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Corrective Control Strategies for Mitigation of Line Overloads during Contingencies

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This paper presents a new corrective control strategy to mitigate the transmission line overloading, with the help of a local optimisation concept. A new Direct Acylic Graph (DAG) technique for selection of participating generators and buses with respect to a contingency is presented. Particle Swarm Optimisation (PSO) technique has been employed for generator rescheduling and/or load shedding problem locally to restore the system from abnormal to normal operating state. The effectiveness of the proposed approach is demonstrated for different contingency cases in IEEE 14 and 30 bus systems. The result shows that the proposed approach is computationally fast, reliable and efficient, in restoring the system to normal state after a contingency with minimal control actions.

Keywords: *Direct Acyclic Graph, local optimisation, corrective control strategy, particle swarm optimisation, generator rescheduling, load shedding.*

1.0 INTRODUCTION

When a major power system disturbance occurs, protection and control actions are required to stop the power system degradation. A situation in which operational limits are violated is described by [1] as an emergency state and the actions required for correcting these states are called corrective control actions. The control strategies to limit the transmission line loading within the security limits are generator rescheduling and/or load shedding. The selection of generators and load buses for control action is a crucial task for the system operator. A fast identification of the participating generators, load buses and a proper control action are essential for secure and reliable operation of power system. The concept of local optimisation provides a new secure operating point with minimum control actions in the vicinity of the contingency. A few buses are processed for local optimisation, irrespective of the size of the network. Under this condition, a minimum number of control actions like rescheduling of generators/load shedding for the participating generators and loads are efficient for the affected power system.

In literature many methods for congestion management via corrective control actions have been reported. The different defence plan of different countries during emergency is proposed in [2] and a multi-objective fuzzy linear programming technique to obtain the optimal preventive control action is proposed in [3]. Alleviation of line overloads by generator rescheduling/load shedding based on RBF neural network for emergency control is reported in [4]. Conjugate gradient search technique to minimise the line overloads in conjuction with the local optimisation is given by [5]. There are

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several publications available that describe direct methods of line overloads alleviation using generation rescheduling and load shedding [6-8]. In these methods the system operator has no choice over the selection of the generators or tagged buses to alleviate the overloads.

Optimal Power Flow (OPF) is arguably the most accurate method for congestion management [9]. However, OPF calculation is computationally expensive and time consuming. Since the constraints and objectives in the OPF problem are non-linear, Particle Swarm Optimisation (PSO) method proposed by Kennedy and Eberhart [10] has been one of the popular methods used for solving complex non-linear optimisation problems. Relative Electrical Distance (RED) concept based real power generation rescheduling for line overload alleviation is proposed by [11], where as multi-objective PSO based generator rescheduling/load shedding for alleviation of overload in transmission network is proposed by [12]. In this type of control, all the generators in a system may be divided into two groups, but in practical cases some generators do not supply power to a particular line. In such cases, all the generators are handled unnecessarily, which increase the complexity of the control strategy.

The main intent of the paper is to propose a technique to identify the participating generators for corrective control actions. In this DAG is used to identify the participating generators and buses which are based on the concept of reach of a generator, generator area and links. With respect to the contingency, the participating generators are classified into two groups based on the power flow directions. Generations in one group of generators are increased while in the other group are decreased. Generators which are contributing (generator flows contributing to the contingency line) to the contingency line are identified as Generator Decrease (GD) group and the generators which are not contributing to the contingency line are categorised as Generator Increase (GI) group. The corrective control strategy is modeled as an optimisation problem. From literature it has been found that PSO technique is robust and fast in solving non-linear, non-differentiable problems. The ability of PSO technique is utilised for solving the optimisation problem. The corrective control action and overload alleviation is a PSO based generator rescheduling and/or load shedding method applied to the GI and GD groups. The proposed corrective control action provides a pareto optimal solution of generator rescheduling and load shedding which would bring back the system to normal state.

2.0 GRAPH THEORETIC APPROACH

In a power system, all generators do not supply power to all loads. The generators which are supplying power to a particular load can be identified easily by graph theory. Graph theory converts the entire power system into a unidirectional hierarchical structure, based on the power flow contribution from the generators to the loads. Graph theory organises the buses and lines of the network into a homogeneous group according to the concept of 'reach of a generator', 'generator area' and 'links'. The homogeneous groups is called Direct Acyclic Graph (DAG) and it is unidirectional in nature. If the generator areas are represented as nodes and the links as branches, then the power system can be represented as a Directed Acyclic Graph by joining the generator areas and the links. This graph is directed because the direction of the flow in a link is specified.

2.1 Directed Acyclic Graph (DAG)

A graph is a set of nodes and a set of edges. A cycle is a path with the same node at the beginning and the end. An acyclic graph is a graph with no path that starts and ends at the same node. A Directed Acyclic Graph (DAG) contains no cycles; this means that if there is a route from node 'a' to node 'b', then there is no way back. A source is a node (vertex) with no incoming edges, while a sink is a node (vertex) with no outgoing edges. A finite DAG has at least one source and at least one sink. For a power sytem the generators and loads are treated as sources and sinks, respectively.

2.1.1 Reach of a Generator (ROG)

The reach of a generator is defined as the set of buses which are reached by power produced by that generator. Power from a generator reaches a particular bus if it is possible to find a path through the network from the generator to the bus for which the direction of travel is always consistent with the direction of the flow as computed by a power flow program or a state estimator [13, 14]. For large systems, the reach of a generator (ROG) can be determined using the algorithm, explained in the flowchart shown in Fig. 1.

