A Network Congestion Management Approach Considering the Risk of Cascading Failures

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***Abstract*—This paper proposes a novel cost-efficient scheme for managing congestion in power systems. The proposed scheme manages network congestion at acceptable levels with optimal operation cost and reduced risk of cascading failures. The scheme works in two phases. As the first option, it attempts to reduce congestion through an optimal (optimized for fuel cost) rescheduling of generation. If the revised generation schedule fails to reduce congestion, it tries the next option, namely, optimal (minimizing the impact on revenues and customers) load shedding. The scheme employs Particle Swarm Optimization technique to optimize the individual options and uses Fuzzy Satisfying technique to choose the best solution from the set of Pareto optimal solutions. The proposed system has been evaluated on IEEE 30 and 118 bus test systems. The results of this evaluation are included as well.**

I. INTRODUCTION

Electric power networks are the most complex man made systems and the network complexity is increasing rapidly with the sharp increase in load demand. They are prone to various kinds of faults/disturbances and therefore they are designed to be reliable and robust enough to withstand the credible disturbances. Modern power networks are protected with lot of advanced protection systems and trained operators continuously monitor the system, still large blackouts/cascading failures are happening around the globe [1]. Most of these cascading disturbances start from a single fault when the power system operates in normal condition and the effect of this single event propagates in the network like a ripple in water and finally cause widespread failure due its domino effect. As cascading disturbances are relatively low probability events, usually the response to these events are not well planned by the utilities and therefore, when cascading failures start, operators feel uncertain with the limited contingency specific guidelines available to them. As most of the cascading disturbances are caused from congestion [2], congestion management may be an important preventive tool for avoiding these disturbances. As during steady state progression of the disturbance, the time interval between any two events may vary from few minutes to hours [3], operator may get enough time to remove the congestion to mitigate the risk of cascading failures.

In the literature, many methods are reported for congestion management in power systems. Generation rescheduling and load shedding are used in [4], [5] for alleviation of congestion. In these methods system operator has no choice of selecting the participating generator and/or load buses. Reference [6] proposed a mathematical model of bus Sensitivity Factors (SFs) which relate the bus injections to change in line currents. These SFs are used to alleviate the congestion by selecting high sensitive generator and/or load buses. However, this method does not consider the economic aspects of generation rescheduling and/or load shedding. Because of increasing competitive pressure in the electric industry, alleviation of congestion can no longer be the only criteria, economic aspect also needs to be considered. Reference [7] proposed a direct method for alleviation of congestion where both cost of load shedding and generation rescheduling are considered. However, this method does not consider the realistic power system behavior (load and generation behavior, change in system frequency, etc.) during congestion management. In fact, system behavior may change significantly caused by major contingencies like generator outage or tie line outage. Considering these realistic system behaviors, a congestion management method has been proposed in [8]. Reference [9] improves the method in [8] by incorporating sensitive factors for selecting sensitive generators and/or loads. Congestion management methods proposed in [8]-[9] optimize the cost of operation and tolerable overload on transmission lines as sometimes a small overload for a short time saves huge amount of money. However, these methods do not consider the risk of overload even for a short period of time. Little overload on any line may trigger the cascading failures due to malfunctioning of protection system. US 2003 blackout is an example of that. Therefore, it may not be wise to tolerate any overload without analyzing the possibility of cascading failures.

In this paper, a new congestion management scheme is proposed where trade-off has been made among the cost of operation, tolerable congestion and the risk of cascading failures. For any congestion/overload situation all the possible cascading paths are identified along with the path risk which combines the severity and the probability of the path. Cumulative risk of all possible paths along with cost of operation and congestion are minimized in this approach. Generation rescheduling has been done first to overcome the congestion and if generation rescheduling alone is not sufficient to alleviate the congestion, load shedding has been done as a last option. A multi objective Particle swarm optimization method has been used to generate the trade-off solutions and a fuzzy satisfying method has been incorporated to select the best compromise solution from the set of Pareto optimal solutions.

