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Congestion Management Considering Economic and Efficient Generation Rescheduling

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Abstract*— Increasing interconnections and usage of power networks makes the system to work at almost full loading capacities. Any type of disturbance in such scenario results in congestion of the existing network. This condition, if not managed within required time may result in system collapse. This paper presents a simple and economic transmission line overload alleviation method that is very much required in day-to-day operation and control of power systems. This method of managing the congestion aims primarily at improving the voltage stability of the system while relieving the overload and does this economically to the possible extent. Relative Electrical Distances (RED) between the loads and generators is the criterion for relieving the overload in a transmission line, by rescheduling the generation. The process of rescheduling is done economically by making use of fuzzy logic considering the incremental fuel costs of the generators. This method is illustrated using IEEE 39-node New England system and a real-life system, 75-node North Indian power system

***Index Terms*—Congestion management, Generation rescheduling, Voltage stability, Fuzzy Logic**

I. INTRODUCTION

Congestion management is an important technical challenge in power system operation. The electric power market background makes the operation of system further complicated. The consumers should be supplied with reliable power even in cases of contingencies in the system. The cost of managing congestion also needs to be considered and maintained as minimum as possible in this process.

Control of power flow in a deregulated environment depends on multiple factors, and needs more attention to avoid techno economical disputes. Several control algorithms are reported in the literature [1-4] in this regard. Most of these algorithms depend on conventional optimization techniques. Zheng and Chowdhury [1] have suggested that generation has to be rescheduled when congestion occurs in a deregulated power system, to ensure system security. Lobato et al. [2] have presented optimization methods to understand and mitigate network congestion.

Generation scheduling method has been proposed in Lei et al. [3] to manage congestion in deregulated Chinese power system based on fast linear optimization. Later, both generation cost and line overload index are considered as multi objectives to minimize in [4]. But, large computation times, particularly for extensive systems is the short coming of these traditional optimization techniques. Hence, these methods are not suitable under emergency operating conditions for the purpose of managing congestion to ensure system security.

For efficient control of security issues such as congestion, solution must be sought on-line. The tools used for this task should be able to detect situations that may lead to cascading failures in times of emergency in a very short time. These timely decisions can help the operators of the Energy Control Centre (ECC) to drive the system away from cascade tripping and a possible voltage collapse. In the process of improving the computational speeds of the security improvement tools, artificial intelligent techniques like Fuzzy logic and Expert systems [5, 6] seemed to serve the purpose. They may be appropriate for assisting dispatchers in ECC both in terms of speed of response as well as decision making. By using Operational Load Flow, Bansilal D. Thukaram and K. Parthasarathy [5] have made use of phase shifting transformers along with generation rescheduling for reducing the overload in the congested line. A. N. Udupa et al. [6] demonstrated the use of Generation Shift Sensitivity Factor (GSSF) for the same task. These methods can be applied for traditional power systems. Kothari et al. [7] presented reviews on issues concerning congestion and its management in the deregulated environment. In online environment under emergency conditions, decisions have to be taken very quickly, in the vicinity of optimal operating condition. In this regard, a simple and efficient method has been proposed based on RED concept in [8]. However, cost involved in rescheduling of generators is not considered here while trying to manage congestion.

Generation rescheduling is one of the mostly used methods for the same purpose, it being simple and non-expensive. This paper proposes congestion management technique utilizing RED concept and incremental fuel cost of rescheduling generators using Fuzzy logic. This results in minimum number of generators for rescheduling and less cost involved in the rescheduling process.

The scheme of work in the paper is organized as follows. The basis of generation rescheduling, Relative Electrical Distances (RED) concept is explained in section II. The task of congestion management is illustrated using three different approaches: I, II & III here. Management of congestion by rescheduling generation is implemented using only RED based method in Approach-I. Economics of rescheduling is not considered in this approach. In Approach-II, the economics of rescheduling the generators is considered by making use of their incremental fuel costs alone. So the effect of rescheduling only economically, neglecting the

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desirable proportions, is dealt in this approach. Approach-III, the proposed method, deals with rescheduling process using fuzzy logic, which considers both incremental fuel cost and desired proportion of generations, D_{LG}, as suggested by RED method. A comparison of all three approaches is presented for the considered test systems.