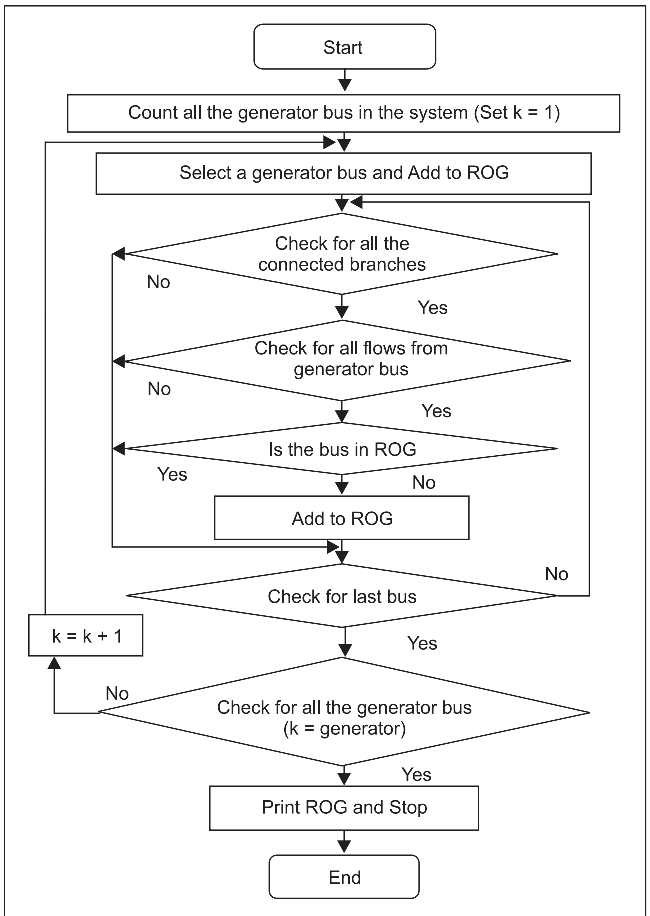

FIG. 1 FLOW CHART FOR REACH OF A GENERATOR (ROG)

2.1.2 Generator area (GA)

The generator area is defined as a set of contiguous buses supplied by the same generator. Unconnected sets of buses supplied by the same generator are treated as separate generator area. A bus therefore belongs to one and only one generator area. The rank of generator area is defined as the number of generators supplying power to the buses. It can never be lower than one or higher than the number of generators in the system. For networks of a more realistic size, the generator area can be determined using the algorithm which is explained in the flowchart shown in Fig. 2.

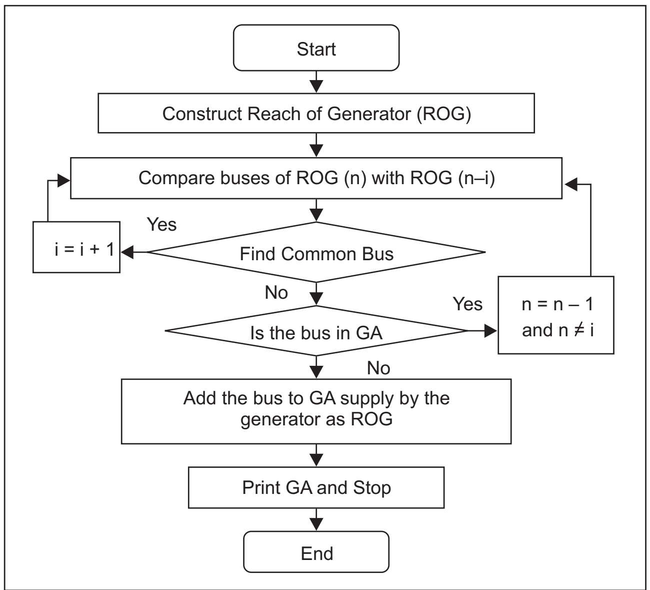

FIG. 2 FLOWCHART FOR GENERATOR AREA (GA)

2.1.3 Links

Having divided the buses into generator area, each branch is either internal to (i.e. it connects two buses which are part of the same generator area) or external (i.e. it connects two buses which are part of different generator area) to a generator area. One or more external branches connecting the different generator area will be called a link. It is very important to note that the actual flows in all the branches of a link are all in the same direction. Furthermore, this flow in a link is always from a generator area of rank N to generator area of rank M where M is always strictly greater than N.

