









**Table 1:** Connection Matrix for IEEE 14-bus System

Connection Matrix	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
2	1	0	1	1	1	0	0	0	0	0	0	0	0	0
3	0	1	0	1	0	0	0	0	0	0	0	0	0	0
4	1	1	1	0	1	0	1	0	1	0	0	0	0	0
5	0	1	0	1	0	1	0	0	0	0	0	0	0	0
6	0	0	0	0	1	0	0	0	0	0	1	1	1	0
7	0	0	0	1	0	0	1	1	0	0	0	0	0	0
8	0	0	0	0	0	1	0	0	0	0	0	0	0	0
9	0	0	0	1	0	0	1	0	0	1	0	0	0	1
10	0	0	0	0	0	0	0	1	0	1	0	0	0	0
11	0	0	0	0	0	1	0	0	0	1	0	0	0	0
12	0	0	0	0	0	1	0	0	0	0	0	0	1	0
13	0	0	0	0	0	1	0	0	0	0	0	1	0	1
14	0	0	0	0	0	0	0	1	0	0	0	1	0	0

## 4. Hybrid of Genetic and Cuckoo Search Algorithm

### 4.1 Basics of Genetic Algorithm

Genetic Algorithm (GA) is a search strategy [12-13] that is used to provide a best solution for the optimization problem. It strikes a balance between the exploration and exploitation of the domain and the solutions respectively. The major steps for the Genetic Algorithm are comprised as follows:

1. Population
2. Reproduction
3. Crossover
4. Mutation

### 4.2 Basics of Cuckoo search Algorithm

Cuckoo search Algorithm (CS) is an optimization algorithm [14] which is based on the behavior of some cuckoo species. CS algorithm is a combination of the Levy flight behavior of some birds and fruit flies. The cuckoo species mostly lay their eggs in the nest of other host bird. The host bird found that the eggs are not its own; then the eggs are destroyed by the host bird. This results the development of the cuckoo eggs which mimic the eggs of the local host birds. Thus, the CS algorithm is mostly used for the various optimization problems. Major steps involved in the CS algorithm are:

1. Population
2. Levy flight
3. Host Egg elimination
4. New egg generation

### 4.3 Hybrid Cuckoo search and Genetic Algorithm (CS-GA)

CS-GA algorithm is a combination of Genetic algorithm and Cuckoo search algorithm which is a population based algorithm used to provide the global solution. In CS-GA algorithm, the initial population is generated randomly and the initial solution is given to the entire space. At first, the crossover and the mutation process will be placed for each generation of the algorithm. After each generation the best value is selected by applying some form of elitism. Before the end of each generation Levy flight will perform to increase the exploration of the solution for next generation. The more detailed algorithm is represented in Algorithm.1.

### Algorithm.1. Pseudo Code for the CS-GA Optimization Algorithm

**Begin**

**Objective function  $f(x)$ ;**

**Step 1: Initialization.** Set the generation counter  $t=1$ ;  
**initialize population randomly.**

**(Initialize  $N_p$  number of host nests randomly each host nest have an egg corresponds to a potential solution to the given problem);**

**Step 2: Fitness evaluation.** Evaluate fitness  $f(x)$ ;

**While ( $t < \text{Max Generation}$ ) or (stop criterion); / New population /**

**Generate new population via genetic operators (selection, crossover and mutation)**

**Evaluate fitness (the best individual perform Lévy flight)**

**Generate a new solution (say  $x_{\text{new}}$ ) via Lévy flights;**

**Evaluate its quality/fitness  $F_{x_{\text{new}}}$ ;**

**Choose a solution (say  $x_j$ ) randomly among  $N_{\text{pnew}}$  and evaluate its fitness ( $F_j$ );**

**If ( $F_{x_{\text{new}}} < F_j$ ) then**

**Replace  $j$  by a new solution;**

**end if**

**Store the best solution;**

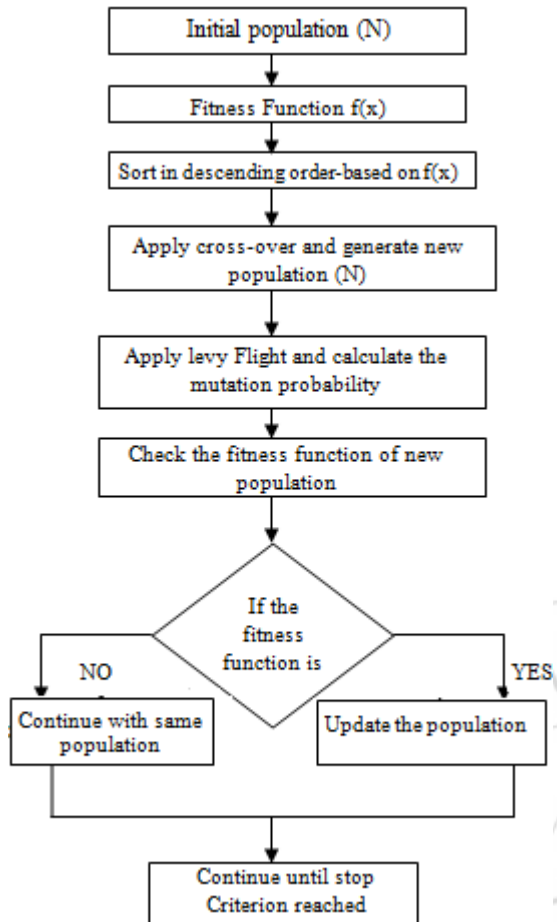
**$t = t+1$ ;**

**Step 3: end while**

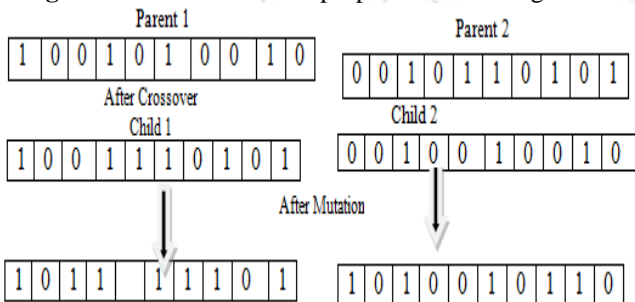
**Step 4: Retrieve the best solution among the current best solution stored in each generation**