II. BASIS FOR GENERATION RESCHEDULING - RED

Consider a system where n is the total number of buses with 1,2,……g; g is the number of generator buses, and g+1,……n are remaining (n-g) buses.

For a given system we can write,

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \qquad (1)$$

Where, I_G, I_L, and V_G, V_L represent complex current and voltage vectors at the generator nodes and load nodes. $[Y_{GG}]$, $[Y_{GL}]$, $[Y_{LL}]$, $[Y_{LG}]$ are corresponding partitioned portions of network Y-bus matrix. Rearranging (1) we get

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \qquad (2)$$

Where, $F_{LG} = - [Y_{LL}] -1 [Y_{LG}]$.

The elements of $[F_{LG}]$ matrix are complex and its columns correspond to the generator bus numbers and rows correspond to the load bus numbers. Relative Electrical Distance (RED) is the relative location of load nodes with respect to generator nodes, and is obtained from $[F_{LG}]$ matrix.

$$[R_{LG}] = [A] - abs\{[F_{LG}]\} \qquad (3)$$

Where, [A] is the matrix with (n-g) number of rows and g number of columns, with all elements equal to 1.

The desired proportions of generators for desired load sharing is also obtained from $[F_{LG}]$ matrix, and is given by

$$[D_{LG}] = abs\{[F_{LG}]\} \qquad (4)$$

$[D_{LG}]$ matrix gives the information, for each load bus, about the amount of power that should be taken from each generator under normal and network contingencies, as far as the system performance is considered with respect to the voltage profiles, bus angles and voltage stability L-index. This matrix is used as the basis for the desired generation scheduling. If each consumer takes the power from each generator according to the $[D_{LG}]$ matrix the system will have minimum transmission loss, minimum angle separation between generator buses and minimum L-indices.

The methodology used for relieving congestion in case of any contingency can be explained as follows. For a particular operating condition, Congested transmission lines (over loaded lines) are identified and the contribution of each generator to the congested line is estimated [9]. Among all the generators, those which are contributing to the congested line(generators that have a share in the flow of overloaded line) are identified as Generation Decrease group (GD group).This is the group where generation decrease is recommended to relieve the overloaded line ;And the generators which are not contributing to the congested line (generators that do not have a share in the flow of overloaded line) are categorized under Generation Increase group (GI group). This is the group where generation increase is recommended.

At any instant of time, total generation change in GD group must be same as the total generation change in the GI group. The amount of generation change required to relieve the congestion of the mostly congested line is estimated. Then the total amount of required capacity change is shared by the generators of the GD group in proportion to the margins available on these generators. Here, the margins of the generators of GD group are estimated based on D_{LG} matrix. The same amount of generation change is to be met from the generators of GI group to avoid load shedding.

III. ECONOMIC GENERATION RESCHEDULING USING FUZZY LOGIC (PROPOSED APPROACH)

Generation rescheduling in this method is done economically using Incremental fuel costs and efficiently using D_{LG} values of RED method. Fuzzy Logic is used to obtain an optimal scheduling value, utilizing both the above-mentioned methods. Instead of rescheduling all generators of GI group, Fuzzy Inference System (FIS) helps in selecting only few generators, thereby, the time involved in changing the settings of generators is reduced in case of an emergency situation. The method is explained as follows.

Since these congestion management studies are first performed offline, all the contingencies are simulated at varying load conditions and the probable schedules of the generators are calculated beforehand, so that they might be of use under emergency operating conditions. If in any case, the then operating condition of system does not match with the conditions available offline, then algorithm may be followed.

A. Algorithm for proposed Approach

Step 1: The solution of the load flows of the system, or the status obtained from the state estimator gives the picture of the system regarding voltages and power flows. If any transmission line is overloaded, proceed to the next step, otherwise stop.

Step 2: Based on RED concept, form the F_{LG} and D_{LG} matrices. The elements of D_{LG} matrix corresponding to the overloaded line give the estimate of desired generation from all the generators. The line with highest overload is considered in case of multiple line overloads.

Step 3: Find the contribution of each generator towards this highly overloaded line.

Step 4: Split up the generators into two groups, GD group consisting of generators which actually contribute to the overloaded line, and GI group consisting of non-contributing generators.

Step 5: Estimate the margin available on each contributing generator using D_{LG} matrix.

