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Emergency Control Analysis Procedure using Multi-Objective Fuzzy Linear Programming Technique

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Abstract- *This paper proposes an effective procedure to control the power systems during different emergency conditions using the fuzzy linear programming (FLP) technique. This procedure depends on the optimal preventive control action, which is prepared before the emergency occurrence. The multi-objective preventive control actions are: minimizing the generation cost function, maximizing the generation reserve at certain generation or at all generation system, and maximizing the preventive control actions for one or more critical transmission lines, while all the system constraints are satisfied. The results demonstrate the capabilities of the proposed procedure to generate well-controlled of emergency conditions. The comparison with conventional procedures, which hasn't prepared preventive actions, shows the superiority of the proposed procedure and confirms its potential to remove the effects of emergency problems.*

Keywords - Emergency, Fuzzy Linear Programming, Preventive Control Actions, Security.

1. INTRODUCTION

The basic function of electric power systems is to feed the load demand at economical, secure, quality, and continuity. The new rescheduling of steady state can be predicted by emergency analysis. An emergency analysis is used to detect most severs outages and emergency constraints, which are augmented to the base case to assure a preventive control actions effects. Emergency may occurred due to line/ lines outages, outage in parts of generation units or increase in load demand. When a line is switched on/off the system through the actions of circuit breakers, line currents are redistributing throughout the network and bus voltages changes. Also, other factors like unit's outage, relays actions, lightning, and storms may lead to emergency in large-scale power systems. If the transient died down then the system reaches steady state. The main effect of violations continuity is the damage may occur if the violations not removed. So, planning of emergencies control strategies is an important aspect of secure and economical operation of the power systems. The branch of emergency control strategies is active searching filed in power system operations. Reference [1] presented an optimal on-line control strategy with different objectives according to the operational case and solved such problems using linear programming technique for system voltages and reactive powers. An emergency control algorithm using fuzzy set theory was proposed [2]. Considering the criteria of selecting between voltage violations and overload violations and makes prioritizing processes in emergency situations, the authors in [3] presented the emergency constrained optimal power flow (OPF) problem formulated in a decomposed form and proposed different fuzzy goals for the constrained OPF problem under contingencies. Reference [4] presented a nonlinear method to solve the economic dispatch with generation emergency constraints on the basis of Dantzig-Wolfe decomposition principles. K. R. W. Bell et al. [5] presented an approach to solve the security problem considering the operator heuristics. Reference [6] presented the fuzzy modeling of generation unit, real load, and power flows in critical lines and proposed FLP based approach to solve the static security problem and proposed the use of phase shifter to alleviate the overflow in transmission lines for emergency conditions. They used the fuzzy real load distribution in their approach, which solved using FLP technique with fuzzy constraints and objectives. The preventive control strategy [7] was used to prepare different reserve levels, which achieved for one or more generation unit or for critical line/lines, to alleviate the emergency conditions. In [8], different security regions that satisfy the condition of secure and economic solution of power dispatch controller at different positions. Two fuzzy models namely, triangular and trapezoidal are proposed in [9] to determine the suitable model for each power system constraint.

In this paper, different emergency conditions for generation units, lines, and load demand are considered. The proposed procedure is based on multi-objective FLP technique and modifies the system objectives and constraints to be related for each emergency type. The trapezoidal fuzzy modeling of power generation units and power demand are considered as proposed. While, The triangular fuzzy modeling of power flow in transmission lines are considered as proposed in [9].

2. PROBLEM FORMULATION

Emergency Problem

The emergency condition may be occurred as a result of outage of one or more lines, outage of generation units and increase in power demand. The emergency problem formulation is obtained through an overflow in one or more, under voltage at load bus and under frequency of some buses. A serious emergency condition is the outage of generation units, which is limited by the load requirements and leads to system de-loading.

In this paper, the outage of generation plant is achieved by gradually outages of partial generation units.

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In the case of sufficient power generation outage to feed load requirements, the main problem is the violation in one or more lines. The use of the preventive actions from these lines presents high guarantee for the power systems operation. But in the case of the power generation units is not sufficient to meet the load requirement, another procedure is proposed based on load shedding procedure.