The paper is organized as follows. Section II briefly presents the congestion management formulation. Section III details the method of risk assessment of cascading failures and Section IV describes the multi-objective particle swarm optimization method. Section V presents the fuzzy approach for selecting best compromise solution, and section VI describes the congestion management strategy. Section VII presents the simulation results whereas Section VIII concludes the proposed work.

II. PROBLEM FORMULATION

The objective of the proposed congestion management is to minimize the congestion as well as the risk of cascading failures and cost of operation i.e. cumulative cost of generation and load shedding. In general bid curves provided by the generation utilities are piecewise linear and these bid curves are derived from actual generation cost curves. In this paper, actual cost curves are used for optimal scheduling of generation. The cost curve for load shedding can be based on subjective factors such as importance of load, loss of goodwill, commercial factors such as loss of revenue, etc. However, due to lack of exact data, uniform quadratic load shedding cost curves are used in this paper. Mathematically congestion management problem can be represented as:

Objective 1: Minimize congestion

$$Minimize\, F1 = \sum_{i=1}^{nl} (S_i - S_i^{max})^2 \tag{1}$$

where, $F1$ is cumulative overload, nl is number of overloaded line, S_i is MVA flow on line i, and S_i^{max} is MVA capacity of line i.

Objective 2: Minimize cost of operation

$$\begin{aligned} Minimize\, F2 &= \sum_{i=1}^{ng} (a_i + b_i P_{gi} + c_i P_{gi}^2) \\ &+ |e_i \times \sin(f_i \times (P_{gi} - P_{mini}))| \\ &+ \sum_{k=1}^{pl} (a_k^{'} + b_k^{'} L_{s,k} + c_k^{'} L_{s,k}^2) \end{aligned} \tag{2}$$

where, F_2 is total operation cost, ng is number of participating generators, pl is number of participating loads, P_{gi} is generation of i^{th} generator, P_{mini} is minimum generation of i^{th} generator, $L_{s,k}$ is amount of load shedding at bus k, a_i, b_i, c_i are cost coefficients of generator i, $a_k^{'}, b_k^{'}, c_k^{'}$ are cost coefficients of load k and e_i, f_i are coefficients of generator i reflecting valve point loading effect.

Objective 3: Minimize cascading risk

$$Minimize\, F3 = \sum_{i=1}^{nl} \sum_{j=1}^{nc_i} R_i^j \tag{3}$$

where, $F3$ is cumulative risk of cascading failures, nl is number of overloaded lines, nc_i is number of possible cascades associated with overloaded line i, R_i^j is the risk of j^{th} cascading path associated with the overloaded line i.

Above objectives are subjected to the constraints of load-generation balance and physical and operation limits of equipments (generators, transmission lines and transformers).

III. RISK ASSESSMENT OF CASCADING FAILURES

Protection system malfunctioning play a major role in cascading failures. Almost 75% of major cascading failures included protection system malfunction [10]. Protection devices may malfunction due to various reasons such as over current, voltage drop, error in relay setting, etc. During congestion in electric grid, over current and voltage drop phenomena are quite common which may trigger the protection failures. Therefore, in this paper identification of cascading failures focused on protection failures.

In power systems transmission lines are in general protected by impedance and over current relays. During congestion over current relays are mostly exposed to protection failures. During congestion generators also may suffer from inadequate reactive power support which may cause voltage drop in generator bus. This voltage drop may trigger incorrect operation of generator protection systems. Therefore, this paper focused on over current protection failures of transmission lines and voltage base protection failures of generators.

