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Optimal PMU Placement using Binary Particle Swarm and Artificial Bee Colony with Channel Limitations and Redundancy.

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***Abstract:** Phasor Measurement Unit (PMU) being expensive and to be placed optimally, a meta-heuristic approach of Binary particle swarm optimization (BPSO) and Binary artificial bee colony optimization (BABC) is made for the optimal allocation of PMU in a power system. The PMU locations resulted are served by basic system conditions like network configuration, critical generators, and loads. The pattern of locations on including Zero-Injection Buess (ZIB) is also discussed. The redundancy in case of PMU loss is coined so as to obtain a complete observability of the power system. the channel limitations of device is also taken into consideration for better results in real-time systems. Optimal PMU locations for IEEE 30-bus and 14-bus systems with channel limits are compared with all above considerations. The number of PMU locations is reduced as channel limits increases. The simulated PMU locations are decreased with improved observability by Binary Artificial Bee Colony Optimization as compared to Binary Particle Swarm Optimization.*

***Index Terms:**, Observability, Phasor Measurement Unit, Binary Artificial Bee Colony Optimization, Binary Particle Swarm Optimization.*

I. INTRODUCTION

Synchrophasor technology is one of the innovative approaches in modern power system analysis and operations. It helps in accurate Wide Area Monitoring Service (WAMS) in large networks [3]. Synchrophasor data of connected system like voltage phasors, current phasors, phase angles, frequency, Rate Of change of Frequency (ROCOF) with respect to GPS are given by Phasor Measurement Unit (PMU)[4] .This helps in recording the infeasible data during faults or blackouts. It also facilitates in accurate handling of faults in the system. The record of phasor data available for longer periods and disturbance recordings provides a valuable input in analyzing the status of the system [4]. We can predict the consequences well in advance and also helps in designing the network expansion [3]. The values at each instant are taken as a snapshot of the system and are delivered with respect to unified GPS clock [5]. The mode of communication through PMU connectivity is fast and accurate. It helps in the analysis of faults, contingencies, blackouts and islanding of system.

Placement studies of PMU in n-bus system adopt optimization algorithms as a mathematical procedure for power grids on large-scale. Optimality in synchrophasor technology secures the observability in the system. The placement analysis of PMU is taken considering the base case, Zero Injection Buses (ZIB) and redundancy of a system into consideration.

The synchrophasor data available from PMU finds many applications in power grid. It ensures power system control. Observability at bus level can be done using Bus Observability Index (BOI). Similarly observability at system level can be monitored using System Observability Redundancy Index (SORI) [4]. State estimation is accurately defined by PMU. The recorded data available from PMU can be used for Model validation [4]. The optimally placed PMUs in the system ensure observability and secure the connected system as phasor control is more accurate and fast [5].

II. PHASOR MEASUREMENT UNIT

Phasor Measurement Unit (PMU) is a measuring device which is placed at a bus to convert the analog current and voltage values that are drawn from current transformers and voltage transformers respectively into a GPS synchronized phasor data [4]. It takes inputs from the system at every instance and gives a time-stamp over the data. The phasor values and phase angles are resulted as a synchrophasor data are more accurate [7]. It helps in better power system analysis and monitoring with ensured observability [5].

PMU connected to a bus in the system has its respective observable region as per connectivity and channels it possessed [1]. It can observe the status of connected buses also by simple KCL and KVL rules. However the system conditions and considerations must be studied for a system before deciding the PMU placement. The significance of generation or load at the bus is also a factor of decision [7]. With topology concern of the connected system, ZIB and radial buses do not require PMU as these buses are already observable by other PMUs [7]. PMU placed at a bus measures the voltage and current phasors from analog signals. [2].

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With the line data and current phasors measured, the voltage at the connected buses over the incidence lines can also be calculated by means of KVL and KCL. Estimation of voltage phasors is limited only for adjacent buses if all its current phasors are available. [5].

Here, PMUs with unlimited channels are considered for the base case. Bus Voltage and line currents in the incident branches are measured with these PMUs. Theoretical determination of power flow in unobserved lines can easily be done from the phasor data if neither loads nor sources are connected to it [1]. Due to uncertainties in line parameters, PMU with more channels get errors in phasor values [5].These uncertainties propogates further by usage of KCL. So use of infinite channeled PMUs should be avoided [5].

The optimal trace of PMU locations in a connected system with consideration of channel limitations is taken in this paper.