Fuzzy LP Power Dispatch

Fuzzy logic represents an effective alternative compared to conventional approaches. It attempts to qualify linguistic terms. Equations (1) – (6) present the power dispatch problem with fuzzy objective function and fuzzy system constraints as:

$$Min\ F = \sum_{i=1}^{NG} F_i\left(\tilde{PG}_i\right) \tag{1}$$

Subject to:

- Fuzzy power balance constraint.

$$\sum_{i=1}^{NG} \tilde{PG}_i = \sum_{j=1}^{NB} \tilde{PD} + P_{loss}, \tag{2}$$

- The fuzzy critical power flow constraint

$$PF_k^{\min} \le \tilde{PF}_k \le PF_k^{\max} \tag{3}$$

The power flow in line k (PF_k) can be computed from the following equation as [10]:

$$PF_k = \sum_{i=1}^{NG}\left(D_{k,i}.PG_i\right) \tag{4}$$

- Fuzzy PG output limits constraints

$$PG_i^{\min} \le \tilde{PG}_i \le PG_i^{\max} \tag{5}$$

- Power reserve constraint

$$\sum_{i=1}^{NG} CAPG_i - \tilde{PG}_i - Y_i \ge REQSPN \tag{6}$$

$$CAPG_i - \tilde{PG}_i - Y_i \ge SPNMAX_i\ ,\ i = 1,....,NG \tag{7}$$

Preventive Control Action Procedure [7]

The preventive control actions can be prepared from one or more generation units and/or one or more transmission lines. The proposed preventive control actions objective and constraints are:

i) Preventive control actions for each generation unit

The maximal effect of the preventive control action for each generation unit can be expressed as:

$$\begin{aligned} &Max\ YG_i,\\ &PG_{io} - \tilde{PG}_i \le YG_i \end{aligned} \tag{8}$$

ii) Preventive control actions for all generation units

Equation (8) is restated, as a multi-objective problem to obtain the maximal effect of the preventive control actions for all generators simultaneously, as:

$$\begin{aligned} &Max\ YG_i,\\ &PG_{io} - \tilde{PG}_i \le YG_i, i = 1,....., NG \end{aligned} \tag{9}$$

iii) Preventive control actions for each critical transmission line

The maximal effect of the preventive control action for each critical line can be expressed as:

$$\begin{aligned} &Max\ YF_k,\\ &PF_{ko} - \tilde{PF}_k \le YF_k \end{aligned} \tag{10}$$

iv) Preventive actions for all critical transmission lines

Equation (10) is restated, as a multi-objective problem to obtain the maximum effect of the preventive control actions for all critical lines at the same time, as shown in equation (11):

$$\begin{aligned} &Max\ YF_k,\\ &PF_{ko} - \tilde{PF}_k \le YF_k, k = 1,....., NL \end{aligned} \tag{11}$$

3. PROPOSED PROCEDURE

Two initial states before the emergency condition occurrence are presented. The difference between the two cases is the initial state, which is considered. In the first case, the initial state is dependent on FLP correctives. But, the second case depends on the initial state, which is obtained from the preventive control actions. In this case, the operator prepares some preventive control actions from the power generation and the transmission lines to alleviate the emergency conditions.

In the emergency condition, the operator must take a suitable decision depends on the type of the emergency conditions. The proposed procedure for the emergency conditions is simulated as follows: -

- Preparing the optimal power dispatch based on FLP dispatch (***case 1***).
- Preparing preventive control actions as an initial state (***case 2***).
- Simulating the emergency conditions.
- Comparing between the two cases according to the effects of initial states and corrective time. The corrective time is proportional to the amount of the control variables changed as: -

$$T_i\ \alpha\ \Delta(PG_i) \tag{12}$$

Other cases are considered after the emergency occurrence: -

case 3. Load flow calculation using the MATPOWER [11] after emergency occurrence.

case 4. Load flow calculation after emergency occurrence depends on the initial state of the FLP calculations (case 1).

case 5. Load flow calculation after emergency occurrence depends on the initial state of the preventive actions (case 2).

case 6. Fuzzy LP calculations after the emergency occurrence depend on case 3.

case 7. Fuzzy LP calculations after the emergency occurrence depend on case 4.

case 8. Fuzzy LP calculations after the emergency occurrence depend on case 5.