In cascading failures, equipment outage happens sequentially and a string of such outages called cascade. For a particular outage, next outage likely to happen from a region of vulnerability which is an area within the reach or setting of a relay or relay scheme that would cause it to mis-operate if other supervising or control parameters did not prevent its operation. In case of over current protection, if any line trips, over current relays which sense this fault as a back up relay at the lines connected to end buses of the tripped line are exposed to protection failures. Similarly if any generator trips, then all lines connected to the generator bus would be exposed to protection failures. Tripping probability of any exposed line or generator is dynamic and depends on loading on line or generator. Probability functions defined in [11] are used to calculate tripping probabilities of lines or generators. Probability of a cascade is calculated by multiplying the individual event probabilities as follows:

$$P_i = \prod_{k=1}^{n_i} p_k \tag{4}$$

where

P_i is the probability of sequence i;
n_i is the number of events in sequence i;
p_k is the individual probability of the event k in sequence i.

Severity (S_i) of any cascade i has been quantified based on proximity to voltage instability, load loss, overload, available power margin and frequency violation. Risk (R_i) of any cascade i has been defined as the product of severity and probability as follows:

$$R_i = S_i \times P_i \tag{5}$$

Possible cascades for any operating condition are identified using event tree approach proposed in [11]. An event tree (as shown in Figure 1) is a graphical representation of the logic model that identifies and quantifies the possible outcomes following an initiating event. In Figure 1, root node represents the initial operating condition and other nodes represent state of the power system following any outage. Branch between any two nodes represents outage of a component. Node with no forward branch is called end node. Each path from root to end node represents a cascade.

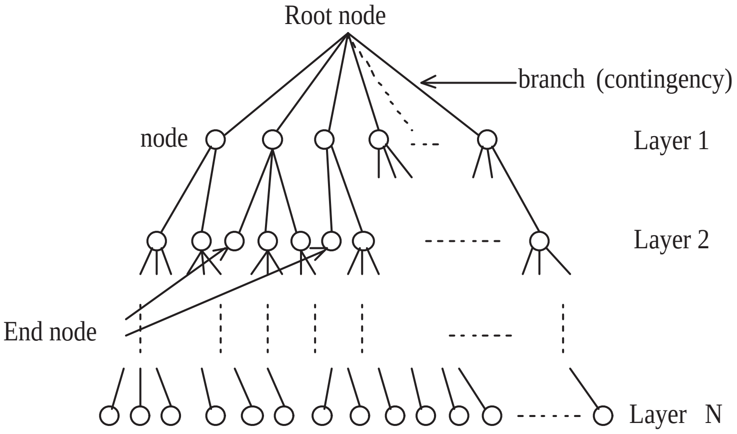

Fig. 1. Search of cascading failures

From the root node all possible outages are evaluated first. Each outage generates a new node in Layer 1. High risk nodes in layer 1 are further explored. This process continues until the system load loss is beyond the specified limit or load flow solution diverges. To restrict the search on the promising region, in each layer, low risk nodes are discarded and only high risk stable nodes are considered for further exploration. This reduces computational burden considerably. Simulation is carried out until the search is completed upto a specified depth (layer).

IV. MULTI OBJECTIVE PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is a population based search technique. Each individual potential solution in PSO is called particle. Each particle in a swarm fly around in a multidimensional search space based on its own experience and experiences of neighboring particles.

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

$$\begin{aligned} V_{t+1}^i = w \times V_t^i &+ c_1 \times rand() \times (P_t^i - X_t^i) \\ &+ c_2 \times rand() \times (P_t^g - X_t^i) \end{aligned} \tag{6}$$

$$X_{t+1}^i = X_t^i + V_{t+1}^i \qquad \forall i = 1, \ldots, N \tag{7}$$

where, w is inertia weight, c_1, c_2 are acceleration constant, $rand()$ is uniform random number in the range [-1,1], P_t^g is global best at time t, P_t^i is best position that particle i could find so far.