A. Synchro-phasor technology

The system parameters like voltage, current, power, frequency, phase angle etc,, are measured conventionally. The analog signal data from current transformers and potential transformers are communicated fast with new methods. Monitoring of the system using the SCADA is the major transformation in the field of protection and analysis [4]. The SCADA measurements helps in correcting the values accordingly but the state estimate and time cannot be traced.

PMU is a synchro-phasor technology. It measures parameter as a phasor data synchronized to GPS clock. The phasor value with time stamp is recorded and communicated by receivers fast. This recorded data helps in future expansion of connected system and in taking major decisions [3]. The islanding of the system can also be handled effectively if monitored by PMUs.

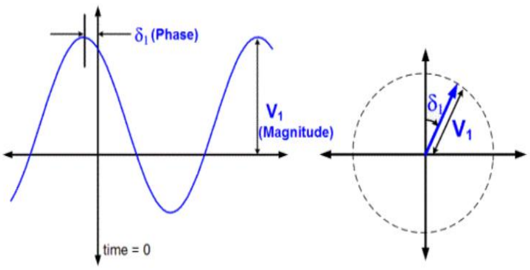

Fig 1. Representation of synchro-phasor

III. PMU PLACEMENT FOR POWER SYSTEM OBSERVABILITY

PMU measures the voltage phasor of both connected and all its incident buses using line parameters and current phasors [1]. However this is possible only for a PMU with infinite channels available. The significance for a bus in the system alters with concerns like generation, loads connected, integration of renewable or as a major substations [10].

The objectives for placement of PMU in this paper are:

(1)To reduce the required PMU number and making the system observable.

(2)To enhance the redundancy for all buses in the system

(3)Optimal placement of PMU with limited channels.

The observability of the system is calculated at each bus using BOI (Bus Observability Index) [7]. This index indicates how many times a bus is observed by all PMUs in the system. The redundancy of PMU placement can be noticed with elements in BOI matrix.. Addition of all buses BOI gives SORI of the system [4] .Placing of PMU at each bus is not required and is not recommended due to cost factor [3]. The channels available in PMU determine the readable area of the connected system by it [3]. PMU with infinite channels is assumed for any optimal placement problem but here in this paper the PMU with various channel limits are simulated and accordingly the locations are traced.

A. Zero Injection Buses (ZIB):

It is a bus at which there is neither injection of power nor connected to loads but is just a connected bus [2]. PMU placement can be ignored at ZIB with certain considerations. The sum of all currents in ZIB is zero as the incoming currents equalize with outgoing currents.

An unobservable ZIB is made observable, if every adjacent bus to it is observable [7].

The unobserved ZIB bus can be made observable if all its adjacent buses except one are unobserved by means of KCL equations.

The unobservable group of ZIBs can be made observable if all buses connected to them are moved into observable regions.

So we can summarize that ZIBs can be made observable by indirect measurements also. As a result, ZIBs can be excluded and only remained buses needs PMU placement to attain observability [2].

B. Critical-buses:

The significant buses in the system and also the bus at which parameters are sensitive and needs a clear monitoring can be regarded as critical buses. Placement of PMU is necessary at these critical buses as it helps in fast and accurate handling of any events.

C. Effect of PMU loss on observability of the system-Need of Redundancy*:*

Several contingencies may occur due to system uncertainity, it may even lead to blackouts due to inadequate monitoring system. As per N-1 criterion, the optimal allocation of PMUs in a system will effective even on a single PMU loss i.e, observability of the system must be maintained. Therefore, every bus must be observed by at least two (if redundancy=2) case PMUs so as to ensure observability for PMU loss or malfunctioning.

D. PMU- channel limits:

Phasor Measurement Units are generally assumed to measure any number of parameters. The device has a channel to measure the parameter of a connected line or a bus [3]. Sufficient channeled PMU is assumed in general for the optimal placement of PMU. But in practical situations, requirement of channels varies with the connectivity, significance and uncertainties of given system [9]. Based on channels required, the number and placement of PMUs changes. The smart decision of optimal PMU placement is done only after considering the channel limits of PMU. The observability, redundancy and cost factors are effectively served [9] .