Linearization of the generation Cost Function

The quadratic form of generation cost functions is formulated as nonlinear optimization problem as:-

$$F_i(PG_i) = a_i.PG_i^{\ 2} + b_i.PG_i + c_i \tag{13}$$

The solution of the OPD problem using FLP technique requires linear objective function. The generation cost function, of unit i, in linear form for small variation in unit i power generation output can be written as:-

$$F_i = \left.\frac{dF_i}{dPG_i}\right|_{PG_i = PG_i^0} .PG_i \tag{14}$$

$$F_i = \left(2a_i PG_i + b_i\right)\Big|_{PG_i = PG_i^0} .PG_i \tag{15}$$

$$F_i = \left(2a_i PG_i^{\,0} + b_i\right).PG_i \tag{16}$$

Then, the approximate form of total generation cost function is written as: -

$$F_i = \sum_{i=1}^{NG} (2a_i PG_i^{(0)} + b_i).PG_i \tag{17}$$

Fuzzy Modeling of Constraints and Objectives

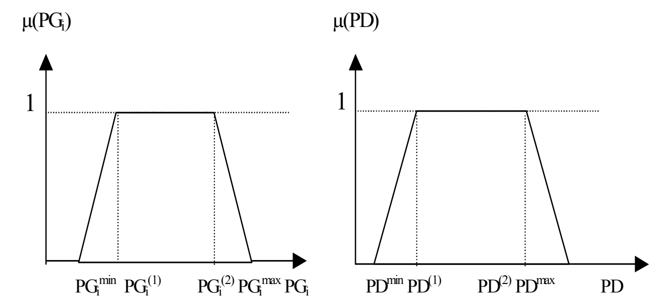
i) Fuzzy modeling of constraints

The trapezoidal fuzzy modeling of the power generation and the power demand are presented as shown in Fig. 1, The trapezoidal membership functions of the power generation at bus i and the power demand are described as shown in Equations (18) and (19). The membership of power generation at bus i is:

$$\mu_{PG_i}(PG_i) = \begin{cases} 0 & PG_i < PG_i^{min} \\ \left(PG_i - PG_i^{min}\right)/\left(PG_i^{(1)} - PG_i^{min}\right) & PG_i^{min} \le PG \le PG^{(1)} \\ 1 & PG^{(1)} \le PG_i \le PG_i^{(2)} \\ \left(PG_i^{max} - PG_i\right)/\left(PG_i^{max} - PG_i^{(2)}\right) & PG_i^{(2)} \le PG_i \le PG_i^{max} \\ 0 & PG_i > PG_i^{max} \end{cases} \tag{18}$$

The membership of the trapezoidal membership model of the power demand is:

$$\mu_{PD}(PD) = \begin{cases} 0 & PD < PD^{min} \\ \left(PD - PD^{min}\right)/\left(PD^{(1)} - PD^{min}\right) & PD^{min} \le PD \le PD^{(1)} \\ 1 & PD^{(1)} \le PD \le PD^{(2)} \\ \left(PD^{max} - PD\right)/\left(PD^{max} - PD^{(2)}\right) & PD^{(2)} \le PD \le PD^{max} \\ 0 & PD > PD^{max} \end{cases} \tag{19}$$



a. Power generation membership for unit i b. Power demand membership function

Fig. 1. Trapezoidal membership models.

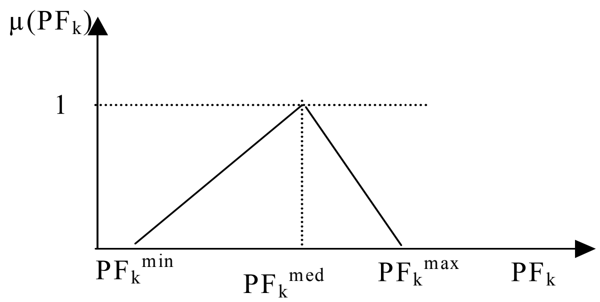


Fig. 2. Triangular fuzzy membership function for power flow.

A triangular fuzzy modeling for the transmission line flow at critical line k (PF_k) is shown in Fig. 2. It is seen that a membership function equal to 1 is assigned to PF_k^{med} . Each line flow is represented by two linear constraints for the upper and lower limits. The membership function for the line flow limits at line k is described as:

$$\mu_{PF_k}(PF_k) = \begin{cases} 0 & PF_k < PF_k^{min} \\ \left(\left(PF_k - PF_k^{min}\right)/\left(PF_k^{med} - PF_k^{min}\right)\right) & PF_k^{min} \le PF_k \le PF_k^{med} \\ \left(\left(PF_k^{max} - PF_k\right)/\left(PF_k^{max} - PF_k^{med}\right)\right) & PF_k^{min} \le PF_k \le PF_k^{max} \\ 0 & PF > PF_k^{max} \end{cases} \tag{20}$$