3.0 PARTICLE SWARM OPTIMISATION (PSO)

PSO is a simple and efficient population-based optimisation method proposed by Kennedy and Eberhart [10]. PSO is motivated by social behaviour of organisms such as fish schooling and bird flocking. In PSO, potential solutions called particles fly around in a multidimensional problem space. Population of particles is called swarm. Each particle in a swarm flies in the search space towards the optimum or a quasi-optimum solution based on its own experience, experience of nearby particles, and global best position among particles in the swarm. Let us define a search space S as n-dimension and the swarm consists of N particles. At time t, each particle i has its position defined by $X^i_1 = \{x^i_1, x^i_2, ... x^i_n\}$ and a velocity defined by $V^i_1 = \{v^i_1, v^i_2, ... v^i_n\}$ in 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

$$V^i_{t+1} = w\ x\ \mathrm{V}^i_t + \mathrm{c}_1\ x\ \mathrm{rand}()\ x\ (P^i_t - X^i_t) + c_2\ x\ \mathrm{rand}()\ x\ (P^{i,g}_t - X^i_t) \qquad (1)$$

$$X^i_{t+l} = X^i_t + V^i_{t+l}\ i = 1, 2, ..., N \qquad (2)$$

Where

N : number of particles in the swarm
n : number of elements in a particle
w : initial weight of the particle
t : generation number
c_1, c_2 : acceleration constant
rand () : uniform random value in the range [0, 1]
$\mathrm{P}^{i,g}_t$: global best position of particle in the population
P^i_t : best position of 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 (i.e., searching of new area) while 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 [15]. This can be done by using

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}}\ \mathrm{x}\ iter \qquad (3)$$

Where w_{max} and w_{min} are maximum and minimum weight, respectively, *iter* is iteration number, and $iter_{max}$ is 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, particle may not explore sufficiently, and if V_{max} is very high, it may oscillate about optimal solution. Velocity clamping effect has been introduced to avoid the phenomenon of "swarm explosion". In the proposed method, velocity is controlled within a band as

$$V_{\max,\,t} = V_{\max} - \frac{V_{\max} - V_{\min}}{iter_{\max}}\ \mathrm{x}\ iter \qquad (4)$$

Where $V_{max,\,t}$ is maximum velocity at generation t, and V_{max} and V_{min} are initial and final velocity, respectively. Acceleration constant c_1 called cognitive parameter pulls each particle towards local best position whereas constant c_2 called social parameter pulls the particle towards global best position. Usually c_1 and c_2 ranges from 0 to 4 [16].

4.0 MATHEMATICAL FORMULATION FOR CORRECTIVE CONTROL STRATEGY

The corrective control strategy by generator rescheduling/load shedding has been divided into two groups (GD and GI) of optimisation problem as follows:

4.1 Modeling for Generator Decrease (GD) group

In the Generator Decrease group, the goal is to reduce the generation with respect to load such that the bus voltage constraints are within the limits. This problem can be solved by classical economic load dispatch with line flow and voltage limits as constraints. The objective of the constrained economic dispatch problem (i.e. voltage and line flow constraints) is to determine the most economic loading of the generators such that the load demand in the GD group are within their limits. The objective is to determine the optimal set of generation Pg_i ($i = 1, 2, \ldots. NG$) so as to minimize the total cost of generation "F_t" given by

$$\text{Minimize } f(x) \cong F_t = \sum_{i=1}^{NG} (a_i P_{gi}^2 + b_i P_{gi} + c_i) \quad (5)$$

Subject to

Equality constriants:

$$g(x) = 0 \cong \sum_{i=1}^{NG} (P_{gi}) - P_d - P_L = 0 \quad (6)$$

Inequality constraints :

$$h(x) \le 0 \cong \left[\begin{array}{l} P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \\ V_l^{\min} \le V_l \le V_l^{\max} \\ S_{il} \le S_{il}^{\max} \end{array} \right. \quad (7)$$

Where

a_i, b_i, c_i : are the cost coefficient of generators

P_{gi} : real power generated by the generator 'i'

V_l : voltage of the generator buses.

S_{il} : the power flow limit of the lines

P_d and P_L : the total demand and loss of the system

NG : number of participating generators

Fitness function F_t^* used in PSO for this group is formulated including all the constraints as follows.

$$F_l^* = F_l + K_l \sum_{i=1}^{NB} (V_{Li} - V_{Li}^{Lim})^2 + K_2 \sum_{i=1}^{NL} (S_{ij} - S_{ij}^{\max})^2 + K_3 (P_{Stock} - P_{Stock}^{Lim})^2 \quad (8)$$

Where

NB : number of participating buses in the group

NL : number of lines in the group

K_1, K_2, K_3: are the penalty factors (normally large positive real value).

4.2 Modeling for Generator Increase (GI) group

The aim of the Generator Increase group is to increase the generation within the generator limits so as to meet the demand, if not possible, switching to load shedding. As generation increases in this group, there may be an overload in some of the lines. Alleviation of overloads in the GI group can be formulated as an optimisation problem as follows.

The objective function

$$f(x) = 0 \cong \sum_{ij \in all} (S_{ij} - S_{ij}^{\max} * Sf)^2 = 0 \quad (9)$$

Subject to

Equality constraints:

$$g(x) = 0 \cong \left[\begin{array}{l} P_i - \sum\limits_{j \in \text{all}} G_{ij} v_i^2 - v_i v_j [G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)] = 0 \\ Q_i + \sum\limits_{j \in \text{all}} B_{ij} v_i^2 + v_i v_j [B_{ij} \cos(\theta_i - \theta_j) - G_{ij} \sin(\theta_i - \theta_j)] = 0 \end{array} \right. \quad (10)$$

Inequality constraints:

$$h(x) \le 0 \cong \left[\begin{array}{l} P_i^{\min} \le P_i \le P_i^{\max} \\ Q_i^{\min} \le Q_i \le Q_i^{\max} \\ V_i^{\min} \le V_i \le V_i^{\max} \end{array} \right. \quad (11)$$

Where

S_{ij} : the MVA flow on the line

S_f : factor of safety (generally 0.9 to 0.95)

G_{ij} and B_{ij} : conductance and susceptance of the line 'i to j'

P_i and Q_i : real and reactive power of bus 'i'

Fitness function F_l^* used in PSO for this group is formulated as follows.

$$F_l^* = \sum_{j=1}^{NL} (S_{ij} - S_{ij}^{\max} \times Sf)^2 + K_1 \sum_{i=1}^{NB} (V_{Li} - V_{Li}^{Lim})^2 \quad (12)$$

Where

NB : number of participating buses in the group

NL : number of lines in the group

K_1 : the penalty factors (normally large positive real value).

