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Local Optimization Based Corrective Control Strategies for Mitigation of Overloads using Direct Acyclic Graph

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Abstract: This study presents a local optimization based corrective control strategy to mitigate transmission line overloads, which are initiated due to a contingency. Generator rescheduling and/or load shedding is performed locally, to restore the system from abnormal to normal operating state. Local optimization based overload alleviation requires appropriate selection of generator and load buses for minimum control action. A new technique for selection of participating generators and load buses using Direct Acyclic Graph (DAG) is also proposed. Particle Swarm Optimization (PSO) technique solves the corrective control optimization problem with in security constraints such as line flows and bus voltage limits. The effectiveness of the proposed approach is demonstrated for different contingency cases in IEEE 30 and 57 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.

Key words: Direct acyclic graph, participating bus identification, overload alleviation, corrective control strategy, particle swarm optimization, generator rescheduling, load shedding

INTRODUCTION

Overloading of a transmission network in a power system can occur due to various reasons including line outages. The network overloading may lead to tripping of overloaded lines, consequential tripping of other lines, an undesirable incident of power system collapse, leading to partial or even complete blackout. The control strategies to limit the transmission line loading within the security limits are generator rescheduling and/or load shedding. Under this condition, a minimum number of control actions for the participating generators and loads are efficient for the affected power system. A new secure operating point is obtained with minimum control actions in the vicinity of the contingency lines introduced by the concept of local optimization. However, all generator and load buses in the system need not take part in overload alleviation when a contingency occurs. A few buses are processed for local optimization, irrespective of the size of the network. The selection of generators and load buses for control action is a crucial task for the system operator. Accurate as well as fast computation, identification of the participating generators and load buses are essential for precise and reliable control actions for the power system.

A situation in which operational limits are violated is described by Fink and Carlsen (1978) as an emergency state and the actions required correcting this states is called corrective control action. In study many methods for mitigation of overloads by congestion management based corrective control have been reported. The different defence plan of different countries during emergency is proposed by Voropai *et al*. (2005) and a multi objective fuzzy linear programming technique to obtain the optimal preventive control action is proposed by Abou El-Ela *et al*. (2005). Alleviation of line overloads by generator rescheduling/load shedding based on RBF neural network is reported by Ram *et al*. (2007). Conjugate gradient search technique to minimize the line overloads in conjunction with the local optimization is given by Shandilya *et al*. (1993).

Several researchers Medicheral *et al*. (1981), Chan and Schweppe (1979) and Talukdar *et al*. (2005) have indicated transmission line overload alleviation using generation rescheduling/load shedding. In these methods, the system operator has no choice over the selection of the generators or tagged buses.

Relative Electrical Distance (RED) based real power rescheduling for the participating generators to alleviate

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overload of lines is proposed by Yesuratnam and Thukaram (2007), where as multi-objective PSO based generator rescheduling/load shedding for alleviation of overload in transmission network is proposed by Hazra and Sinha (2007). Sensitivity optimized based participating generator selection and control actions to the congested line are proposed by Dutta and Singh (2008). In this type of control, all the generators in a system may divide 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, increasing the complexity of the control strategy. The OPF technique is the most accurate method for congestion management given by Christie *et al*. (2000), however, OPF calculation is computationally expensive and time consuming. The objectives and constraints in power system optimization problem are non-linear in nature. The popular Particle Swarm Optimization (PSO) method proposed by Kennedy and Eberhart (1995) has been used for solving complex nonlinear optimization problems.

The amount of rescheduling/load shedding for the identified generators and loads is addressed. In this study, the 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. The participating generators and buses are classified into two groups with respect to the contingency. Generations in one group of Generators are Increased (GI), while in the other group Generations are Decreased (GD). Generators, which are contributing to the contingency line are identified as GD group and the generators, which are not contributing to the contingency line are categorized as GI group. The corrective control action for overload alleviation is a PSO based generator rescheduling and/or load shedding method applied to the GI and GD groups. Ease of identification of the participating generators and minimum numbers of control actions are the important features of the proposed method.

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 organizes 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 group 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.

Direct 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 system the generators and loads are treated as sources and sinks, respectively.

Reach of a Generator (ROG): ROG 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 power flow program or state estimator given by Bialek (1996) and Kirschen *et al*. (1997). Large systems, the ROG can be determined using the algorithm, explained in flowchart shown in Fig. 1.