In multi objective optimization, there may not exist a global solution, instead there exists a set of Pareto optimal solutions. Therefore, instead of global best, best local guide for each particle is identified from the archive of Pareto optimal solutions using sigma method [12]. Sometimes Pareto optimal solutions obtained in multi-objective optimization may be concentrated in a part of the search space which may overlook more efficient solutions in the other parts of the search space. To preserve diversity among Pareto optimal solutions a diversity preserving technique based on crowding ($crwd$) and dispersion ($disp$) distances (as defined in Table I) has been used. In each iteration solution with least crowding value is removed from archive. When the crowding values of few solutions are equal, then the solution with least dispersion is removed. To preserve the end solutions, large crowding values are assigned to them.

TABLE I
CALCULATION OF CROWDING AND DISPERSION DISTANCES

```
$l = |A|$                                          number of solutions in Archive
for i=1 to $l$, set $crwd[i] = disp[i] = 0$       initialize distances
for j=1 to m                                       for each objective
    A=sort(A, m)                                   sort using each objective value
    $crwd[j][1] = crwd[j][l] = \infty$             end solutions are preserved
    for i=2 to ($l$-1)                             for all other solutions
        $crwd[j][i] = min(d_{i-1,i}, d_{i,i+1})$   d represents Euclidian distance
        $disp[j][i] = max(d_{i-1,i}, d_{i,i+1})$
for i=1 to $l$
    $crwd[i] = \sum_{j=1}^{m}[crwd[j][i]]$
    $disp[i] = \sum_{j=1}^{m}[disp[j][i]]$
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V. SELECTION OF COMPROMISE SOLUTION

Multi objective optimization provides a set of Pareto optimal solutions. A fuzzy satisfying method is used to find the best compromise solution from a set of Pareto optimal solutions.

For each objective fuzzy membership is defined by linear function as follows:

$$\mu_i = \begin{array}{ll} 1 & if \;\; f_i \leq f_i^{min} \\ \frac{f_i^{max} - f_i}{f_i^{max} - f_i^{max}} & if \;\; f_i^{min} < f_i < f_i^{max} \\ 0 & if \;\; f_i \geq f_i^{max} \end{array} \tag{8}$$

where

μ_i is membership value of objective i;

f_i^{min} is the value of objective i which is completely satisfactory;

f_i^{max} is the value of objective i which is completely unsatisfactory.

For each Pareto solution normalized membership function is found as follows:

$$\mu^k = \frac{\sum_{i=1}^{N_{obj}} \mu_i^k}{\sum_{k=1}^{M} \sum_{i=1}^{N_{obj}} \mu_i^k} \tag{9}$$

where,

N_{obj} is the number of objective functions;

M is number of Pareto optimal solutions;

μ^k is membership value of non dominated solution k.

The non-dominating solution that attains the maximum membership μ^k is chosen as the best compromise solution.

VI. CONGESTION MANAGEMENT STRATEGY

In congestion management all the utilities (generation and load) interested in participating congestion management may not be equally effective/sensitive in managing congestion. To select the effective generators and loads a sensitivity index (f_i) proposed in [9] has been used in this paper. The sensitivity index has been defined as follows:

$$\begin{aligned} f_i = \frac{\Delta I_{km}}{\Delta P_i} &= \frac{\partial I_{km}}{\partial \delta_k}\frac{X_{ki}}{|V_i|} + \frac{\partial I_{km}}{\partial \delta_m}\frac{X_{mi}}{|V_i|} \\ &+ \beta_i \left(\frac{\partial I_{km}}{V_k}\frac{Y_{ki}}{|V_i|} + \frac{\partial I_{km}}{V_m}\frac{Y_{mi}}{|V_i|} \right) \end{aligned} \tag{10}$$