5.0 CORRECTIVE CONTROL STRATEGY ALGORITHM

To alleviate line overloads due to contingency of one or more lines in the system, the following sequence of control actions are expected from the operator.

1. Decrease the bus power injections at the sending end bus of the contingency line. This is incorporated by decreasing the generation at this bus and/or at the buses feeding power to it.
2. Maintain the bus power injections constant at the receiving end bus of the contingency line by increasing the generation at this bus and/or at the buses feeding power to it.
3. If the load demand is not met satisfying all the line constraints, then curtail the load at the receiving-end participating loads to which power is being fed from this bus.

The proposed PSO based corrective control method uses DAG for identifying the participating generators and load buses. Based on powerflow/state estimation results and the graph theory concept the DAG is constructed and stored in a database. After a contingency, the DAG is reconstructed. Comparing the pre and post contingency DAG, the GD and GI groups are identified. The generator rescheduling and/or load shedding optimisation problems for the GD and GI group are solved by PSO technique. Adjustment of generation and loads for the participating generators and load buses obtained from PSO technique are the corrective control actions for alleviation of overloads. In GD group, adjust the generation to load within minimum generation cost, where as in GI group, adjust the generation and load such that there are no overloads in any lines in this group. The implementation procedure of the proposed algorithm is given below.

Step 1 : Initialise randomly the individual of the population according to the limits of each generating unit (except slack bus) including individual dimensions, searching points and velocities. The new velocity strategy equation is formulated and the maximum and minimum velocity limits of each individual are calculated using (13) and (14)

$$V_d^{\max} = \left(\frac{P_d^{\max} - P_d^{\min}}{2} \right) \times \beta \quad (13)$$

$$V_d^{\min} = -\left(\frac{P_d^{\max} - P_d^{\min}}{2} \right) \times \beta \quad (14)$$

Where $P_d^{\max} = \sum_{i=1}^{n} P_i^{\max}$ and $P_d^{\min} = \sum_{i=1}^{n} P_i^{\min}$ i = 1, 2, ...n (number of generators) and $\beta = 0.01$ a smaller value for smooth convergence.

Step 2 : Compute slack bus generator vector, losses and line flows using Newton–Raphson load flow method for the above generators.

Step 3 : To account for slack unit limit violation and voltage limit violation, the total operating cost is augmented by non-negative penalty terms K_1, K_2 and K_3. Calculate augmented cost F_l^* using (8) for GD group and (12) for GI group.

Step 4 : Among the population, the minimum augmented fuel cost value is taken as the best value. The best-augmented fuel cost value in the population is denoted as the Gbest. Remaining individuals are assigned as the Pbest.

Step 5 : Modify the velocity V of each individual real power generating unit P_{gi} using (1).

Step 6 : Check the limits on velocity using (15)

$$\text{If } V_{id}^{(t+1)} > V_d^{\max}, \text{ then } V_{id}^{(t+1)} = V_d^{\max}$$
$$\text{If } V_{id}^{(t+1)} < V_d^{\min}, \text{ then } V_{id}^{(t+1)} = V_d^{\min} \quad (15)$$

Step 7 : Modify member position of each individual P_{gi} using (16).

$$Pg_{id}^{(t+1)} = Pg_{id}^{(t)} + V_{id}^{(t+1)} \quad (16)$$

Step 8 : $Pg_{id}^{(t+1)}$ must satisfy the capacity limits of the generators and are given by (17)

$$\text{If } Pg_{id}^{(t+1)} > Pg_{id}^{\max}, \text{ then } Pg_{id}^{(t+1)} = Pg_{id}^{\max}$$
$$\text{If } Pg_{id}^{(t+1)} < Pg_{id}^{\min}, \text{ then } Pg_{id}^{(t+1)} = Pg_{id}^{\min} \quad (17)$$

Step 9 : Modified member positions in step 8 are taken as initial value for N–R load flow method. Compute slack bus power and line flows using N–R load flow method.

Step 10 : Calculate the augmented fuel cost using (8) for GD group and (12) for GI group and Gbest and Pbest values are assigned. If the Gbest value is better than Gbest value in Step 4 current value is set to Gbest. If the present Pbest value is better than Pbest value in Step 4, current value is set to Pbest.

Step 11 : In GD group if the iteration reaches the maximum go to Step 13, otherwise go to Step 4 and the Gbest and Pbest values obtained in Step 4 are replaced by latest Gbest and Pbest values acquired in Step 10. In GI group if the iteration reaches the maximum and the solution does not converge, then go to step 12.