ii) Objectives fuzzy modeling

Different objective functions are considered in the proposed procedure. These are minimizing the generation cost function and maximizing the preventive control actions for power generation reserve and line power flows. The fuzzy modeling of the generation cost function is shown in Fig 3. Equation (21) can be represented the fuzzy membership function of the cost which is less than or equal the permissible cost as:

$$\mu_C(C) = \begin{cases} 1 & C < C^{min} \\ \left(\left(C - C^{min}\right)/\left(C^{max} - C^{min}\right)\right) & C^{min} \le C \le C^{max} \\ 0 & C > C^{max} \end{cases} \tag{21}$$

The fuzzy membership function for maximizing the effect of the preventive control actions from generation units and/or from transmission lines can be represented as Equation (22) and as shown in Fig. 4.

$$\mu_Y(Y) = \begin{cases} 0 & Y < Y^{min} \\ \left(\left(Y^{max} - Y\right)/\left(Y^{max} - Y^{min}\right)\right) & Y^{min} \le Y \le Y^{max} \\ 1 & Y > Y^{max} \end{cases} \tag{22}$$

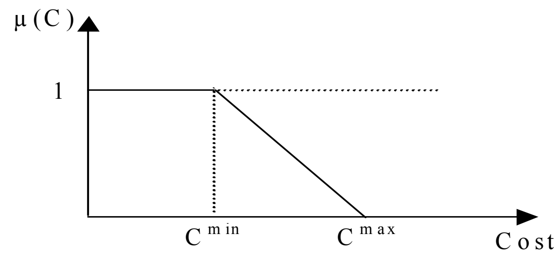


Fig. 3. Fuzzy membership function for the cost objective.

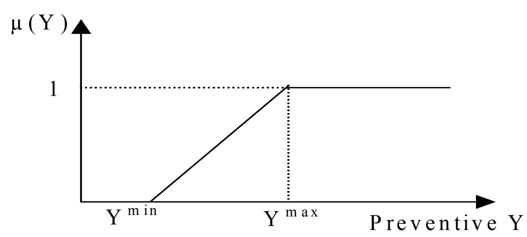


Fig. 4. Fuzzy membership function for the preventive control action Y.

FLP Optimization Model

The FLP optimization technique is used to solve the fuzzy-based OPD problem ((1) - (7)). The degree of satisfaction the fuzzy cost and fuzzy constraints, (Equations (18) - (22)), can be represented by a membership variable λ. The satisfaction variable λ is defined as the minimum of all membership functions of the fuzzy objectives constraints. The fuzzy-based optimal OPD solution maximizes satisfaction variable λ. Then, the relationship between the satisfaction factor λ and other membership functions can be written as the minimum of all membership functions. The mathematical representation is:

$$\max_{PG_i,\ \lambda} \lambda, \tag{23}$$

$$s.t.\ \lambda \le \mu_m(.), m = 1,....,NC, \tag{24}$$

$$and \quad 0 \le \lambda \le 1 \tag{25}$$

Equation (19) can be extended to include different power system constraints as:

$$\lambda \le \mu_C\left(C\left(PG_i\right)\right), \tag{26}$$

$$\lambda \le \mu_Y\left(Y\left(PG_i\right)\right), i = 1,...., NG, \tag{27}$$

$$\lambda \le \mu_{PG_i}\left(PG_i\right), i = 1,...., NG, \tag{28}$$

$$\lambda \le \mu_{PD}\left(PD(PG_i)\right) \tag{29}$$

$$\lambda \le \mu_{PF_k}\left(PF_k(PF_k)\right), k = 1,....., NL, \tag{30}$$

The objective functions fuzzy constraints are:

$$C + (C^{\max} - C^{\max})\lambda \le C^{\min} \tag{31}$$

$$-Y + (Y^{\max} - Y^{\min})\lambda \le -Y^{\min} \tag{32}$$

The trapezoidal fuzzy model of power generation unit i in Equation (28) can be rewritten as: -

For power generation units:

$$-PG_i + (PG_i^{(1)} - PG_i^{\min})\lambda \le -PG_i^{\min}, i = 1,2,..., NG, \tag{33}$$

$$PG_i + (PG_i^{\max} - PG_i^{(2)})\lambda \le PG_i^{\max}, i = 1,2,...., NG. \tag{34}$$