Step 6: Estimate the required generation decrease ΔP^- to relieve the congestion using the actual contributions of generators in the congested line.

Step 7: The total power ΔP^{-} of all generators of GD group together constitute the rescheduling amount of power

Step 8: For distribution of the rescheduling amount of power among GI group of generators, D_{LG} coefficients and incremental fuel costs of generators of this group are given as inputs to the Fuzzy Inference System (FIS).

Step 9: These generators are assigned a priority by the FIS, based on which the rescheduling power is allotted. Generator with highest priority is first assigned additional power depending on the margin available on it.

Step 10: The remaining power is allotted to generator with next priority considering its margin. This results in allotting the reschedule amount of power to few generators only.

Step 11: After distributing total ΔP among few GI group generators, perform the operational load flow and check if congestion is relieved. If congestion still persists on the overloaded line or other lines, go back to step 2.

B. Fuzzy Inference System (FIS)

The system that carries out mapping of input variables to the output variables using fuzzy logic is termed as a Fuzzy Inference System (FIS). Decisions depend on the mapping strategies developed. In the present approach, non-contributing generators as well as cost of these generators are the influential factors to decide the amount of power to be rescheduled among them to reduce the congestion in the transmission line.

The FIS is designed with the following input variables

1. D_{LG} coefficients of GI group generators
2. Incremental fuel costs of GI group generators

The share of a particular non-contributing generator depends on its relative electrical distance from the location of congested line. Elements of D_{LG} matrix, as given in equation (4) are referred to as D_{LG} coefficients, represent the relative electrical distance of the generator with respect to the congested line. As mentioned earlier in section II, D_{LG} coefficients of the generators suggest the amount of power they can contribute to the considered line, hence the system parameters like real power loss and voltage stability indices are better than other amounts of contributions. FIS is designed to decide the order in which non-contributing generators have to be considered for rescheduling. This is decided by FIS with considered inputs and associated fuzzy rules. The output of the proposed approach is to decide the priority of GI group generators; A generator has higher priority if its D_{LG} coefficient is large and incremental fuel cost is reasonably less. The range of priority is set to vary from 0 to 1, where 1 indicates the highest priority. The generator with highest priority is allotted with rescheduling power in the beginning, depending on the margin available on it. The leftover rescheduling power is allotted to the generator of next highest priority, considering available margins and is repeated until total rescheduling power allotment is done. Hence, few generators with higher priority of GI group are rescheduled. The remaining generators with least priority are not disturbed. This is how the number of generators to be rescheduled is reduced, resulting in saving time and cost involved in managing congestion.

C. Membership Functions and Rule Base of FIS

D_{LG} coefficient is categorized into five membership functions namely, Very Low Contribution (VLCn); Low Contribution (LCn); Medium Contribution (MCn); High Contribution (HCn) and Very High Contribution (VHCn). Similarly, Incremental fuel cost is also categorized into five membership functions namely, Very Low Cost (VL); Low Cost (L); Medium Cost (M); High Cost (H) and Very High Cost (VH). Similarly, Output of the FIS, Priority of the generator also consists of five membership functions, namely, Very Less Priority (P5); Less Priority (P4); Medium Priority (P3); High Priority (H2) and Very High Priority (P1) [9]. All the membership functions, as shown in Fig.1 are considered to be triangular in nature in order to have an even distribution of variables throughout the range.

A fuzzy rule base is developed to assign priority to generators as given in Table I. P1 through P5 are the priorities assigned to the generators, where, P1 corresponds to highest priority with value of 1; and P5 corresponds to least priority with a value of 0.