The possible combinations with available channel limits is taken for each bus. This can be given by the (eq-1&2).

$$BC_i = \frac{BI_i!}{(BI_i-(L-1))!(L-1)!} \quad \text{.........(1)}$$

$$BR_i = \begin{cases} BC_i \text{ if } L \le BI_i \\ 1 \text{ if } BI_i < L \end{cases} \quad \text{............(2)}$$

BR_i = combination of branches for i^{th} bus.
L= Channel limit
BI_i = No. of buses adjacent to i
BC_i = No. of possible combinations Lout of BI_i

PMU with more channels has more observable region [9]. PMUs are to be selected basing on the branch weights of a bus and their work efficiency in system

IV. BINARY PARTICLE SWARM OPTIMIZATION (BPSO)

This Optimization is inspired from the social behavior of flock of birds, fish or swarm. It is a meta-heuristic mode of approach in attaining the optimized solution for the given input function, satisfying the constraints of given problem [10].

The individual particle knowledge is guided by the social behavior of the flock [10]. The binary mode of PSO consists of only two values 1 and 0 denoting the presence and absence respectively. We have below terms in this algorithm

Pop: number of particles employed in finding the optimal solution
X: position vector of each particle
V: velocity vector of each particle.
PBEST: Particle best position.
GBEST: best position opted by the group.
c1: acceleration coefficient of individual particle.
c2: acceleration coefficient of group.
random numbers ranging [0-1] are taken for r1 and r2.
Here, c1=c2=2;
c1+c2=4

$$\mathbf{x}_i(t) = \mathbf{x}_i(t-1) + \mathbf{v}_i(t) \quad \text{......................(3)}$$

$$\mathbf{v}_i(t)=\mathbf{v}_i(t-1)+[r1*c1*PBEST_i * \mathbf{x}_i(t-1)]+ [r2*c2*GBEST_{i.} * \mathbf{x}_i(t-1)] \quad \text{..............(4)}$$

The velocity component of i^{th} particle gets updated by on considering the behavior, state of individual particles and group as per (eq-4). The position vector of is calculated accordingly on updating it with calculated velocity component [10]. This is given by (eq-3) and the velocity constraints in (eq-5)

V_{ij}=-v_{max} if (v_{ij} <v_{max})................(5)
=-v_{min} if (v_{ij} >-v_{min})

Maximum and minimum voltage constraints for voltage are taken as above to avoid oscillations. In BPSO, the position vector takes binary values (0,1) which determines the presence or absence of PMU. Here a sigmoid function is taken to allocate values for x in (eq-6) as in [10]

$$sig(v_{ij}) = (1/(1+e^{-v_{ij}}))\text{.........(6)}$$

x_{ij} =1 if rand< sig (v_{ij})
=0 if otherwise

(1-*sig* (v_{ij})) is the probability of getting zero whereas *sig* (v_{ij}) gives the probability of one. [1]. The velocity vector is altered by sigmoid logic for binary values and position is updated accordingly.

To increase search efficiency, the below rules on updating velocity vector should be taken into consideration:

a) The velocity of particle is updated as per (eq-4) if PBEST and GBEST are feasible solutions.

b) The velocity is updated as per (eq-7) if GBEST is feasible and PBEST is not feasible.

$$V_i(t)= [c*r*GBEST_{i*}\mathbf{x}_i(t-1)]+ V_i(t-1)\text{...... (7)}$$

Where c=c1+c2 and *r* is a random number in the range [0, 1].

c) If PBEST and GBEST are not feasible, then maximum values of random fractions are set to the velocity of particles as per (eq-8).

$$V_i(t)=r*[n_1v_{1max}\ n_2v_{2max}\ n_3v_{3max} \ldots\ n_nv_{nmax}]\text{......(8)}$$

Where v_{1max} ...v_{nmax} are maximum specified values and random number (r) of range [-1, 1];

Required PMUs for placement are reduced as observable regions of only few buses makes most of the phasors available for a system The main objective of placement is to enhance redundancy and minimize the PMU number in the system [8].Complete observability has to be ensured.. Fitness (F) of each particle of swarm is evaluated using (eq-9) [10].

$$F=\min[(w_2*N_{PMU})+(J_1*C)+(w_1*N_{obs})]\text{..... (9)}$$

Here,C, w_2 ,and w_1 are weights,
N_{obs}: observed buses number.
N_{PMU}: total PMUs number

J_1 is the redundancy measurement defined as below (eq-10)

$$J_1= (M-A*X)^T(M-A*X)\text{..........(10)}$$

Here, M is the redundancy matrix, PMU placement status is given by X and A is the incidence matrix, and is taken as follows desired redundancy is n then take m_i=n-1.

The term (*M – A*X*) indicates the difference of actual and desired number of times the buses are observed in a system. Here, the minimizing of (M-A*X) improves the redundancy of PMU placement.