And for power demand in Equation (29) as:

$$-PD + (PD^{(1)} - PD^{\min})\lambda \le -PD^{\min} \tag{35}$$

$$PD + (PD^{\max} - PD^{(2)})\lambda \le PD^{\max} \tag{36}$$

While, the triangular fuzzy model of critical transmission lines in Equation (30) can be rewritten as:-

$$-PF_k + (PF_k^{med} - PF_k^{\min})\lambda \le -PF_k^{\min}, k = 1,2,..., NL \tag{37}$$

$$PF_k + (PF_k^{\max} - PF_k^{med})\lambda \le PF_k^{\max}, k = 1,2,..., NL, \tag{38}$$

4. APPLICATIONS

Test Systems

The 5-Bus test system [7], and 30-bus test systems [12] are used to study the proposed emergency control procedure. For the 5-bus test system, the generation units are located at buses 1, 2, and 5. Two lines are considered as critical lines, which are line No. 1 and line No. 5. The 30-bus test system has 6-generation units and 41 transmission lines. Lines No. 1, 2, 5, 6, 9, 11, 14, and 40 are considered as critical lines.

Studied Cases

i) Line outages

a. 5-Bus test system

Table 1 shows the proposed emergency control procedure to remove the overflows in the critical transmission lines after the outage of line No. 3 for the 5-bus test system. While Tables 2 shows the comparison between the changes in the relative corrective time referred to case 6 for 5-bus test system.

b. 30-Bus test system

Table 3 shows the proposed emergency control procedure to remove the overflows in the critical transmission lines after the outage of line No. 3 for the 5-bus test system, while Table 4 shows the comparison between the changes in the relative corrective time referred to case 6 for 30-bus test systems.

Table 1. Proposed corrective procedures to remove the effects of line No. 3 outage

Variables	Max. Limit	Before Emergency		After Emergency					
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
PG_1	120	81.51	42.25	90.66	81.51	42.25	49.92	49.68	42.25
PG_2	90	60.19	86.88	60	60.19	86.88	83.27	82.51	86.88
PG_5	60	47.44	60	40	47.44	60	57.48	56.95	60
PF_1	34	32.93	0.25	30.29	23.30	-9.8	-3.75	-3.64	-9.8
PF_2	35	29.98	22.99	41.87*	39.74*	33.25	34.78	34.58	33.25
PF_3	30	28.43	30	Outage					
PF_4	45	31.19	30.51	43.65	43.77	42.44	42.93	42.53	42.44
PF_5	35	33.90	25.8	46.15*	40.35*	32.57	34.78	34.58	32.57
PF_6	45	10.34	5.0	-6.46	-8.33	-14.63	-13.50	-13.46	-14.63
PF_7	20	-6.41	-10.98	-10.06	-12.35	-17.23	-16.28	-16.17	-17.23
Gen. Costs		426.99	473	430	426.99	473	468.23	463.78	473

(*) denotes to the violated lines

Table 2. Relative corrective times for line No. 3 outage

Variables	Case 6	Case 7	Case 8
PG_1	1	0.781	0
PG_2	1	0.9918	0
PG_5	1	0.5749	0

Table 3. Proposed procedure to the remove the overflow for forced outage of line 2

Variables (MW)	Max. Limit	Before emergency		After emergency					
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
PG_1	200	108.75	81.78	126.76	108.75	81.78	80.89	98.01	81.78
PG_2	80	54.10	73.73	57.56	54.10	73.73	74.25	74.68	73.73
PG_5	50	43.55	50.00	24.56	43.55	50.00	43.59	24.27	50.00
PG_8	35	30.01	30.30	35.00	30.01	30.30	30.09	35.00	30.30
PG_{11}	30	15.31	15.91	17.93	15.31	15.91	22.90	26.86	15.91
PG_{13}	40	27.00	27.00	16.91	27.00	27.00	27.00	19.91	27.00
PF_1	80	66.10	41.30	126.76*	108.32*	62.47	79.99	79.05	62.47
PF_2	40	39.49	36.91	Outage					
PF_5	50	45.07	41.37	63.32*	51.55*	35.64	49.98	49.41	35.64
PF_6	40	29.11	28.12	48.33*	43.39*	36.53	40.00	38.35	36.53
PF_9	32	30.45	27.61	31.55	24.15	14.31	25.59	26.48	14.31
PF_{11}	10	9.37	9.09	10.6*	9.91	8.89	5.09	3.53	8.89
PF_{14}	28	24.68	25.00	28.53*	25.22	22.18	28.00	27.76	22.18
PF_{40}	3	2.94	3.00	3.69*	2.99	2.33	3.00	2.99	2.33
Gen. Cost $/HR		819.14	871.57	819.14	871.57	854.65	804.40	871.57	819.14