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.

Links: Having divided the buses into generator area, each branch is either internal (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.

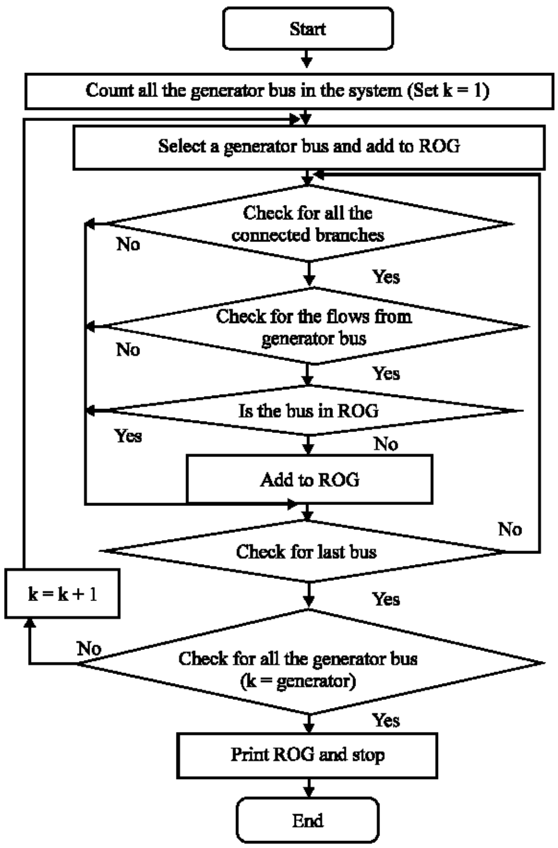

Fig. 1: Construction of Reach of a Generator (ROG)

Particle swarm optimization: Particle Swarm Optimization (PSO) is a simple and efficient population-based optimization method proposed by Kennedy and Eberhart (1995). PSO is motivated by social behavior 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 search space S is n-dimension and the swarm consists of N particles. At time t, each particle i has its position defined by:

$$X_t^i = \{x_1^i, x_2^i, \ldots, x_n^i\}$$

and a velocity defined by

$$V_t^i = \{v_1^i, v_2^i, \ldots, v_n^i\}$$

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:

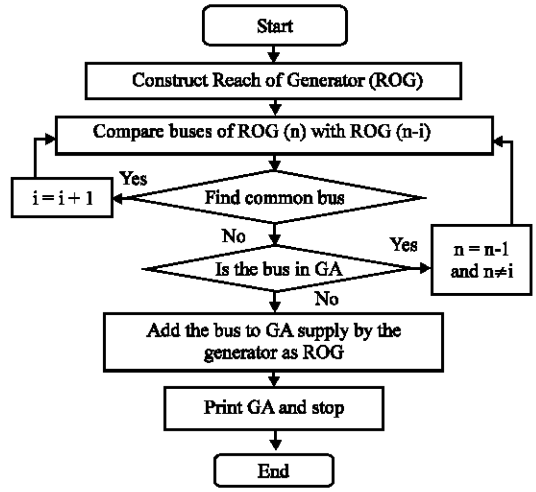

Fig. 2: Construction of Generator Area (GA)

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

$$X_{t+1}^i = X_t^i + V_{t+1}^i \quad i = 1, 2, \ldots, N \quad (2)$$

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 as given by Bhaskar and Mohan (2008). This can be done by using:

$$w = w_{max} \frac{w_{max} - w_{min}}{iter_{max}} \times iter \quad (3)$$

where:

w_{max}, w_{min} = Maximum and minimum weight, respectively, iter is iteration number
$iter_{max}$ = 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:

$$V_{max,t} = V_{max} \frac{V_{max} - V_{min}}{iter_{max}} \times iter \quad (4)$$

where,

$V_{max,t}$ = Maximum velocity at generation t
V_{max} and V_{min} = 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 equals to c_2 and ranges from 0-4 given by Zwe-Lee (2003).