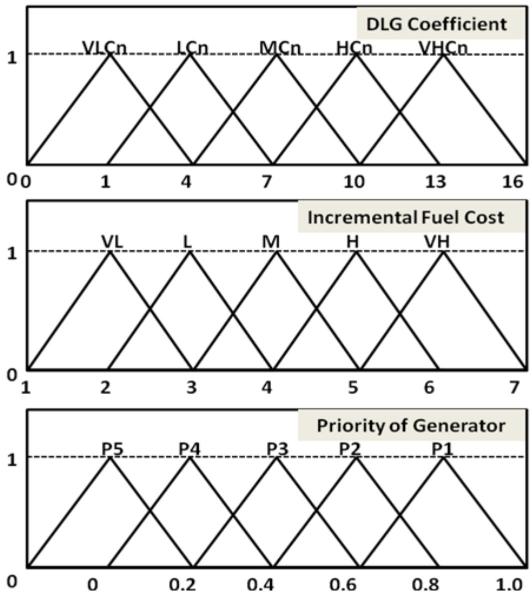

Fig.1. Membership functions of input and output variables

Fuzzy rules are similar to the general {If (..), then (..)} rules. One of the fuzzy rules can be illustrated as follows: “If D_{LG} coefficient of a generator is VLCn, and the Incremental Fuel cost is VH, then priority of that generators is given to be P5.”

Similarly, 25 rules are designed as the number of inputs is 5 and number of outputs is 5. The two inputs of FIS are combined using ‘and’ clause.

RED based congestion management method has been illustrated using IEEE 39-node New England System. This system is a simplified representation of the 345kV transmission system in the New England region having 10 generators and 29 load nodes as shown in Fig. 2.

Table I. Fuzzy rule base

1.	2. Incremental Fuel cost					
3. D_{LG} Coefficient	4.	5. VL	6. L	7. M	8. H	9. VH
	10. VLCn	11. P4	12. P4	13. P4	14. P5	15. P5
	16. LCn	17. P3	18. P3	19. P4	20. P4	21. P5
	22. MCn	23. P2	24. P2	25. P3	26. P4	27. P4
	28. HCn	29. P1	30. P2	31. P2	32. P3	33. P4
	34. VHCn	35. P1	36. P1	37. P2	38. P3	39. P4

IV. RESULTS & DISCUSSIONS

Congestion management method is illustrated by simulating a line outage contingency so that one or more lines are congested. This overload in the line is first relieved using Approach-I. For IEEE 39-node New England system, an example is illustrated to explain the process. As a consequence of line L10-13 outage, line L5-6 is overloaded with a power flow of 726.1 MVA (flow limit is 500 MVA). The flow in this overloaded line is contributed by generators G31 and G32 with percentages 55.8 and 44.2 respectively [10]. Therefore, G31 and G32 generators come under GD group and GI group consists of the other generators. Actual values of contributions to the congested line are indicated in Table II. These are the elements of D_{LG} matrix corresponding to the overloaded line.

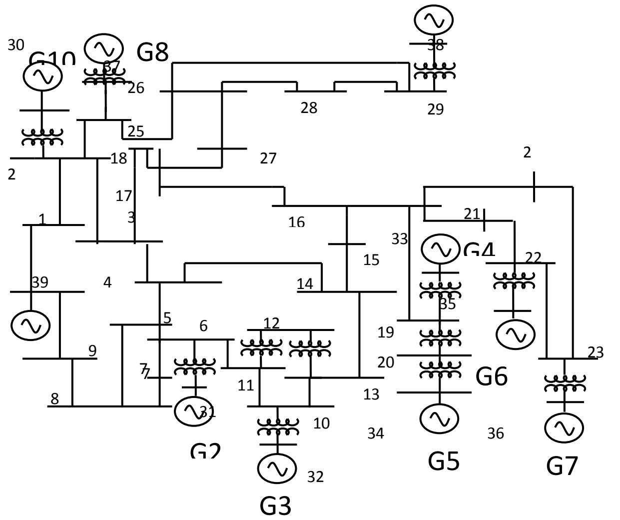

Fig 2. IEEE 39-node system

Margin available at G31 is (36.7-55.8) = -19.1%

Margin available at G32 is (29.1-44.2) = -15.1%.

The quantity of generation reduction suggested at these two generators is in the ratio of their margins. By changing the generation at G31, 128.3 MVA can be relived and at G32, 99.0 MVA in the overloaded line can be relived.

Amount of generation decrease suggested at

G31 is $\Delta P31- = 128.3/0.558 = 230.0$ MW.

G32 is $\Delta P32- = 99.0/0.442 = 224.0$ MW.

The total Generation decrease for the GD group is (230+224) =454 MW.

Generators in GI group are allotted with rescheduling power in the ratio of their D_{LG} values.