In case for any PMU loss, the fitness equation is modified as (eq-11).

$$F=\min[(w_1*N_{obs})+(w_2*N_{PMU})+(w_3*N_L)+(w_4*S)]\text{........(11)}$$

N_L: That are not observed double times(n=2)

S : Measurement redundancy with PMU loss.

N_L=|D, x>0|| = (A*X-b)

b refers to binary vector where b=[n n n n . . . .],if twice redundant system is required, take n=2

$S= [\sum_{i\text{-}N} (D_i)]$.

Table I. Parameters for BPSO

Terms	Values
Particle's number	4* (number of buses)
Iterations (i)	[2000]
Weight for number of observed buses	-2
Weight for number of PMUs	1
Weight of number of buses that are not observed double times.	2
Weight for measurement redundancy single PMU loss	-(0.02)
Weight for redundancy measurement	0.01

V. Binary Artificial Bee Colony Optimization:

Optimal search in this approach is designed based on behavior of bee colony. A bee always targets on nectar i.e, its food resource [6]. Employed bees move in the direction of targeted viable food source and unemployed bees scan for remained available food centers in search space. Bees are employed as per roulette wheel selection basing on richness of food sources [6].Fitness function is calculated for each available food source. If the quantity of food available declines, the fitness equation gets disturbed and so eventually leads to abandon food source. The unemployed bees left over after fitness calculation and abandon process are set to search for new sources [6].

At first, bees are employed on random basis according to (eq-12)

$$X_{ij}= X_{min,j}+rand(0,1)*(X_{max,j}-X_{min,j})......(12)$$

The below (eq-13-15) represent the work record of each bee in colony for generating new sources of food in search area.

$$W_{ij}= X_{ij} +rand1 (-1, 1)*(X_{ij} – X_{kj}) ....(13)$$

$$sig (W_{ij})=(1/(1+e(^{-W_{ij}}))) ....(14)$$

$$W_{ij} =1 \quad \text{if } sig (W_{ij})>rand1......(15)$$
$$0 \quad \text{if } sig(W_{ij})<rand1$$

The selection probability of food source is done as per (eq-16) basing on the feasibility, quantity and availability of it. The quantity plays a key role in decision making.

$$\text{Probability } (P)=(F(X_{ij})/(\sum F(X_{ij}))..........(16)$$

In this proposed Binary artificial bee colony optimization, new food source is searched based on viability of present food reserves. Neighborhood of food is formulated in proposed Binary ABC algorithm (BABC) by using randperm(D,N) approach.

$W_{ij}=1$ where j belongs to Randperm (D,N)
N distinct integers are selected randomly from [1, 2,3,,,,D].

This searches for same PMU number (result at each iteration) and jump from current field to improve the search rate for the problem. Redefining search criteria with (eq-16) than by (eq-12) gives optimal results in reasonable time and quality. The prioritization for a food source is made as per (eq-16) and accordingly the bees of colony are recruited either for search function or to target the food. The unemployed bees resulted due to fitness and probability weakens are set for onsite lookers.

Fitness or objective function for PMU placement in ABC algorithm is given as

$$F=C*10+\sum W_i*X_i \quad ....(17)$$

where, $W_i =(1/d_i)$ and d_i is number of connected nodes

VI. Binary PSO and Binary ABC for Optimal PMU Placement (OPP):

Local optimum problem is clear and can be resolved easily in this ABC optimization [6] rather than in BPSO optimization [1]. Here local optimum is resolved by embedding the process of abandoning the unfitted food sources. Simulation time taken for ABC is also less as compared to BPSO. The application of optimal PMU placement is more feasible, accurate and less complex in ABC [6]. The considerations in a system like ZIB, critical bus, redundancy and channel limits are clearly taken in the objective function.

The search criteria is finely checked at each iteration in case of BABC optimization. Certain optimal parameters for PMU placement are more feasible and reliable in BABC rather than in BPSO.