MATHEMATICAL FORMULATION

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

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 lineflow 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,..., NG) so as to minimize the total cost of generation F_t given by:

$$F_t = \sum_{i=1}^{NG} (a_i P_{gi}^2 + b_i p_{gi} + c_i) \tag{5}$$

Subject to equality constraints:

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

Inequality constraints:

$$h(x) \le 0 \cong \begin{bmatrix} P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \\ V_l^{min} \le V_l \le V_l^{max} \\ S_{il} \le S_{il}^{max} \end{bmatrix} \tag{7}$$

Fitness function used in PSO for this group is formulated including all the constraints as follows:

$$\begin{aligned} F_t^* &= F_t + K_1 \sum_{i=1}^{NB} (V_{Li} - V_{Li}^{Lim})^2 \\ &+ K_2 \sum_{j=1}^{NL} (S_{ij} - S_{ij}^{max})^2 + K_3 (P_{slack} - P_{slack}^{Lim})^2 \end{aligned} \tag{8}$$

Modeling for Generator Increase (GI) group: In the generator increase group, our aim is to increase the generation within the generator limits so as to meet the demand, if not possible, switch to load shedding. As generation increases in this group, there may be an overload in some of the lines. The alleviation of overload in the GI group can be formulated as an optimization problem as follows. The objective function is removal of overloads i.e.,

$$\begin{aligned} f(x)=0 &\cong \sum_{ij \in all} (S_{ij} - S_{ij}^{max} * Sf)^2 = 0 \\ S_{ij} &= P_{ij} + jQ_{ij} \end{aligned} \tag{9}$$

Subject to equality constraints:

$$g(x) = 0 \cong \begin{bmatrix} P_i - \sum_{j \in all} G_{ij} v_i^2 - v_i v_j [G_{ij} \cos \\ (\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)] = 0 \\ Q_i + \sum_{j \in all} B_{ij} v_i^2 + v_i v_j [B_{ij} \cos \\ (\theta_i - \theta_j) - G_{ij} \sin(\theta_i - \theta_j)] = 0 \end{bmatrix} \tag{10}$$

Inequality constraints:

$$h(x) \le 0 \cong \begin{bmatrix} P_i^{min} \le P_i \le P_i^{max} \\ Q_i^{min} \le Q_i \le Q_i^{max} \\ V_i^{min} \le V_i \le V_i^{max} \end{bmatrix} \tag{11}$$

Fitness function used in PSO for this group is formulated as follows:

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

CORRECTIVE CONTROL ALGORITHM

A secure operating point may be obtained by generator rescheduling and/or load shedding in the vicinity of contingency. The proposed corrective control method uses DAG for identifying the participating generator 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 optimization 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

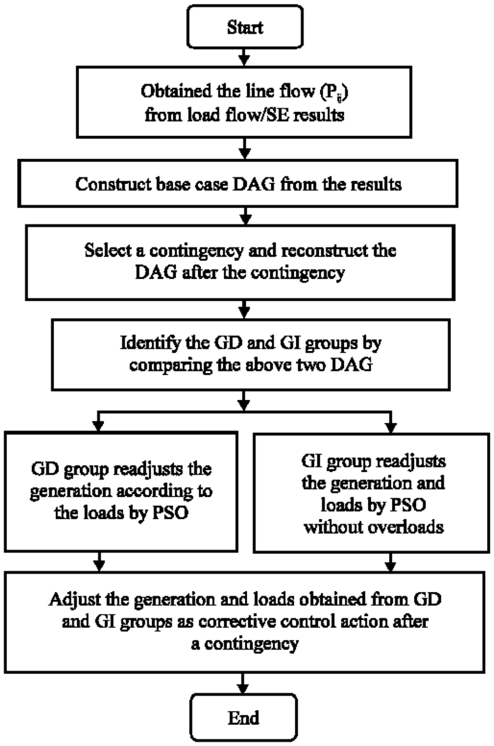

Fig. 3: Corrective control strategy flowchart

that there are no overloads in any lines in this group. The flowchart of the proposed corrective control strategy is given in Fig. 3. The implementation procedure of the proposed algorithm as following.

Step 1: Initialize 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 Eq. (13) and (14):

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

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

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)
β = 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 K1-K3. Calculate augmented cost F_t^* using Eq. (8) for GD group and Eq. (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 Eq. (1).