**End**

In this paper, CS-GA optimization algorithm is proposed to minimize the fitness function  $F(X)$  i.e. number of PMUs required to observe the complete details of the buses presented in the IEEE  $N$  bus system. Initially, connection matrix  $A$  is generated for the given IEEE  $N$  bus system and initial population is generated to in order to compute the fitness function. In first generation, optimal location of one PMU is optimized by using the crossover and mutation operators as shown in figure.3. When various locations are comfortable with the placement for one PMU, initial locations are sorted based on the fitness function. Therefore, new generation of the PMU locations are created by using the crossover and mutation operations. In the proposed CS-GA algorithm, mutation probability of the new population is calculated by the Levy Flights step of the CS algorithm. These steps are followed to select the optimum locations of one PMU and accordingly, combinations of the PMUs are taken into the next generations of the CS-GA algorithm. Therefore, combinations of the locations are generated in the initial populations and new generations to define the optimal locations of  $N$ -PMUs in IEEE- $N$  bus systems.



**Figure.2.** Flow chart of the proposed CS-GA algorithm



**Figure 3:** Crossover and Mutation operations in CS-GA algorithm

### Simulation Results

In this section, we present the results of the optimal no. of PMUs and their optimal locations optimized using the proposed CS-GA algorithm. To prove the efficiency of the proposed method, we benchmark the connection and bus data of the IEEE-14, IEEE-24, and IEEE-30 and IEEE-39 bus systems. In table.2, the optimal no. of PMUs required for the IEEE-14 bus system using the proposed CS-GA algorithm is presented. To measure the full observability, 3 PMUs are needed and their optimal locations are also presented in table.2 as 5, 4 and 6 respectively.

**Table 2:** Optimal PMU Placement results for IEEE-14 bus system

System	Optimal PMU	Connection	Total Coverage
IEEE-14 bus	1	4	5
	2	4,13	8
	3	5,4,6	11

In table.3, the optimal no. of PMUs required for the IEEE-24 bus system using the proposed CS-GA algorithm is presented. To measure the full observability, 8 PMUs are needed and their optimal locations are also presented in table.3 as 17, 8, 3, 16, 1, 10, 23 and 9 respectively. From these results, we can see that the variation of the CS-GA algorithm with different set of bus systems since optimal location of one PMU is different for both the IEEE-14 and IEEE-24 bus systems. However, it brings the best solution when required PMUs are increased w.r.t. the size of the connection matrix.

**Table 3:** Optimal PMU Placement results for IEEE-24 bus system

System	Optimal PMU	Connection	Total Coverage
IEEE-24 bus	1	9	5
	2	10,16	9
	3	10,16,12	13
	4	16,10,11,15	15
	5	12,21,9,15,16	18
	6	10,9,15,16,11,21	19
	7	16,17,23,15,10,12,9	21
	8	17,8,3,16,1,10,23,9	22

**Table.4.** Optimal PMU Placement results for IEEE-30 bus system

System	Optimal PMU	Connection	Total Coverage
IEEE-30 bus	1	6	7
	2	10,6	12
	3	6,10,12	16
	4	10,6,15,2	19
	5	2,10,27,12,6	21
	6	25,6,10,6,15,27	22
	7	4,25,12,7,10,6,15	26
	8	6,2,15,25,27,12,4,10	29
	9	15,2,12,24,25,6,9,10	29

**Table.5.** Optimal PMU Placement results for IEEE-39 bus system

System	Optimal PMU	Connection	Total Coverage
IEEE-39 bus	1	16	5
	2	16,2	9
	3	26,6,16	13
	4	16,2,6,13	16
	5	6,16,2,26,3	19
	6	16,6,2,19,11,26	22
	7	29,17,2,16,22,6,5	24
	8	17,16,2,23,25,14,6,29	25
	9	16,25,2,6,23,26,22,10,14	26
	10	19,26,3,16,11,29,10,23,2,6	31
	11	22,19,25,8,23,6,2,3,11,16,26	32
	12	26,29,11,10,2,6,22,19,16,23,3,25	34

In table.4 and table.5, the performance of the proposed CS-GA is presented for the IEEE-30 and IEEE-39 bus systems respectively. For IEEE-30 bus system, totally 9 PMUs are required while 12 PMUs are needed to observe the full topology of IEEE-39 bus system.

### 5. Conclusion

In this paper, a hybrid of the Genetic algorithm and Cuckoo Search algorithm was presented in order to combine the advantages of the both optimization algorithms. The

proposed CS-GA algorithm was presented to solve the optimization problems in the PMUs placement for the power system. The proposed CS-GA approach can find better optimal solutions for the IEEE N bus systems. The overall optimal solution obtained was efficient to take care of system observability under normal operating condition as well as for single PMU loss cases. The proposed method has only required minimum number of PMUs to cover complete observability of power systems. Experimental results have shown that the proposed CS-GA was more comfortable for finding the optimum no. of PMUs and their optimal locations in the IEEE-14, IEEE-24, and IEEE-30 and IEEE-39 bus systems.

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