The Generation rescheduling is as follows:

$\Delta P30+=71$ MW $\Delta P33+=47$ MW $\Delta P34+=21$ MW
$\Delta P35+=49$ MW $\Delta P36+=27$ MW $\Delta P37+=42$ MW
$\Delta P38+=26$ MW $\Delta P39+=173$ MW
$\Delta P31-= 230$ MW $\Delta P32-= 224$ MW

The generation to be rescheduled is as follows in the case of Approach-II, where only incremental fuel costs of the generator are considered.

$\Delta P36+ = 140$ MW $\Delta P39+ = 200$ MW $\Delta P30+ = 114$MW
$\Delta P31- = 230$MW $\Delta P32- = 224$MW

Table II. D_{LG} values of the overloaded line

G30	G31	G32	G33	G34	G35	G36	G37	G38	G39
6.5	**36.7**	**29.1**	**4.3**	**1.9**	**4.5**	**2.5**	**3.8**	**2.4**	**15.9**

The amount of generation reduction required at GD group generators (G31 and G32) is 230 MW and 224 MW respectively. Hence, the total amount of power to be rescheduled is 454 MW. All this power is to be allotted to the generators of GI group.

In the proposed approach, FIS is designed to determine priority of GI group generators. So, the generators are listed in the order of their priority. It can be observed from Table III, that for this example, G39 is ranked 1 and has a margin of 200 MW. Out of 454 MW, 200 MW is allotted to G39. The generator with next better rank is G30. Since the margin available is 250 MW, of the remaining power 250 MW is allotted to G30. Since some amount of power has to be allotted yet, the generator with better rank, G36 is allotted 4 MW. The new schedule of all generators using this proposed fuzzy logic approach is given below.

$\Delta P31- = 230$ MW, $\Delta P32- = 224$ MW
$\Delta P39+ = 200$MW, $\Delta P30+ = 250$ MW, $\Delta P36+ = 4$MW

Table III. Priorities of GI group generators of IEEE 39-node system

GI group Generators	Priority (obtained using FIS)	Rank of Generator (Based on Priority)
G30	0.44	2
G33	0.228	4
G34	0.087	8
G35	0.196	6
G36	0.300	3
G37	0.199	5
G38	0.170	7
G39	0.700	1

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Table IV. Performance parameters of IEEE 39-node system

System Performance parameter	Pre-Rescheduling Flow	Rescheduling based on RED (Approach-I)	Rescheduling based on Economy (Approach-II)	Rescheduling based on FLC (Approach-III)
Flow in congested line 5-6 (MVA)	726.1 (145 %)	443.1 (89%)	443.9 (89%)	442.3 (88%)
Ploss (MW)	46.33	49.99	46.64	43.66
Vmin (pu)	0.982	0.982	0.982	0.982
Max (Li)	0.1108	0.1040	0.1038	0.1049
Σ L2	0.1457	0.1411	0.1404	0.1402
ve	0.0305	0.0295	0.0296	0.0311
No. of generators rescheduled	--	10	5	5
Cost of Rescheduling of GI group generators ($/h)	--	54.87	20.18	20.70

From the Table IV, it is clear that generation rescheduling in all the three approaches leads to relieving congestion of the overloaded line. First approach comes up with better parameters of the system operation but this approach is not suggested as the cost involved in managing congestion is relatively more. The second approach that is aimed at economic rescheduling of generators results in less cost of rescheduling as the number of generators considered has been reduced. The proposed Fuzzy logic-based approach provides the more optimal solution, the power losses are least, voltage stability improvement is observed and the cost of rescheduling is also almost as minimum as possible, similar to second approach.

From this analysis, it is obvious that the number of generator settings to be adjusted is reduced and the cost involved in doing so is also decreased inherently. The proposed approach enhances the system security as well as reduces the cost involved in congestion management process. Hence, this approach is most suitable for the dispatcher in ECC during emergencies.

The above results obtained from the proposed approach are compared with the results in Reference [8]. The outage of line 4-14 is considered to observe the rescheduling effect of mitigating congestion in the line 5-6. The results [9] of comparison are listed in Table V. It can be observed that the main objective of reducing the congestion in the overloaded line is achieved along with the added advantage of reduced number of generators adjustment for rescheduling and reduced cost of rescheduling.

