisation problem using PSO. The equality, inequality and security constraints; however remain same for the conventional and the proposed algorithms. In this planned algorithm, the objective function has been modified by a scaling factor, which appears only during line flow constraints violets. As the optimisation process tries to minimize the objective function, the scaling factor associated with maximum line congestion directs it to produce a new generation schedule, which offers the specified line flow.

Objective function for conventional cost optimisation

$$\text{Minimize } F = \sum_{n=1}^{NG} C_n \text{ \$/hr} \quad (6)$$

$$\text{where, } C_n = A(P_{gi}^0)^2 + BP_{gi}^0 + C \quad (7)$$

Objective function for the proposed optimisation

$$\text{Minimize } F = \sum_{n=1}^{NG} C_n + sf \times P_{ij \max} \text{ \$/hr} \quad (8)$$

The constraints are common for all the above objective functions and are as follows:

Equality or power balance constraints

$$\sum_{G=1}^{NG} \sum_{g \in G} (P_{gi}^0 + \Delta P_{gi}^j) - (P_i^0 - LCP^j) = \sum_{k=1}^N |V_i^j| |V_k^j| |Y_{ik}^j| \cos(\theta_i^j - \theta_k^j - \delta_{ik}^j) \quad (9)$$

$$\sum_{G=1}^{NG} \sum_{g \in G} (Q_{gi}^0 + \Delta Q_{gi}^j) - (Q_{li}^0 - LCQ^j) = \sum_{k=1}^N |V_i^j| |V_k^j| |Y_{ik}^j| \sin(\theta_i^j - \theta_k^j - \delta_{ik}^j) \quad (10)$$

Inequality or generator output constraints

$$P_{gi}^{\min} \leq P_{gi}^0 \leq P_{gi}^{\max} \quad (11)$$

$$Q_{gi}^{\min} \leq Q_{gi}^0 \leq Q_{gi}^{\max} \quad (12)$$

$$\Delta P_{gi}^{\min} \leq \Delta P_{gi}^j \leq \Delta P_{gi}^{\max} \quad (13)$$

$$\Delta Q_{gi}^{\min} \leq \Delta Q_{gi}^j \leq \Delta Q_{gi}^{\max} \quad (14)$$

$$\text{Voltage constraint: } |V_i^{\min}| \leq |V_i^j| \leq |V_i^{\max}| \quad (15)$$

$$\text{Transmission constraint: } P_{ij \min} \leq P_{ij} \leq P_{ij \max} \quad (16)$$

$$\text{Load curtailment limits : } 0 \leq LCP^j \leq P_l^{\max} \quad (17)$$

$$Q_{li}^{\min} \leq LCQ_i^j \leq Q_{li}^{\max} \quad (18)$$

where, 0 -normal state index (superscript), j -contingency state index (superscript), i, k -bus index (subscript), g -generation unit index (subscript), G -GENCO index (subscript), N -number of buses, NG -number of GENCOs, A, B, C -cost co-efficient of generators, P_{ij}^0 - line flow in MW between bus i and bus j before tripping, P_{ij}^j -line flow in MW between bus i and bus j after tripping, P_i^0 -total power injected to bus i before tripping the same line, P_i^j -total power injected to bus i after tripping the same line, sf -scaling factor for congestion management, $P_{ij \max}$ -maximum line flow to be allowed between i^{th} and j^{th} bus, P_{gi}^0 -real power dispatched in MW, Q_{gi}^0 -reactive power dispatched in MVar, ΔP_{gi}^j -real power re-dispatched in MW, LCP^j -real power load curtailment in MW, ΔQ_{gi}^j - reactive power re-dispatched in MVar, LCQ^j -reactive power load curtailment in MVar, $|V_i^j| \angle \theta_i^j$ -bus voltage in kV, $|V_i|^{\max}$ -maximum voltage limit in kV, $|V_i|^{\min}$ -min. voltage limit in kV, P_l^{\max} -maximum real power load in MW, Q_{li}^{\max} - maximum reactive power load in MVar, Q_{li}^{\min} -minimum reactive power load in MVar

Simulation and results

The feasibility and effectiveness of the proposed method has been demonstrated in the IEEE 30 bus test system as sketched in Fig. 1. For the entire simulation, logic

program in PSO algorithm has been employed to formulate ac power flow model and to analyse contingencies. The standard parameters settings for all the simulations of the adopted PSO have been depicted in Table I.