Step 12 : Reduce the load using the load reduction factor (LRF) given in equation (18) and jump to Step 4 after replacing Gbest and Pbest values by latest values obtained in Step 10.

$$\text{LRF} = \frac{\text{Net Load at overload bus} - \text{Allowable Power to the bus}}{\text{Total MVA Load}}$$

Present modified load =

(1-LRF) x Initial MVA load at the bus (18)

Step 13 : The latest Gbest value generated by the individual is the optimal generation for each unit, which is obtained by satisfying the reduced loads and all constraints in GI group.

6.0 SIMULATION AND RESULTS

To verify the effectiveness of the proposed corrective control strategy by generator rescheduling/load shedding based on DAG-PSO method, simulation was carried out on the IEEE 14 and 30 bus power systems. The simulation was done in a 2.66 GHz Pentium IV, 512 MB RAM personal computer. Cost coefficients and MW limits of the generators are given in Appendix A. The selection of contingency cases was considered randomly. The upper and lower limits of load bus voltages were taken as 1.06 p.u. and 0.95 p.u. respectively. The generator bus voltages were fixed to its specified value. Line loading limits (MVA limits) of 125% of base case were considered. In PSO based optimisation method, a population size of 10 with number of iterations limited to a maximum of 50 was taken. PSO parameters $c_1 = 2.0$, $c_2 = 2.1$, $w_{max} = 0.9$, $w_{min} = 0.4$ were selected from [12, 15]. For each test case, 50 independent trials were carried out; and the best cases obtained are tabulated in the Tables. A small variation of ± 10% is observed in each trial.

6.1 Case 1: IEEE 14 bus System

The buses occupied by the generator areas for the base case power flow is given in Table 1.

TABLE 1

GENERATOR AREA OF IEEE 14 BUS SYSTEM

Sl. No.	Generator Area	Bus Numbers
1	GA_1	1
2	GA_2	2, 4, 5
3	GA_3	3
4	GA_4	6, 11, 12, 13
5	GA_5	7, 8, 9
6	GA_6	10, 14

The base case Direct Acyclic Graph (DAG) obtained from Table 1 is shown in Fig. 3.

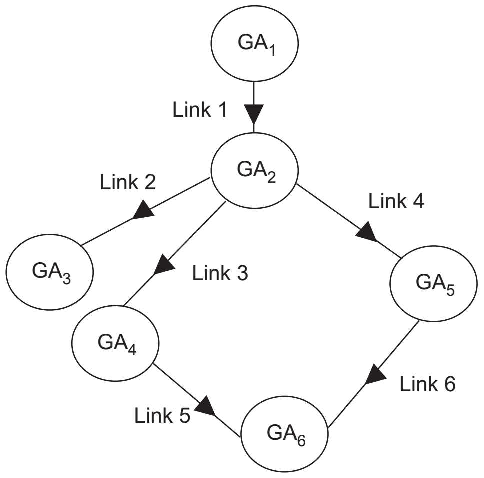

FIG. 3 DAG OF IEEE 14 BUS SYSTEM FOR BASE CASE

The changes of buses occupied by the generator areas due to outage of line 5-6 are given in Table 2.

TABLE 2

GENERATOR AREA AFTER OUTAGE OF LINE 5-6

Sl. No.	Generator Area	Bus Numbers
1	GA_1	1
2	GA_2	2, 4, 5
3	GA_3	3
4	GA_4	6, 12, 13
5	GA_5	7, 8, 9, 10, 11, 14

Comparing the generator areas from Table 1 and Table 2, it is observed that there are change of buses in generator areas GA_4 and GA_5. Before outage the flows in the line 5-6 is supplied from GA_1 and GA_2. Hence the buses in generator area GA_1 and GA_2 are declared as GD group. Similarly after outage of line 5-6 the buses 6 to 14 are rearranged between GA_4 and GA_5. The generator area GA_4 and GA_5 are proclaiming as GI group as shown in Fig. 4.

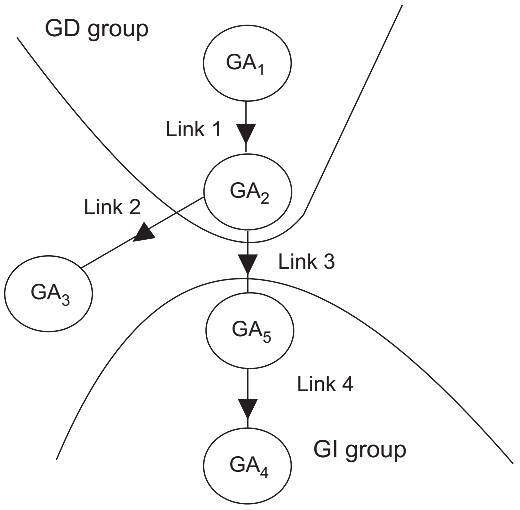

FIG. 4 DAG AFTER OUTAGE OF LINE 5-6

The participating generator and load buses for the contingency lines 5-6 are the buses occupied by the generator areas of GD and GI groups as given in Table 3.

TABLE 3

PARTICIPATING BUSES AND LINES

GD group		GI group			
Bus	**Line**	**Bus**		**Line**	
1	1-2	6	11	6-11	7-9
2	1-5	7	12	6-12	9-10
4	2-4	8	13	6-13	9-14
5	2-5	9	14	12-13	10-11
	5-4	10		7-8	13-14

The nature of PSO convergence characteristics for the GD group is shown in Fig. 5, whereas for GI group is shown in Fig. 6 respectively. The convergence time for GD group varies from 2.46 sec to 2.70 sec and for GI group it varies from 3.68 sec to 3.96 sec. respectively.