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

$$\begin{aligned} &\text{If } V_{id}^{(t+1)} > V_d^{max}, \text{ then } V_{id}^{(t+1)} = V_d^{max} \\ &\text{If } V_{id}^{(t+1)} < V_d^{min}, \text{ then } V_{id}^{(t+1)} = V_d^{mim} \end{aligned} \tag{15}$$

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

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

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

$$\begin{aligned} &\text{If } Pg_{id}^{(t+1)} > Pg_{id}^{max}, \text{then } Pg_{id}^{(t+1)} = Pg_{id}^{max} \\ &\text{If } Pg_{id}^{(t+1)} < Pg_{id}^{min}, \text{then } Pg_{id}^{(t+1)} = Pg_{id}^{min} \end{aligned} \tag{17}$$

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 Eq. (8) for GD group and Eq. (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 converges, then go to step 12.

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

$$\text{LRF} = \frac{\text{Net load at overload bus - allowable power to the bus}}{\text{Total MVA load}}$$

$$\text{Present modified load} = (1\text{-LRF}) \times \text{Initial MVA load at the bus} \tag{18}$$

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 GD and GI group.

RESULTS AND DISCUSSION

To verify the effectiveness of the proposed local optimization based corrective control strategy via generator rescheduling/load shedding, the simulation was carried out for the IEEE 30 and 57 bus power systems. The simulation was done in a 2.66 GHz Pentium IV, 512 MB RAM personal computers. The selection of contingency cases was considered randomly. The upper and lower limits of load bus voltages were taken as 1.06 and 0.95 pu, 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 corrective control algorithm, 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 Hazra and Sinha (2007) and Bhaskar and Mohan (2008). 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.

Example 1: IEEE 30 bus system: The buses occupied by the generator areas for the base case power flow are given in Table 1.

The base case Direct Acyclic Graph (DAG) shown in Fig. 4. The changes of buses occupied by the generator areas due to outage of line 27-28 are given in Table 2.

Table 1: Generator area for base case

Generator area	Bus numbers
GA_1	1, 3
GA_2	2, 4
GA_3	6, 7, 8, 27-30
GA_4	12-16, 18, 23
GA_5	5
GA_6	9, 10, 11, 20, 21, 22
GA_7	17, 19, 24, 25, 26

Table 2: Generator area after outage of line 27-28

Generator area	Bus numbers
GA_1	1, 3
GA_2	2, 4
GA_3	6, 7, 8, 28
GA_4	12-16, 18, 23
GA_5	5
GA_6	9, 10, 11, 20, 21, 22
GA_7	17, 19, 24-27, 29, 30

Table 3: GD and GI group participating buses and lines

GD group		GI group	
Bus	Line	Bus	Line
01	01-2	09	09-10
02	01-3	10	09-11
03	02-4	11	10-17
04	02-6	17	10-20
06	03-4	19	10-21
07	04-6	20	10-22
08	06-7	21	21-22
28	06-8	22	22-24
-	6-28	24	24-25
-	8-28	25	25-26
-	-	26	25-27
-	-	27	27-29
-	-	29	27-30
-	-	30	29-30
-	-	-	19-20

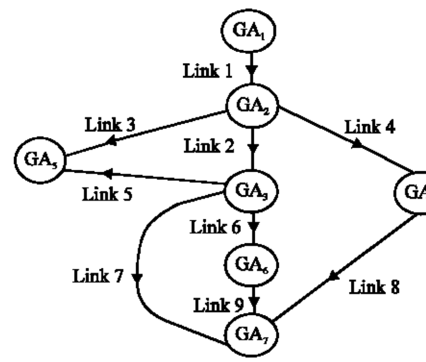

Fig. 4: DAG of IEEE 30 bus system for base case

It is observed by comparing Table 1 and 2 that the buses of generator area GA_3 and GA_7 are modified, where as 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_3. The generator area GA_1-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. 5.