Table V. Comparison results of proposed approach with Reference [8]

Parameter	Reference [8]	Proposed Approach
Flow in line 5-6 after rescheduling	511.8 MVA (102.4%)	494.6 MVA (99%)
Number of Generators for rescheduling	10	4
Cost of Rescheduling	39.46 $/MWhr	11.40 $/MWhr
Power loss	58.0 MW	54.6 MW
ΣL^2	0.7259	0.7246
Ve	0.0331	0.0339

Similar analysis is also summarized for a real 75-node North Indian power system. 75-node Indian power system corresponds to Uttar Pradesh State Electricity Board (UPSEB) system, shown in Fig.3. It has 15 generators, 60 load points and 98 transmission lines (including 24 transformers).

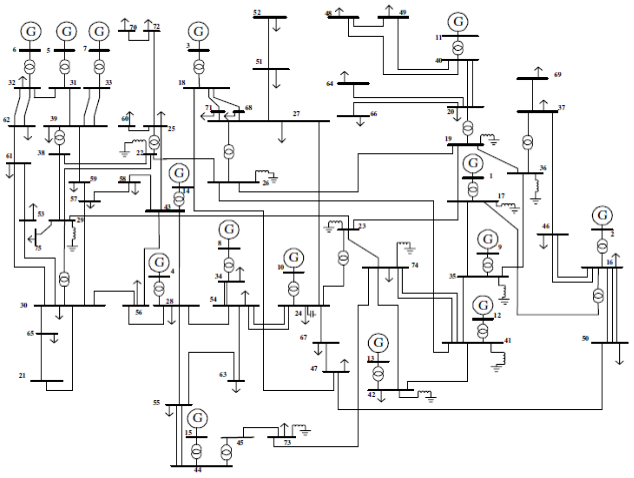

Fig.3. 75-node Indian Utility system

The line connecting the buses 15 and 23 is considered for outage to create a contingency. This results in overloading of the line connecting 23 and 24 buses. The D_{LG} coefficients of all generators with respect to this overloaded line along with priority of all generators of GI group obtained using FIS are presented in Table VI. The results of rescheduling are illustrated in Table VII.

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Table VI. D_{LG} values and Priorities of GI group generators of 75-node system

GI group Generators	D_{LG} values	Priority (obtained using FIS)	Rank of Generator (Based on Priority)
G2	10.7	0.221	12
G3	3.4	0.511	4
G4	9.2	0.343	6
G5	3.4	0.300	8
G6	2.7	0.225	11
G7	1.3	0.300	7
G8	1.5	0.260	10
G9	2.4	0.408	5
G10	7.2	0.525	2
G11	12.8	0.300	9
G14	2.4	0.554	1
G15	2.6	0.525	3

Table VII. Performance parameters of 75-node system

System Performance parameter	Pre Rescheduling	Rescheduling based on RED	Rescheduling based on Economy	Rescheduling based on FLC based economy
Flow in congested line (23-24) (MVA)	679.2 (133%)	582.4 (114%)	597.9 (117%)	567.1 (111%)
P loss (MW)	210.7	166.6	161.1	165.8
Vmin (pu)	0.918	0.936	0.937	0.937
Max (Li)	0.6716	0.5748	0.5489	0.5674
Σ L2	6.437	4.648	4.189	4.681
Ve	0.0655	0.0998	0.1093	0.1005
No. of generators rescheduled	--	15	8	8
Cost of Rescheduling of generators ($/h)	--	82.41	32.61	34.96

V. CONCLUSION

The task of the dispatcher at the ECC is to maintain security of the system in tact under normal or any emergency condition. Some of the emergencies may arise due to congestion in one or more transmission lines because of various reasons. This paper discusses three approaches of relieving congestion in the transmission line. Approach I, considers relative electrical distance and reduces the congestion in the line and improves aspects like voltage security, power loss. But can do so only at a higher operating cost. To overcome this, an Approach II deals with rescheduling of generators based only on cost of the generators. This Approach results in lowest cost of managing congestion, but the system parameters do not seem encouraging. Hence, an Approach III, based on RED and economic operation, using fuzzy logic is proposed in this paper. The developed FIS gives the decision regarding priority considering drawbacks of above two approaches. The system parameters and cost parameters are all improved in the proposed approach. The results obtained on the considered test systems and practical systems reveal that the proposed approach is most helpful for the dispatcher in Energy Control Centre during emergency conditions.

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