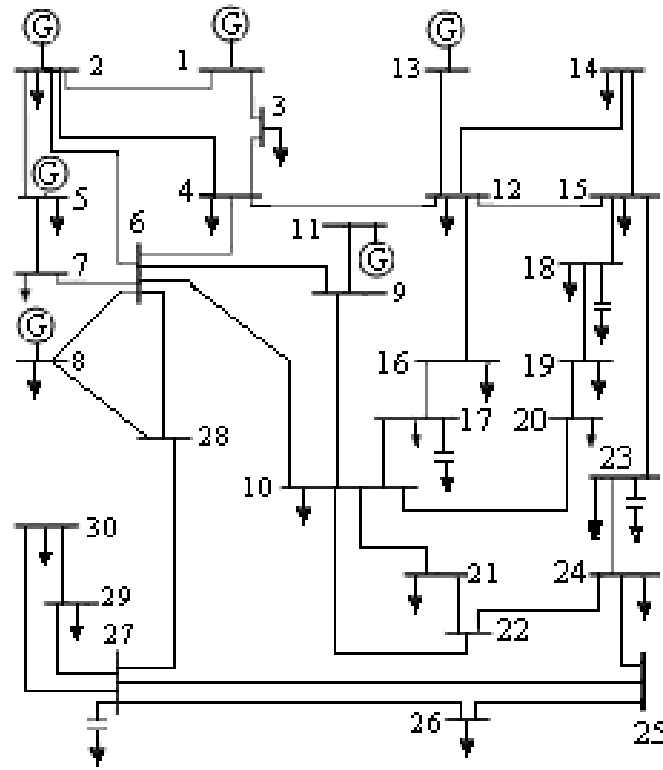


Figure 1: The standard IEEE 30 bus system.

Table I: Parameter Setting of PSO based Optimization.

Name of the parameter	Value
Epochs	20
iterations (epochs) to train	100
acceleration const 1 (local best influence)	2
acceleration const 2 (global best influence)	2
Initial inertia weight	0.9
Final inertia weight	0.4
Epoch when inertial weight at final value	1500
epochs before error gradient criterion terminates run	1e-6

The IEEE 30 bus test system consists of 6 generators and 41 lines. The descriptions of all generator units have been given in Table II.

Table II: Cost Co-Efficient of IEEE 30 Bus System.

Bus no.	Real Power output limit in MW		Cost Co-efficient		
	Min	Max	a (US\$/MW ²)	b (US\$/MW)	c (US\$)
1	50	200	0.00375	2.00	0
2	20	80	0.01750	1.75	0
5	15	50	0.06250	1.00	0
8	10	35	0.00834	3.25	0
11	10	30	0.02500	3.00	0
13	12	40	0.02500	3.00	0

The total simulation is divided into four sections. Section I prepares a graphical representation of severity of the buses with the help of proposed SSI for proper security assessment. Here, (n-1) contingency has been assumed. A comparison between the conventional cost optimization technique and proposed congestion constrained cost optimization technique has been studied in Section II under same type of contingencies. Section III deals with congestion management cost for a specific level of line flow during different contingencies and in Section IV the possible improvements in operating conditions with the proposed algorithm has been depicted.

Section I: Selection of vulnerable lines by SSI

For congestion management, the most vulnerable lines in respect of congestion need to be selected as they are the possible weak links of the system. For this, initially the study concentrates on the determination of vulnerable lines using (1). The figure (Fig. 2) represents 17 lines with their sensitivity indices in descending order. With the help of this contingency table, weaker lines of the system can be identified so that proper security control can be implemented. Since the rest of the lines have lower values of the index, they would be less congested during possible (n-1) line contingencies of the system. Hence their outages have not been analysed in this simulation.