where, ΔI_{km} is change in line current from bus k to m, ΔP_i is change in real power injection at bus i, X/Y is element of admittance matrix, V is voltage magnitude and δ is voltage phase angle.

Participating generators are selected on the basis of sensitivities of the generation buses. As the power output from a generating station can be increased or decreased (within the operating limits) according to requirements, generator buses with high positive or negative sensitivity value can be selected as a participating generator in congestion management. On the other hand as load can be decreased only, buses with high negative sensitivity values are considered for load shedding. For non-participating buses the sensitivity values are assigned as zero. Active power on generator buses will be reschedule first to remove the congestion but if congestion can not be removed only by generation rescheduling, load shedding is carried out as a last resort at the sensitive load buses. Computational steps of the proposed congestion management scheme is summarized as follows:

1) Identify the congested lines in the grid.
2) Get the set of utilities (generation and load) interested in participating congestion.
3) Calculate sensitivity factors for interested generators and loads with respect to change in current flow on each congested line.
4) Select high sensitive generators from the set of interested generation utilities.
5) Minimize cost of operation, congestion and the risk of cascading failures using multi objective particle swarm optimization method.
6) Check whether congestion is managed.
7) If not, select the high sensitive participating loads along with the selected generators and goto step 5.
8) If solution converges or number of iteration is more than specified goto step 9 otherwise goto step 5.
9) Select the best compromise solution from the set of Pareto optimal solutions using fuzzy approach.
10) Present the solution to the decision maker.

VII. SIMULATION RESULTS

Proposed congestion management method is tested on IEEE 30 and 118 bus test systems. For IEEE 30 bus system minimum and maximum generation limits and transmission line limits are taken from [13]. Minimum and maximum generation limits for IEEE 118 bus are taken from [14]. Due to unavailability of line capacity data for IEEE 118 bus system, line limits for voltage level V1 and V2 are assumed as 150 MVA and 250 MVA respectively and for any transformer limit is assumed as 350 MVA. For IEEE 118 bus system negative generations are treated as load. Generator cost coefficients and load shedding coefficients as given in [9] are used in this simulation. It is assumed that initially the systems were running optimally.

Details of the simulated cases are given in Table II. Line over loads are simulated by reducing line capacity. For each congestion case possible cascading failures are searched upto layer 4 and cumulative risk of these possible cascades are quantified.

TABLE II

SIMULATED CASES

Test system	Simulated cases	
IEEE 30 Bus	1A	Overload simulation by reducing capacity of line 1-2 to 70 MVA
	1B	Overload simulation by reducing capacity of lines 2-5 and 5-7 to 40 MVA and 10 MVA respectively
IEEE 118 Bus	2A	Overload simulation by reducing capacity of lines 5-11 and 11-12 to 35 MVA