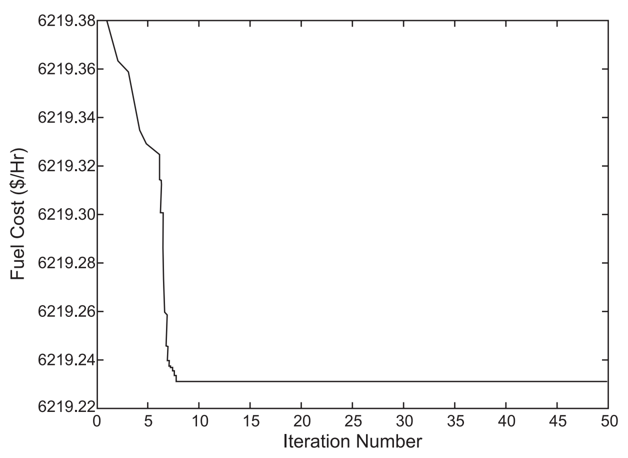

FIG. 5 CONVERGENCE CHARACTERISTICS FOR GD GROUP

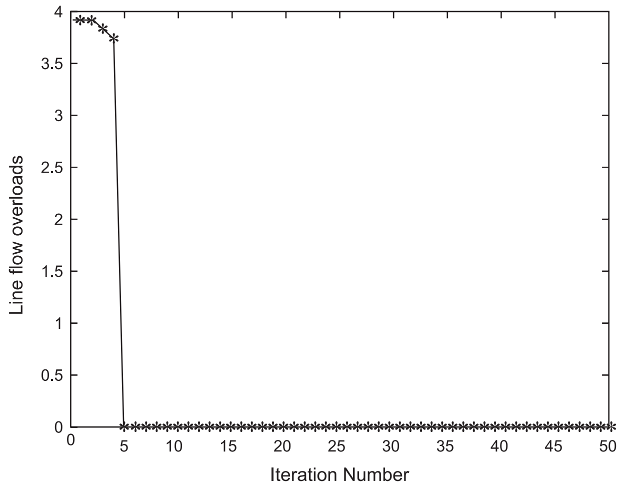

FIG. 6 CONVERGENCE CHARACTERISTICS FOR GI GROUP

Table 4 shows the results of the corrective control strategy of generator rescheduling/load shedding for the outage of line 5-6.

It can be observed from Table 4 that the line flows after the occurrence of contingency (B) exceeds the MVA limits (A). The overloads of lines are removed by rescheduling the generators 1, 2, 6, 8, without load shedding. After implementing the aforementioned corrective control strategy, it can be found that the post-contingency power flows (C) is well within the MVA limits (A).

6.2 Case 2: IEEE 30 bus Systems

The buses occupied by the generator areas for the base case power flow is given in Table 5.

TABLE 5

GENERATOR AREA OF IEEE 30 BUS SYSTEM

Sl. No.	Generator Area	Bus Numbers
1	GA_1	1, 3
2	GA_2	2, 4
3	GA_3	6, 7, 8, 27 - 30
4	GA_4	12 - 16, 18, 23
5	GA_5	5
6	GA_6	9, 10, 11, 20 - 22
7	GA_7	17, 19, 24, 25, 26

TABLE 4

CORRECTIVE CONTROL STRATEGIES OF OUTAGE OF LINE 5-6 FOR IEEE 14 BUS SYSTEM

1. Overload Condition			2. Corrective Control Strategies							
Line 5-6 out	(A) Max Cap.	(B) Contingency flows	Generation			Load			(C) Post cont. flow	Remarks
			Pre-contingency		Control action	Pre-contingency		Control action		
Lines	MVA	MVA	Bus	MW	MW	Bus	MVA	MVA	MVA	
4-7	37.03	57.55	1*	232.39	185.950	2	25.14	25.14	23.04	No load shedding and there is no overload in any lines
4-9	20.12	32.90	2*	40.00	35.184	4	47.96	47.96	13.91	
5-4	79.53	100.83	3	0.00	0.000	5	7.77	7.77	72.53	
6-11	10.15	20.19	6*	0.00	46.105	6	11.11	11.11	8.86	
7-8	21.14	21.51	8*	0.00	6.228	9	33.85	33.85	15.47	
7-9	35.85	58.25				10	10.71	10.71	29.02	
9-10	8.48	33.46				11	3.94	3.94	6.99	
9-14	12.66	27.76				12	6.31	6.31	9.83	
11-10	5.12	23.50				13	14.69	14.69	5.055	
13-14	7.35	11.98				14	15.72	15.72	6.428	

The '*' indicates the alteration of generation and loads as corrective control action at that bus.

The base case Direct Acyclic Graph (DAG) acquired from Table 5 is shown in Fig. 7.