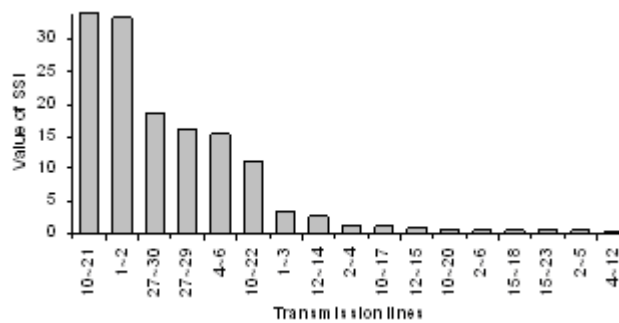


Figure 2: Selection of vulnerable lines by SSI.

Section II: Comparison of different algorithms for congestion management

The proposed algorithm has been applied to the system along with the conventional optimization method for different contingencies. During contingency, when the line flow exceeds a certain limit, a scaling factor has been added with the objective function to be minimized (8). This in effect tries to minimize congestion along with the generation cost. The table (Table III) depicts the comparison of the line flow computed by the conventional and the proposed method with scaling factor. Though, here the line flow limit has been taken as a forecasted value of 72 MW (SIL/2), the algorithm can limit the line flow at any specified value. In deregulated environment, the ISO can use this algorithm to re-schedule the GENCOs for required level of congestion management.

Table III: Comparison of Line Flows Obtained from Different Algorithms.

Line number	Maximum Line flow (MW) calculation using PSO based optimization	
	without congestion anagement	With proposed Congestion constrained cost optimisation
10-21	118.632	71.9999
1-2	151.2315	71.9985
27-30	118.6838	71.9990
27-29	118.6488	71.9999
4-6	129.6440	71.9915
10-22	118.5621	71.9998
1-3	169.5659	71.9999
12-14	118.6401	71.9978
2-4	105.2676	71.9973
10-17	118.4848	71.9983
12-15	118.9263	71.9942
10-20	118.5329	71.9995
2-6	104.4975	71.9896
15-18	118.6642	71.9995
15-23	118.6688	71.9987
2-5	103.5130	71.9944
4-12	118.8794	71.9976

Though the proposed method effectively reduces line flow without any load curtailment, the total generation cost increases due to the change in individual contribution of the generators. If the system has Real Time Congestion Monitoring and Control (RTCMM) [10], the proposed rescheduling can be immediately effected to minimize the damage or provide the useful information for upgrading the grid during contingency. Table IV depicts the comparison of generation costs obtained from conventional OPF, proposed OPF with scaling factor.

Table IV: Comparison of Generation Costs Obtained from Different Algorithms.

Line number	Total generation cost (\$/hr) using PSO	
	Without congestion management (A)	With proposed congestion constrained cost (B)
10-21	803.0751	836.3210
1-2	839.2833	895.2044
27-30	903.5036	936.8287
27-29	803.1002	836.3659
4-6	806.6264	848.1328
10-22	802.0998	835.2446
1-3	815.1886	891.3969
12-14	802.6182	835.8944
2-4	804.0127	822.7905
10-17	802.3837	835.4275
12-15	804.2792	837.9573
10-20	803.3603	836.4654
2-6	805.8647	824.2915
15-18	802.2383	835.5291
15-23	802.2488	835.5661
2-5	836.4455	871.1854
4-12	805.2143	838.4680

Section III: Calculation of congestion management cost

Table V shows the variation of congestion management cost for limiting the line congestion at 50% of the SIL level. The same congestion management may be achieved by load curtailment according to willingness to pay but only with a high management cost of losing load. In this case, the value of load loss (VOLL) is the congestion management cost.

Table VII: Calculation of Congestion Management Cost.