Table 4: Corrective control strategy of outage of line 27-28 for IEEE 30 bus system

Overload condition			Corrective control strategies: Generation			Load				
27-28 out	Line Cap. (A)	Max flows (B)	Contingency Pre-contingency		Control action	Pre-contingency		Control action	Post cont. flow (C)	
Lines	MVA	MVA	Bus	MW	MW	Bus	MVA	MVA	MVA	Remarks
06-09	20.88	22.65	1_2	138.69	113.06	2	25.14	25.14	14.84	22.57 MVA
06-10	14.79	16.14	2_1	57.56	61.83	3	2.68	2.68	11.72	load shed
12-15	24.38	24.91	5	24.56	24.56	4	7.77	7.77	19.06	and no
14-15	2.24	3.15	8_1	35.00	44.97	7	25.27	25.27	1.68	lines are
16-17	5.11	5.31	11_1	17.93	23.12	8	42.43	42.43	3.23	overloaded
10-21	23.83	27.14	13	16.91	16.91	10	6.14	6.14	19.67	after control
10-22	11.43	14.42	-	-	-	17_2	10.71	8.36	9.56	actions
21-22	2.59	6.24	-	-	-	19_2	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_2	10.98	8.59	2.54	-
24-25	1.88	19.47	-	-	-	26_2	4.18	0.45	1.87	-
25-27	4.31	14.19	-	-	-	29_2	2.56	0.28	1.44	-
-	-	-	-	-	-	30_2	10.77	1.16	-	-

$_1$Generation and/or load increase at the bus; $_2$Generation and/or load decrease at the bus

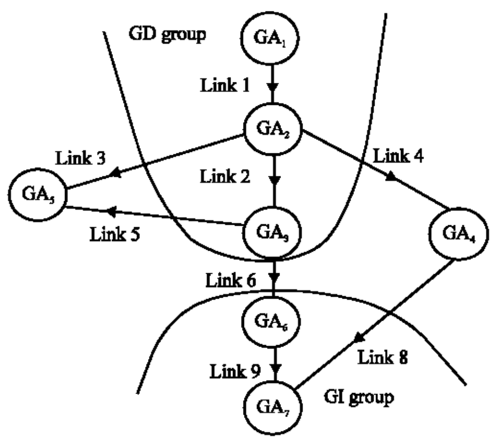

Fig. 5: DAG of IEEE 30 bus system after outage of line 27-28

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 are given in Table 3.

The nature of convergence characteristics of the PSO for GD and GI groups are shown in Fig. 6. The convergence time of GD group varies from 4.48-4.76 sec and for GI group it varies from 5.52-5.67 sec.

Table 4 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-4 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 4.

Table 5: Generator area for base case

Generator area	Bus numbers
GA_1	1, 16, 17
GA_2	2
GA_3	3-5, 14, 15, 18, 19, 44-48
GA_4	6
GA_5	7, 8, 26, 27, 28, 29, 52
GA_6	9, 11, 13, 20 - 25, 30 - 43, 49, 53-57
GA_7	10, 12, 50, 51

Table 6: Generator area after outage of line22-38

Generator area	Bus numbers
GA_1	1, 16, 17
GA_2	2
GA_3	3-5, 14, 15, 18 -22, 44-48
GA_4	6
GA_5	7, 8, 23 -30, 52
GA_6	9, 11, 13, 31- 43, 49, 53 - 57
GA_7	10, 12, 50, 51

Example 2: IEEE 57 bus system: The buses occupied by the generator areas for the base case power flow are given in Table 5.

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

The changes of buses occupied by the generator areas due to outage of line 22-38 are given in Table 6.

It is observed by comparing Table 5 and 6 that the buses of generator area GA_3, GA_5 and GA_6 are modified, where, as there are no change of buses in the generator area GA_1, GA_2, GA_4 and GA_7 after the contingency. Before outage the flows in the line 22-38 is supplied from GA_6. The generator area GA_6 is considered as GD group where, as generator area GA_3, GA_4 and GA_5 are considered as GI group as shown in Fig. 8.

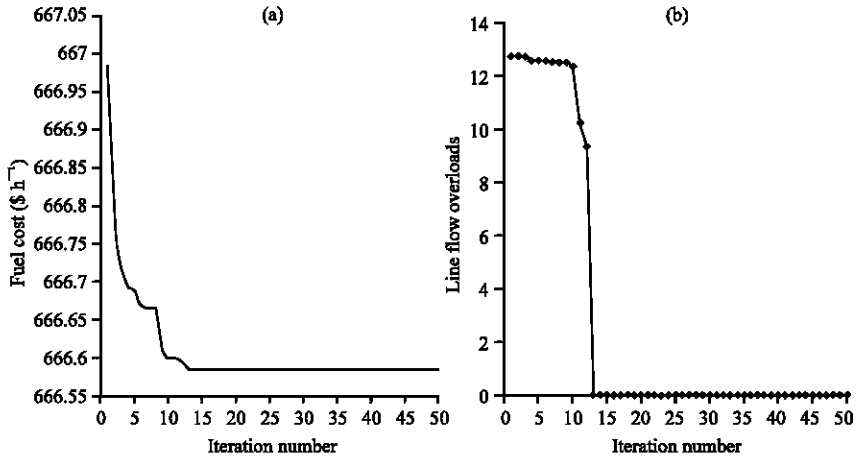

Fig. 6: Convergence characteristics for outage of line 27-28, a: GD group and b: GI group