Table 4. Comparison between the relative corrective times for forced outage of line 2

Variables (PU)	Case 6	Case 7	Case 8
PG_1	1	0.23414	0
PG_2	1	1.233074	0
PG_5	1	-1.01314	0
PG_8	1	-1.01629	0
PG_{11}	1	2.323944	0
PG_{13}	1	-0.70268	0

ii) Sudden increased in power demand

This condition may occur as a result of one of the following:-

a) Sudden power demand increased at all buses

In this case, the load demand is changed at all buses, simultaneously. The effects of the emergency condition appear as a change of the total power demand. One crisp constraint is presented for balance power requirements.

b) Sudden power demand increased at certain bus

The power demand models are presented by increasing load demand at certain bus j. The power demand at bus j can be calculated according the node balance as follow:

$$PD_j = PG_j - \sum_{i=1}^{LC} PF_{j,i} \tag{39}$$

Tables 5 and 6 show the results of the proposed procedure of FLP to remove the overflows in the critical lines at sudden increasing in power demand for 5-bus and 30-bus test systems, respectively, while, Tables 7 and 8 show comparison studies between the relative corrective time of the proposed procedures.

Table 5. Proposed corrective procedures to remove the effects of increased load demand at bus 3 "ΔPL = 3 MW"

Variables (MW)	Max Limit	Before Emergency		After Emergency					
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
PG_1	120	81.51	42.25	92.81	84.37	54.25	82.4	81.63	54.25
PG_2	90	60.19	86.88	60	60.19	86.88	62.19	62.13	86.88
PG_5	60	47.44	60	40	47.92	60	48.22	48.7	60
PF_1	34	32.93	0.25	41.4*	34.69*	2.14	33	31.41	2.14
PF_2	35	29.98	22.99	32.92	31.69	24.6	30.78	31.21	24.6
PF_3	30	28.43	30	29.6	29.43	30.0	29.55	29.55	30.0
PF_4	45	31.19	30.51	31.52	31.02	31.69	31.93	30.96	31.69
PF_5	35	33.90	25.8	39.68*	33.89	25.85	33.97	33.39	25.85
PF_6	45	10.34	5.0	11.1	9.26	4.38	8.9	8.9	4.38
PF_7	20	-6.41	-10.98	-4.56	-6.87	-11.1	-7.1	-7.16	-11.1
Gen. Costs		426.99	473	432.21	433.95	495.7	437.21	436.62	495.7

Table 6. Proposed procedure to the remove the overflow for increasing the power demand by 20 MW

Variable (MW)	Max Limit	Before emergency		After emergency					
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
PG_1	200	108.75	81.78	155.24	118.75	91.78	113.61	118.75	91.78
PG_2	80	54.10	73.73	57.56	54.10	73.73	63.64	54.10	73.73
PG_5	50	43.55	50.00	24.56	43.55	50.00	45.83	43.55	50.00
PG_8	35	30.01	30.30	35.00	30.01	30.30	30.13	30.01	30.30
PG_{11}	30	15.31	15.91	17.93	15.31	15.91	24.00	15.31	15.91
PG_{13}	40	27.00	27.00	16.91	27.00	27.00	30.00	27.00	27.00
PF_1	80	66.10	41.30	99.2*	18.11	-6.70	62.61	18.11	-6.70
PF_2	40	39.49	36.91	45.6*	30.20	27.62	39.67	30.20	27.62
PF_5	50	45.07	41.37	55.88*	20.96	17.25	41.43	20.96	17.25
PF_6	40	29.11	28.12	31.89	16.22	15.23	23.53	16.22	15.23
PF_9	32	30.45	27.61	38.8*	16.43	13.58	31.74	16.43	13.58
PF_{11}	10	9.37	9.09	9.96	5.62	5.34	3.17	5.62	5.34
PF_{14}	28	24.68	25.00	27.89	19.03	19.35	27.17	19.03	19.35
PF_{40}	3	2.94	3.00	3.66*	2.48	2.52	2.98	2.48	2.52
Gen Cost		819.14	871.57	856.30	847.66	898.08	932.51	847.66	898.08