For congestion case 1A, generator sensitivities with respect to flow on congested line 1-2 are -0.58, -0.52, -0.46, -0.46 and -0.45 respectively for generators at buses 2, 5, 8, 11 and 13 respectively. For this case all the generators are assumed to be interested in participating congestion management. In this case congestion is manageable only by generation rescheduling. Pareto optimal solutions associated with minimum cost, minimum congestion, minimum risk and best compromise are presented in Table VI. In Table VI first solution is associated with minimum cost (INR 5557999/hr). Though cost is minimum for this case, congestion on line is around 10% and there is a high possibility of a cascading failure (L1-L2) for sequence of trippings of line number 1 (between buses 1&2) and line number 2 (between buses 1&3). If overcurrent relay on line 1 misoperates due to overload and trips the line 1, then lines between buses 1&3, 2&4, 2&6 and 2&5 are exposed to subsequent protection failure. Due to tripping of line 1, flow on line 2 suddenly changes from 44 MVA to 113 MVA. If overcurrent relay of line 2 misoperates due to huge power swing and trips line 2, Bus 1 generating 115 MW power gets isolated from the system. This causes sharp decay in system frequency due to huge unbalance between supply and demand and finally all the generators will be tripped by underfrequency relays and blackout will happen. For solution 1, the risk of this cascading failure is 2.5×10^{-5}. Solution 2 in Table VI is associated with minimum congestion. In this case though there is no congestion in the system, operation cost increases to INR 574277/hr and there is moderate risk (1.2×10^{-5}) of cascading failures. In this case, if line 1 trips, flow on line 2 will swing to 98.67 MVA, hence have a moderate possibility of tripping of line 2 followed by tripping of line 1. For solution 3, risk (1.04×10^{-5}) of cascading failure is minimum. Though there is no congestion in this case, cost of operation (INR 581664/hr) increases significantly. Solution 4 in Table VI is a compromise solution having the highest fuzzy membership value. For this solution operation cost is good, overload is less than 5% and risk of cascading failure is moderate (1.49×10^{-5}). Hence, operator may chose solution 4 which certainly reduces the risk of cascading failures, relieves congestion to a reasonable extent and minimizes cost of operation reasonably.

For congestion case 1B of IEEE 30 bus system, highest sensitive generator at bus 5 is assumed not to be interested in congestion management and congestion has been tried to solve rescheduling the remaining generators. However, in this case congestion can not be removed by rescheduling generators only. Hence, high sensitive loads at buses 5 and 7 are selected in congestion management. Pareto optimal solutions associated with min cost, min congestion, min risk and compromise solution for this case is presented in Table VII. For Pareto solution 1, cost of operation is minimum but overload on line 2-5 is nearly 10% of its capacity and cumulative risk of cascading failure is very high (1.99). Table III shows that for solution 1, there are 5 possible cascades and three of them (L5-L1-G2, L5-L2-L6-L3 and L5-L2-L3-G2) have significant risk. For solution 2 there is no congestion in the network, still there exists 5 possible cascades. However, risk of each cascade reduces to some extent compared to the cascades for solution 1. For solution 3, risk of cascading failure is minimum (0.03×10^{-5}) and there is a possibility of two very low risk cascades (L8-L1-L2 and L5-L8-G2). However, in this case cost of operation (INR 613541/hr) increases significantly compared to solution 1 (INR 588037/hr) and 2 (INR 604990/hr). For the compromise solution there are only two possible cascades and associated cumulative risk (0.76×10^{-1}) is much less compared to solution 1 and 2 and cost is better than solution 2 and 3.

TABLE III
CASCADES ASSOCIATED WITH THE PARETO OPTIMAL SOLUTIONS FOR CONGESTION CASE 1B OF IEEE 30 BUS SYSTEM

Pareto solution	Cascades	Risk
Min cost	L5-L1-G2	5.49×10^{-1}
	L5-L1-L2	3.96×10^{-3}
	L5-L2-L6-L3	6.83×10^{-1}
	L5-L2-L3-G2	6.79×10^{-1}