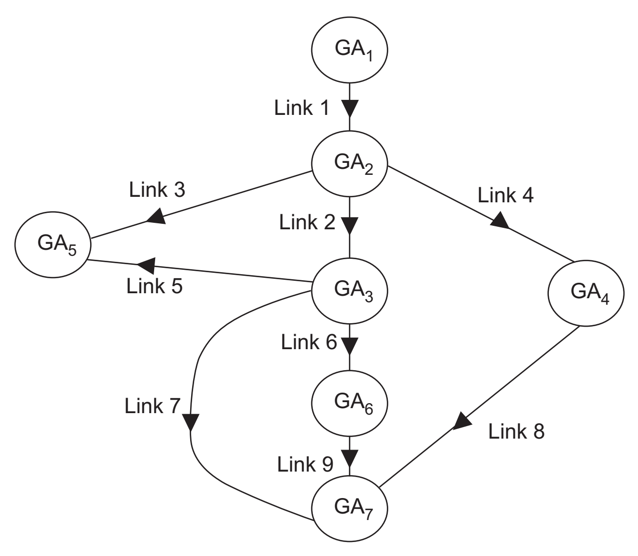

FIG. 7 DAG OF IEEE 30 BUS SYSTEM FOR BASE CASE

The changes of buses occupied by the generator areas due to outage of line 27-28 are given in Table 6.

TABLE 6

GENERATOR AREA AFTER OUTAGE OF LINE 27-28

Sl. No.	Generator Area	Bus Numbers
1	GA$_1$	1, 3
2	GA$_2$	2, 4
3	GA$_3$	6, 7, 8, 28
4	GA$_4$	12 - 16, 18, 23
5	GA$_5$	5
6	GA$_6$	9 - 11, 20 - 22
7	GA$_7$	17, 19, 24 - 27, 29, 30

It is observed by comparing Table 5 and Table 6 that the buses of generator area GA$_3$ and GA$_7$ are modified, whereas there are no change of buses in the generator area GA$_1$, GA$_2$, GA$_4$, GA$_5$ and GA$_6$ after the contingency. Before outage the flows in the line 27-28 is supplied from GA$_1$, GA$_2$ and GA$_3$. The generator area GA$_1$, GA$_2$ and GA$_3$ are considered as GD group where as generator area GA$_6$ and GA$_7$ are considered as GI group as shown in Fig. 8.

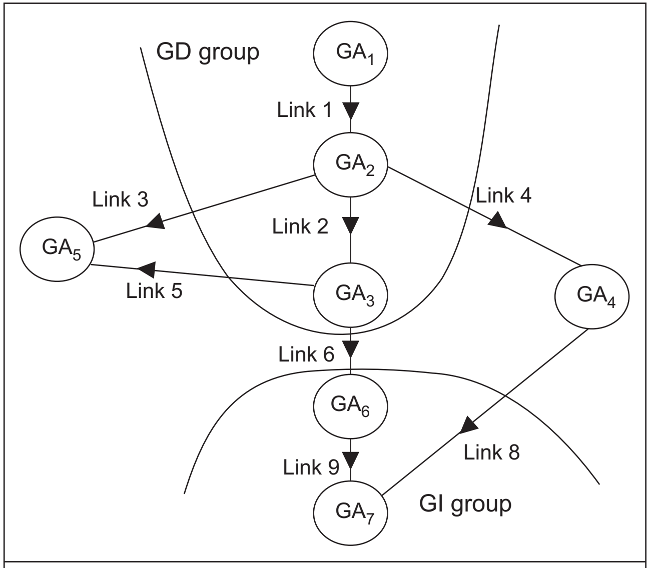

FIG. 8 DAG OF IEEE 30-BUS SYSTEM AFTER OUTAGE OF LINE 27-38

The participating generator and load buses for the contingency line 27-28 are the buses occupied by the generator areas of the GD and GI groups as given in Table 7.

TABLE 7

PARTICIPATING BUSES AND LINES

GD group		GI group			
Bus	Line	Bus		Line	
1	1-2	9	18	9-10	15-18
2	1-3	10	19	9-11	15-23
3	2-4	11	20	10-17	16-17
4	3-4	12	21	10-20	18-19
		13	22	10-21	20-19
		14	23	10-22	21-22
		15	24	12-14	22-24
		16	25	12-15	23-24
		17	26	12-16	24-25
				13-12	25-26
				14-15	

The nature of PSO convergence characteristics for the GD group is shown in Fig. 9, whereas for GI group it is shown in Fig. 10. The convergence time of GD group varies from 4.48 sec to 4.76 sec and for GI group it varies from 5.52 sec to 5.67 sec.