Table 7. Relative Corrective after increase in load demand (ΔPL3=3 MW)

Variables	Case 6	Case 7	Case 8
PG_1	1	0.2632	0
PG_2	1	0.9132	0
PG_5	1	0.0366	0

Table 8. Comparison between the relative corrective times for increasing the power demand by 20 MW

Variables (PU)	Case 6	Case 7	Case 8
PG_1	1	0	0
PG_2	1	0	0
PG_5	1	0	0
PG_8	1	0	0
PG_{11}	1	0	0
PG_{13}	1	0	0

iii) Unexpected generation outages

Table 9 shows the proposed emergency control procedure to remove the overflows in the critical transmission lines after partial generation outage at unit 5 for the 5-bus test system. In Table 10 and for the 30-bus test system, the proposed procedure is presented for the unexpected generation outage of units at buses 5 and 8. Tables 11 and 12 show the comparison between the relative corrective times of the proposed emergency procedures referred to case 6.

Table 9. Proposed corrective procedures of partial outage of generation unit at bus 5

Variables (MW)	Max. Limit	Before Emergency		After Emergency					
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
PG_1	120	81.51	62.49	84.58	84.39	77.89	82.69	82.70	77.89
PG_2	90	60.19	66.65	60	60.19	66.65	61.89	61.88	66.65
PG_5	60	47.44	59.99	47	47	47	47	47	47
PF_1	34	32.93	17.45	35.11*	34.94*	29.40	33.50	33.5	29.40
PF_2	35	29.98	26.22	30.98	30.95	29.99	30.68	30.68	29.99
PF_3	30	28.43	28.57	29.14	29.15	29.59	29.27	29.27	29.59
PF_4	45	31.19	31.65	31.01	31.02	31.37	30.90	30.93	31.37
PF_5	35	33.90	25.26	34.43	34.44	34.6	34.48	34.49	34.6
PF_6	45	10.34	6.76	11.20	11.18	10.68	11.04	11.03	10.68
PF_7	20	-6.41	-10.39	-5.41	-5.42	-5.57	-5.46	-5.47	-5.57
Gen. Costs		426.99	440.25	431.61	431.84	440.09	433.59	433.99	440.09

Table 10. Proposed procedure to remove the overflows for partial generation outage at units 2 and 8

Variables (MW)	Max Limit	Before emergency		After emergency					
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
PG_1	200	108.75	81.78	137.24	108.75	100.94	101.86	108.75	100.94
PG_2	80	54.10	73.73	50	50	50	50	50	50
PG_5	50	43.55	50.00	24.56	43.55	50.00	43.94	43.55	50.00
PG_8	35	30.01	30.30	30	30	30	30	30	30
PG_{11}	30	15.31	15.91	17.93	15.31	15.91	14.14	15.31	15.91
PG_{13}	40	27.00	27.00	16.91	27.00	27.00	36.71	27.00	27.00
PF_1	80	66.10	41.30	91.97*	71.13	65.47	61.33	71.13	65.47
PF_2	40	39.49	36.91	45.26*	37.44	35.47	39.72	37.44	35.47
PF_5	50	45.07	41.37	56.94*	44.73	40.85	43.32	44.73	40.85
PF_6	40	29.11	28.12	34.24*	29.88	28.84	25.61	29.88	28.84
PF_9	32	30.45	27.61	37.75*	30.12	27.30	31.77	30.12	27.30
PF_{11}	10	9.37	9.09	9.91	9.57	9.28	7.82	9.57	9.28
PF_{14}	28	24.68	25.00	27.84	24.88	25.19	21.96	24.88	25.19
PF_{40}	3	2.94	3.00	2.99	2.88	2.88	2.98	2.88	2.88
Gen. Cost		819.14	871.57	756.58	819.14	892.12	827.93	819.14	892.12

Table 11. Comparison between the relative corrective time for partial outage of generation unit 5

Variables (PU)	Case 6	Case 7	Case 8
PG_1	1	0.365	0
PG_2	1	0.365	0
PG_5	1	0	0

Table 12. Comparison between the relative corrective time for partial generation outage at units 2 and 8

Variables (P.U.)	Relative corrective time		
	Case 6	Case 7	Case 8
PG_1	1	0	0
PG_2	-----------	-------	------
PG_5	1	0	0
PG_8	-----------	--------	------
PG_{11}	1	0	0
PG_{13}	1	0	0

From Tables 1-12, it can be summarized the follows: -

1. The pre-emergency optimal power dispatch using the proposed FLP technique is presented in case 1, while case 2 presents the preventive control actions as [9] which are prepared before different emergency occurrence.
2. Case 3 has the largest overflow compared to case 4.
3. In Case 5, the power flows in all transmission lines are within the permissible limits.
4. Cases 6 and 7 present the proposed corrective actions to remove the overflows in the violated lines due to emergencies occurrence. While case 8 presents the proposed procedure to ensure that the overflows in all lines are within their limits.
5. Case 8 does not consume any corrective time to remove the violation in transmission lines after the emergency occurrence.