	L5-L3-L6-L1	8.14×10^{-2}
Min congestion	L5-L1-G2	3.40×10^{-1}
	L5-L1-L2	2.26×10^{-3}
	L5-L2-L3-L6	4.46×10^{-1}
	L5-L2-L3-G2	4.46×10^{-1}
	L5-L3-L6-L1	5.54×10^{-2}
Min risk	L8-L1-L2	1.00×10^{-7}
	L5-L8-G2	2.00×10^{-7}
Compromise	L5-L1-G2	5.64×10^{-3}
	L5-L3-L6-L1	7.05×10^{-2}

L and G represent line and generator respectively

TABLE IV
CASCADES ASSOCIATED WITH THE PARETO OPTIMAL SOLUTIONS FOR CONGESTION CASE 2A OF IEEE 118 BUS SYSTEM

Pareto solution	Cascades	Risk
Min cost	L7-L34-G8	8.31×10^{-3}
	L7-L35-G26	4.06×10^{-3}
	L7-L8-L11-G12	2.81×10^{-3}
	L7-L34-L11-G12	2.30×10^{-3}
	L7-L35-L30-G25	1.01×10^{-2}
	L7-L35-L11-G12	3.80×10^{-3}
Min congestion	L10-L2-L1	2.19×10^{-6}
	L10-L3-L11-L9	1.87×10^{-6}
	L10-L3-L9-G4	8.51×10^{-5}
	L10-L9-L11-L175	1.78×10^{-5}
	L10-L2-L11-L12	1.77×10^{-6}
	L10-L2-L13-L12	2.27×10^{-9}
Min risk	L11-L3-L10-L9	1.67×10^{-6}
	L11-L3-L9-G4	8.55×10^{-5}
Compromise	L10-L2-L1	1.93×10^{-6}
	L10-L3-L11-L9	1.48×10^{-6}
	L10-L3-L9-G4	8.65×10^{-5}
	L10-L9-L11-L175	1.74×10^{-5}
	L10-L2-L11-L12	1.47×10^{-6}
	L10-L2-L13-L12	1.99×10^{-9}

L and G represent line and generator respectively

For case 2A two lines 5-11 and 11-12 are congested at the same time. Bus sensitivity factors with respect to current on each congested line are presented in Table V. Union of high sensitive buses having absolute sensitivity value greater than 0.01 are selected for this congestion management. Pareto solutions for this congestion problem are presented in Table VIII and possible cascades associated with each Pareto solution are presented in Table IV. For solution 1, though operating cost is minimum, some congestions are there in the network and 6 cascading possibilities are there. Cumulative risk of these cascades are very high (0.31×10^{-1}). For solution 2, though there is no congestion in the network, still there are 6 cascading possibilities. However, cumulative risk of these cascades are very low (0.10×10^{-3}). Solution

TABLE V
BUS SENSITIVITY FACTORS WITH RESPECT TO LINE CURRENTS

Bus number	Sensitivities w.r.t. flow on 5-11	Sensitivities w.r.t. flow on line 11-12
12	-0.12821	0.11028
4	0.09065	-0.02750
8	0.08955	-0.01172
10	0.08939	-0.01209
15	-0.03780	0.01264
1	-0.03691	0.06360
19	-0.02736	0.01182
18	-0.02179	0.01280
113	-0.01484	0.01322
6	-0.00018	0.04490

3 has only 2 very low risk cascades but its operating cost is significantly higher than solution 1 and 2. Solution 4 is somewhat trade-off solution where operation cost is close to the minimum cost and has tolerable congestion with little cumulative risk (0.10×10^{-3}) of cascading failures. Hence, in this case operator may chose solution 4 for secure and economic operation of power systems.

VIII. CONCLUSION

In the era of grid restructuring, congestion in power network is quite common. Therefore, managing network congestion becomes a big challenge for the power system operators. During congestion management due to economic pressure, operators may allow 10-15% overload on the network. However, this small congestion may turns into a widespread blackout due to malfunctioning of protective elements. Therefore, during congestion management it is very important to analyze whether there is any significant risk of cascading failures before tolerating any congestion in the grid. This paper proposes a new congestion management approach considering the risk of cascading failures. During congestion management cost of operation along with the risk of cascading failures are minimized in this approach. Firstly, it attempts to reduce congestion through an optimal rescheduling of generation. If the revised generation schedule fails to reduce congestion, it tries optimal load shedding. The scheme employs Particle Swarm Optimization technique to optimize the individual options and uses Fuzzy Satisfying technique to choose the best solution from the set of Pareto optimal solutions. Simulation results presented in this paper show that proposed congestion management scheme can manage any network congestion at an acceptable levels economically. This also ensures the grid operation safe from the cascading failures. Therefore, proposed congestion management scheme may be very effective to manage the network congestion judicially.