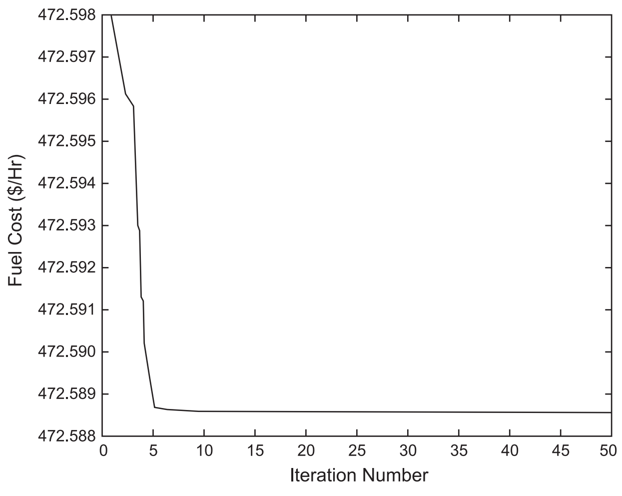

FIG. 9 CONVERGENCE CHARACTERISTICS FOR GD GROUP

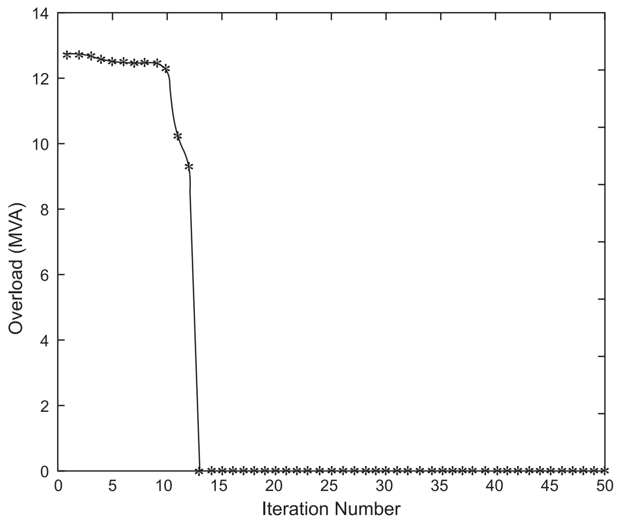

FIG. 10 CONVERGENCE CHARACTERISTICS FOR GI GROUP

TABLE 8

CORRECTIVE CONTROL STRATEGIES OF OUTAGE OF LINE 27-28 FOR IEEE 30 BUS SYSTEM

1. Overload Condition			**2. Corrective Control Strategies**							
Line 27-28 out	**(A) Max Cap.**	**(B) Contingency flows**	**Generation**			**Load**			**(C) Post cont. flow**	**Remarks**
			Pre-contingency		**Control action**	**Pre-contingency**		**Control action**		
Lines	**MVA**	**MVA**	**Bus**	**MW**	**MW**	**Bus**	**MVA**	**MVA**	**MVA**	
6-9	20.88	22.65	1*	138.69	113.06	2	25.14	25.14	14.84	22.57 MVA load shed and no lines are overloaded after control actions
6-10	14.79	16.14	2*	57.56	61.83	3	2.68	2.68	11.72	
12-15	24.38	24.91	5	24.56	24.56	4	7.77	7.77	19.06	
14-15	2.24	3.15	8*	35.00	44.97	7	25.27	25.27	1.68	
16-17	5.11	5.31	11*	17.93	23.12	8	42.43	42.43	3.23	
10-21	23.83	27.14	13	16.91	16.91	10	6.14	6.14	19.67	
10-22	11.43	14.42				17*	10.71	8.36	9.56	
21-22	2.59	6.24				19*	10.09	7.88	2.09	
15-23	7.74	12.94				20	2.31	2.31	6.17	
22-24	8.98	20.27				21	20.77	20.77	8.43	
23-24	3.19	9.08				24*	10.98	8.59	2.54	
24.25	1.88	19.47				26*	4.18	0.45	1.87	
25-27	4.31	14.19				29*	2.56	0.28	1.44	
						30*	1.77	1.16		

The '*' indicates the alteration of generation and loads as corrective control action at that bus.

Table 8 shows the results of the corrective control strategy of generator rescheduling/load shedding for the outage of line 27-28. It can be observed from Table 8 that the line flows after the occurrence of contingency (B) exceeds the MVA limits (A). The line overloading are removed by rescheduling generators 1, 2, 8, 11 and a 22.57 MVA of load shedding, shared by load buses 17, 19, 24, 26, 29, 30. The post-contingency flows (C) are within the MVA limits (A) after the control strategy as seen from Table 8.

From the above results, we observe that the proposed method can alleviate the line overloads due to contingency, in any system within minimal control actions, thereby preventing the cascading of outages, leading to blackout or system collapse.

7.0 CONCLUSIONS

A novel approach to corrective control strategy of generation rescheduling and/or load shedding with subject to contingencies is presented. Identification of an effective generator and/or load buses due to a contingency is achieved using Direct Acyclic Graph (DAG). The concept of local optimisation is utilised, wherein the implementation of control action becomes easy and effective. This facilitates the operator to quickly select the appropriate number of buses for a good sub-optimal solution. This task is achieved by means of a Particle Swarm Optimisation (PSO) method, which provides the best solution with less control decision and actions corresponding to generation and/or load increase/decrease respectively. The solution was sufficient for initiating control actions during emergency as it prevents the system from cascading outages.

APPENDIX A

A1 COST COEFFICIENTS OF GENERATORS FOR IEEE 14 BUS SYSTEM

Bus No.	**c ($/Hr)**	**b ($/MWHr)**	**a ($/MW²Hr)**	**P_{max} (MW)**	**P_{min} (MW)**
1	0	20	0.043	300	0
2	0	20	0.250	140	0
3	0	40	0.010	60	0
6	0	40	0.010	60	0
8	0	40	0.010	60	0

A2 GENERATOR COST COEFFICIENTS FOR IEEE 30 BUS SYSTEM

Bus No.	**c ($/Hr)**	**b ($/MWHr)**	**a ($/MW²Hr)**	**P_{max} (MW)**	**P_{min} (MW)**
1	0	2.00	0.00800	150	0
2	0	1.75	0.01750	80	0
5	0	1.00	0.06250	50	0
8	0	3.25	0.00834	55	0
11	0	3.00	0.02500	40	0
13	0	3.00	0.02500	40	0

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