Line number	Congestion management Cost (\$/hr) using proposed algorithm	Value of lost load (VOLL) or Congestion management Cost (\$/hr) with load curtailment
10-21	33.2459	198.09
1-2	55.9211	225.39
27-30	33.3251	185.70
27-29	33.2657	183.67
4-6	41.5064	184.01
10-22	33.1448	183.61
1-3	76.2083	271.95
12-14	33.2762	183.65

2-4	18.7778	147.73
10-17	33.0438	189.00
12-15	33.6781	194.26
10-20	33.1051	198.06
2-6	18.4268	147.75
15-18	33.2908	157.12
15-23	33.3173	157.12
2-5	34.7399	159.56
4-12	33.2537	157.21

Though, the above table shows the management cost required limiting the line congestion at a particular level (50% of SIL), the proposed algorithm is capable of choosing any specific line flow. Fig.3 depicts congestion management and corresponding cost for single line (1~3) contingency. The lower limit of line flow can ensure excess power flow handling capacity in stressed condition as well as an escalation in new transactions catering capacity. But again, it is quite evident that the higher the level of allowed congestion, the lower is its management cost. But the Loadability of the line is restricted to its SIL level due to angular and voltage stability limit [13, 14] and in practice, to keep a suitable margin for a new load, the limit of congestion may be kept to a level of 60-70% of SIL.

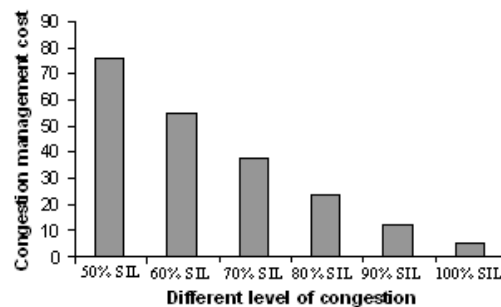


Figure 3: Congestion management cost for different level of congestion.

Section IV: Improvement of operating condition with proposed algorithm

Another important objective of contingency management other than congestion management in real time system operation is to maintain the voltage profile and minimum possible line loss. Figure 4 shows the comparison of bus voltage profiles between the above mentioned two methods. The voltage profile with proposed method is better than the conventional cost optimization method. The proposed method also offers an advantage of reduced line loss. As shown in the figure (Fig. 5), the line loss has reduced considerably with respect to conventional method. Hence, before considering the congestion management cost, ISO should consider the long term effects of reduced line loss.

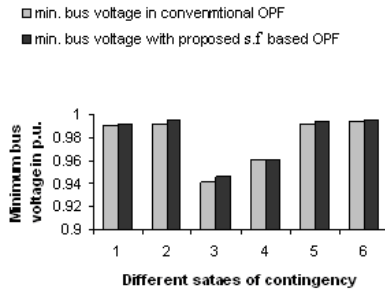


Figure 4: Comparison of voltage profile.

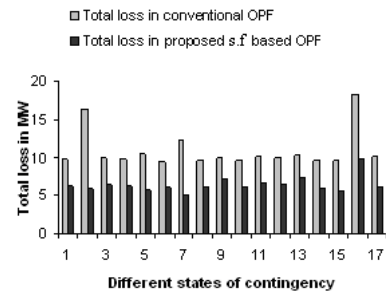


Figure 5: Comparison of line loss.

Conclusions

A PSO based algorithm has been proposed in this paper for congestion management in a contingent system at a minimum management cost as well as without any load curtailment. On violation of a specified line flow, an additional scaling factor has been added to the objective function to direct the PSO based search process to the most feasible optimal solution considering all other constraints. In doing so, line congestion has been limited to a specified value by generation re-scheduling. It has been also been observed that the bus voltage profile of the system has improved and total system loss has decreased appreciably with the application of the proposed algorithm. The net increase in cost in the proposed method is contributed due to generation rescheduling to maintain limited congestion and net decrease in cost is due to voltage improvement and reduced loss. The resultant cost has been compared with that using load curtailment establishing the utility of the proposed technique. For proper security assessment a Security Sensitivity Index has also been proposed in this paper to assist proper selection of contingency. 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 by effectively used by ISO.

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