Table 7: GD and GI group participating buses and lines

GD group		GI group	
Bus	Line	Bus	Line
09	11-11	03	06-07
11	11-13	04	06-08
13	09-13	05	07-08
31	13-49	06	03-04
32	38-49	07	04-05
33	37-38	08	04-06
34	36-37	14	05-06
35	36-35	15	04-18
36	34-35	18	18-19
37	32-34	19	19-20
38	32-31	20	20-21
-	32-33	21	21-22
-	36-40	22	22-23
39	40-56	23	23-24
40	37-39	-	24-25
41	39-57	24	25-30
42	56-57	25	24-26
43	42-56	26	26-27
49	41-56	27	27-28
53	41-42	28	28-29
54	41-43	29	07-29
55	09-41	30	29-52
56	09-43	44	04-15
57	53-54	45	15-45
-	54-55	46	44-45
-	11-55	47	15-14
-	-	48	14-56
-	-	52	46-47
-	-	-	47-48

The participating generator and load buses for the contingency line 22-38 are the buses occupied by the generator areas of the GD and GI groups are given in Table 7.

The nature of the PSO convergence characteristics for the GD group and GI groups are shown in Fig. 9. The convergence time of GD group varies from 15.51-16.38 sec and for GI group it varies from 11.52-17.45 sec, respectively.

The corrective control strategy of generator rescheduling/load shedding is given in Table 8.

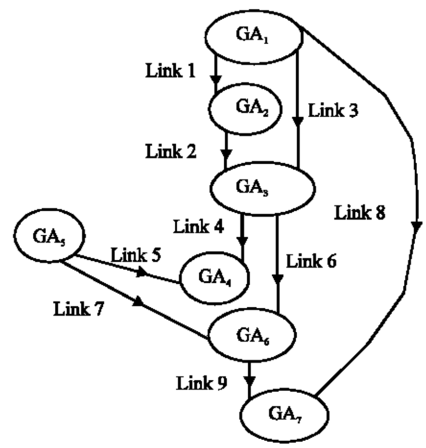

Fig. 7: DAG of IEEE 57 bus system for base case

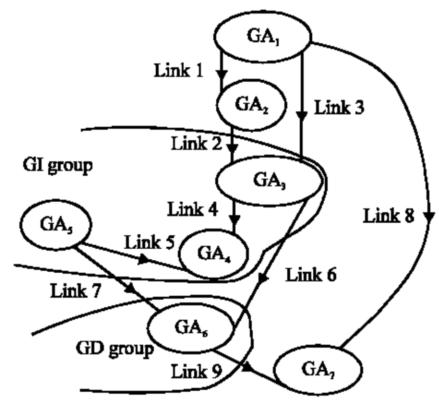

Fig. 8: DAG of IEEE 57 bus system after outage of line 22-38

Observation of Table 8 shows that few lines get overloaded due to the contingency. This effect is removed by rescheduling the generators 3, 6, 8 and a

Table 8: Corrective control strategy of outage of line 22-38 for IEEE 57 bus system