5. CONCLUSIONS

This paper simulates different emergency control procedures for secure and economic power systems operation. The proposed procedure uses the FLP technique and maximizes the effects of preventive control actions from generation units and transmission lines. The proposed procedures have been proven that the use of fuzzy modeling for maximizing the preventive control actions leads to improve the power generation operational settings during different emergency condition and to minimize the corrective times that needed to remove the effects of different emergency conditions. This paper presents an efficient procedure for the power systems operator in order to prepare different reserve levels from both of generation units and the related critical lines to insure the secure operation of power systems. The multi-option reserve levels, which are obtained with preventive actions, help decision maker for secure choice and best plan that able to remove the different effects of emergency situations.

NOMENCLATURE

Control Variables:

PG_i : is the generation outputs of unit i (MW).
PG_i^{min}: is the minimum limit of generation for unit i (MW).
PG_i^{max}: is the maximum limits of generation for unit i (MW).
PG_i^{med} : is a point within the operational range of generation unit i (MW).
$PG_i^{(0)}$: is the initial power generator outputs i (MW).

$PG_i^{(1)}$: is a point within the operational range of generation unit i (MW).
$PG_i^{(2)}$: is a point within the operational range of generation unit i (MW).
NG : is the number of generation buses.
LC: is the number of connected lines to certain bus.

Dependent Variables:

PF_k : is the power flow in line k (MW).
PD : is the total power demand (MW).
$F_i(PG_i)$: is the generation cost of unit i (\$/hr).
$a_i, b_i, and\ c_i$: are the generation cost coefficient of unit i (\$/hr).
C: is total generation costs of all generation units (\$/hr).
PF_k^{min} : is the minimum limit of power flow in critical line k (MW).
PF_k^{max}: is the maximum limit of power flow in critical line k (MW).
PF_k^{med} : is a point in the operational range of critical line k limits (MW).
$PF_k^{(1)}$: is a point in the operational range of critical line k (MW).
$PF_k^{(2)}$: is a point in the range of the power flow in critical line k (MW).
PD^{min} : is the minimum limit of permissible load demand (MW).
PD^{max} : is maximum limit of permissible load demand (MW).
PD^{med} : is the intial value of load demand (MW).
$PD^{(1)}$: is a point within the loading range of the total system demand unit i (MW).
$PD^{(2)}$: is a within the loading range of the total system demand (MW).
C^{min} : is the minimum permissible generation cost (\$/hr).
C^{max}: is the maximum permissible generation cost (\$/hr).
Y^{min} : is the minimum effects of the preventive control actions for the power generation and/or power flow in the critical transmission line (MW).
Y^{max} : is the maximum effects of the preventive control actions for the power generation and/or power flow in the critical transmission line (MW).
$CAPG_i$: is the capacity of generation unit i (MW).
REQSPN: is the required spinning reserve (MW).
$SPNMAX_i$: is the maximum spinning reserve of generation unit i (MW).

Fuzzy Variables:

$\widetilde{PG_i}$: is the fuzzy active power generation (MW).
$\widetilde{PD}$: is the fuzzy load demand included power losses (MW).
$\widetilde{PF_k}$: is the fuzzy active power transmission line flow in line k (MW).
$\mu_{PGi}(PG_i)$: is the lower fuzzy membership function for generator i.
$\mu_{PFk}(PF_k)$: is the lower fuzzy membership function for critical line k.
$\mu_{PD}(PD)$: is the lower fuzzy membership function for load demand.
$\mu_C(C)$: is the fuzzy membership function for objective cost function
$\mu_Y(Y)$: is the fuzzy membership function of preventive control action of power generation units and/or power flow in critical transmission line.
NC refers to the number of fuzzified constraints.
NY refers to the number of preventive control actions constraints

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