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TABLE VI

PARETO OPTIMAL SOLUTIONS FOR CONGESTION MANAGEMENT ON LINE 1-2 FOR IEEE 30 BUS SYSTEM

Congested condition Line 1-2, F: 79.43, C: 70			Pareto solutions															
			Solution 1 Min cost				Solution 2 Min congestion				Solution 3 Min risk				Solution 4 Compromise solution			
Bus	Pg/Pd* mw	Cost INR	Pg/Pd* mw	Cost INR	Cong. mva	Risk $\times 10^{-5}$	Pg/Pd* mw	Cost INR	Cong. mva	Risk $\times 10^{-5}$	Pg/Pd* mw	Cost INR	Cong. mva	Risk $\times 10^{-5}$	Pg/Pd* mw	Cost INR	Cong. mva	Risk $\times 10^{-5}$
1	115.00	550374	111.24	557999	76.9	2.5	97.55	574277	69.99	1.2	94.96	581664	68.87	1.04	104.72	570936	73.19	1.49
2	69.50		70.52				70.09				70.93				69.80			
5	24.99		31.85				43.92				43.34				41.81			
8	26.70		25.14				26.04				27.99				25.59			
11	27.15		25.01				25.74				25.62				24.33			
13	26.29		25.45				25.02				25.44				22.43			

* indicates load, F and C indicate line flow and line capacity respectively in MVA

TABLE VII

PARETO OPTIMAL SOLUTIONS FOR CONGESTION MANAGEMENT ON LINES 2-5 AND 5-7 FOR IEEE 30 BUS SYSTEM

Congested condition Line 2-5, F: 79.43, C: 40 Line 5-7, F: 14.21, C: 10			Pareto solutions															
			Solution 1 Min cost				Solution 2 Min congestion				Solution 3 Min risk				Solution 4 Compromise solution			
Bus	Pg/Pd* mw	Cost INR	Pg/Pd* mw	Cost INR	Cong. mva	Risk	Pg/Pd* mw	Cost INR	Cong. mva	Risk	Pg/Pd* mw	Cost INR	Cong. mva	Risk $\times 10^{-5}$	Pg/Pd* mw	Cost INR	Cong. mva	Risk $\times 10^{-1}$
1	114.99	550374	116.48	588037	43.73	1.99	114.89	604990	39.67	1.28	76.67	613541	38.26	0.03	123.85	598783	43.57	0.76
2	69.50		66.03		7.85		62.86		9.4		63.44		14.03		66.66		7.72	
8	26.70		14.47				21.37				25.77				10.53			
11	27.15		5.90				6.58				23.12				4.71			
13	26.29		26.72				14.17				32.86				23.29			
5*	94.20		72.95				65.49				74.78				68.76			
7*	22.80		13.86				9.51				4.58				16.36			

* indicates load, F and C indicate line flow and line capacity respectively in MVA

TABLE VIII

PARETO OPTIMAL SOLUTIONS FOR CONGESTION MANAGEMENT ON LINES 5-11 AND 11-12 FOR IEEE 118 BUS SYSTEM

Congested condition Line 5-11, F: 43.44, C: 35 Line 11-12, F: 36.89, C: 35			Pareto solutions															
			Solution 1 Min cost				Solution 2 Min congestion				Solution 3 Min risk				Solution 4 Compromise solution			
Bus	Pg/Pd* mw	Cost INR	Pg/Pd* mw	Cost INR	Cong. mva	Risk $\times 10^{-1}$	Pg/Pd* mw	Cost INR	Cong. mva	Risk $\times 10^{-3}$	Pg/Pd* mw	Cost INR	Cong. mva	Risk $\times 10^{-3}$	Pg/Pd* mw	Cost INR	Cong. mva	Risk $\times 10^{-3}$
1	22.22	8371216	62.40	8335808	38.56	0.31	65.34	8380573	33.62	0.10	84.19	8422715	37.67	0.08	8.84	8340967	32.18	0.10
4	80.21		14.90		41.42		45.39		34.64		65.20		23.33		50.12		40.54	
6	60.28		6.30				42.94				22.99				44.34			
8	46.35		31.09				26.21				2.10				43.06			
10	110.26		199.94				44.76				65.72				74.56			
12	151.69		136.55				64.03				84.78				134.73			
15	0.04		79.04				99.98				77.45				96.16			
18	92.90		68.32				99.98				99.98				55.50			
19	70.51		41.15				99.98				86.11				91.74			
113	47.91		48.80				99.98				99.98				89.42			

* indicates load, F and C indicate line flow and line capacity respectively in MVA