			Corrective control strategies							
Overload condition			Generation			Load				
Line 22-38 out	Max cap. (A)	Contingency flows (B)	Pre-contingency		Control action	Pre-contingency		Control action	Post cont flow (C)	
Lines	MVA	MVA	Bus	MW	MW	Bus	MVA	MVA	MVA	Remarks
18-19	6.05	8.04	01	478.90	478.90	03	46.06	46.06	4.21	17.91 MVA
19-20	1.72	4.32	02	0.00	0.00	05	13.60	13.60	0.83	load
20-21	1.44	1.71	03_2	40.00	32.23	06	75.03	75.03	0.38	shedding
21-22	1.44	1.71	06_1	0.00	8.72	08	151.61	151.61	0.38	and there is
24-26	13.31	17.31	08_2	450.00	444.00	14	11.76	11.76	12.37	no overload
26-27	13.32	17.34	09	0.00	0.00	15	22.56	22.56	12.37	in any lines
27-28	25.23	27.30	12	310.00	310.00	18	28.91	28.91	17.45	-
28-29	31.78	32.94	-	-	-	19	3.35	3.35	20.14	-
31-32	2.57	3.80	-	-	-	20_2	2.51	0.47	1.47	-
-	-	-	-	-	-	23_2	6.64	1.25	-	-
-	-	-	-	-	-	25_2	7.07	3.62	-	-
-	-	-	-	-	-	27_2	9.31	4.78	-	-
-	-	-	-	-	-	28_2	5.14	2.64	-	-
-	-	-	-	-	-	29	17.19	17.19	-	-
-	-	-	-	-	-	30	4.03	4.03	-	-
-	-	-	-	-	-	44	12.14	12.14	-	-
-	-	-	-	-	-	47	31.88	31.88	-	-
-	-	-	-	-	-	52	5.37	5.37	-	-

$_1$Generation and/or load increase at the bus; $_2$Generation and/or load decrease at the bus

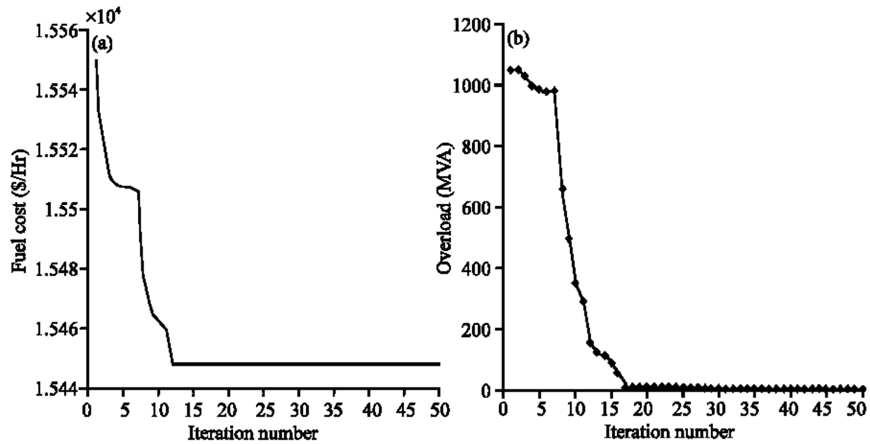

Fig. 9: Convergence characteristics for outage of line 22-38, a): GD group and b): GI group

Table 9: Generator cost coefficients for IEEE 30-bus system

Bus No.	c ($ h^{-1})	b ($ MW Hr^{-1})	a ($ MW^2 Hr^{-1})	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

Table 10: Generator cost coefficients for IEEE 57- bus system

Bus No.	c ($ h^{-1})	b ($ MW Hr^{-1})	a ($ MW^2 Hr^{-1})	P_{max} (MW)	P_{min} (MW)
1	0	20	0.07750	576	0
2	0	40	0.01000	100	0
3	0	20	0.25000	140	0
6	0	40	0.10000	100	0
8	0	20	0.02222	550	0
9	0	40	0.01000	100	0
12	0	20	0.32258	410	0

load shedding of 17.91 MVA, which is shared by load buses 20, 23, 25, 27 and 28. The post-Contingency flows (C) are within the MVA limits (A) after the control strategy.

Generator cost coefficients: The IEEE 30 bus test system consists of 6 generators, 30 buses and 41 lines where as IEEE 57 bus system consists of 7 generators, 57 buses and 80 lines. The generator cost parameters of the systems are given in Table 9 and 10, respectively.

CONCLUSION

This study focuses on a new technique for selection of generator and load buses for overload alleviation due to a contingency. Selection of optimal generator and load bus is an important task of the operator, which can be solved easily by the DAG method. The numbers of participating generators are minimal in the graph theoretic approach compared to the other sensitivity methods. A novel approach to corrective control strategy of generation rescheduling and/or load shedding when subjected to contingencies is presented. The concept of local optimization is utilized, 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 Optimization (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.

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