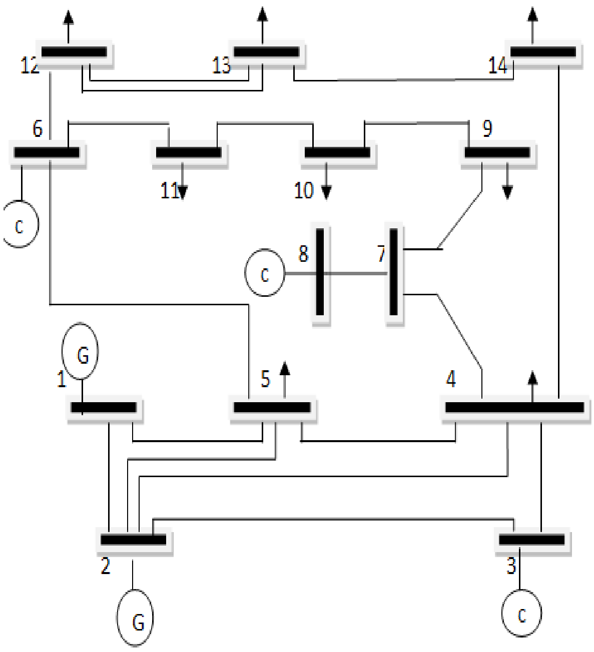

Fig 2.IEEE 14-bus system

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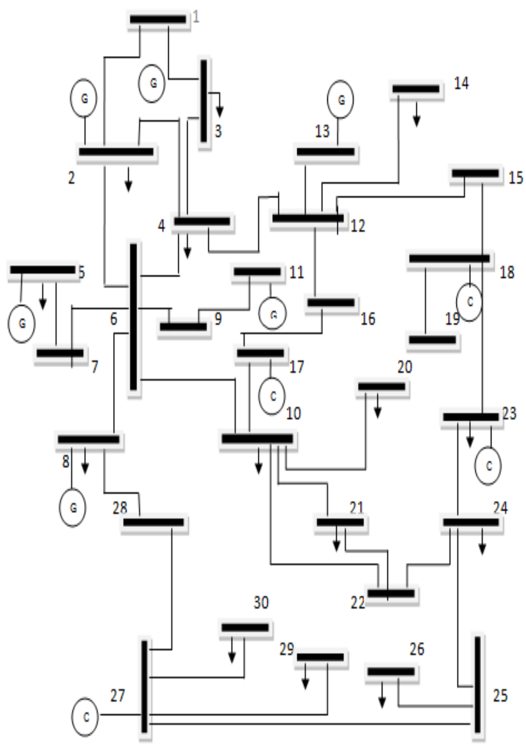

Fig 3. 30-bus IEEE system

VII. RESULTS

The optimal trace of PMUs for a system is obtained. by implementing the Binary Particle Swarm Optimization as proposed. Optimal PMU number and their locations required for 14-bus and 30-bus systems in (table-II)

The location of PMUs get altered if ZIBs are taken into consideration. To secure the desired redundancy for the system, the required PMU number increases.

Table II. Optimal PMU locations by BPSO algorithm

Bus system	Base		ZIB		Redundancy	
	No	PMU	No	PMU	No	PMU
14-bus system	3	1,4,9	3	3,7, 14	4	3,4,5,8
30-bus system	7	1,2,4, 5 ,12 ,14,17	6	3,5,9 ,16 ,28,2 9	20	5,6,7,9 10,11,12, 13,14,16, 18,20,21, 22,23,24, 26,27,28, 30

Comparing the simulated locations of 30-bus system by BPSO and BABC optimization techniques for base case, ZIB , redundancy and with channel limitations is shown in (table-.III).

Table III. Allocation of optimal PMUs for 30-bus system by BPSO and BABC algorithms

Case	BPSO algorithm		BABC algorithm	
30-bus	No	PMUs location	No	PMUs location
Base Case	10	1, 2, 3, 8, 9, 14, 16, 17, 18, 19	8	5, 13, 14, 16, 23, 27, 29, 30
ZIB	7	3, 5, 9, 16, 28, 29, 30	8	4, 11, 13, 18, 21, 22, 23, 30
PMU loss	20	5 ,6 ,7 ,9 ,10, 11, 12, 13, 14, 16, 18, 20, 21, 22, 23, 24, 26, 27, 28, 30	12	5, 6, 7, 8, 9, 12, 15, 22, 23, 25, 26, 28

Table IV. PMUs placed optimally considering the channel limits for 30-bus using BPSO and BABC.

30-bus system	BPSO algorithm		BABC algorithm	
	No	PMU location	No	PMU Locations
Channel Limits 2	15	1,2,3,4,5, 7,10,12, 14,16,17, 19,21,22, 30	11	1,2,3,4,5,7,1 5, 21,23,24,25
Channel Limits 3	11	2,5,6,7,8, 11,12, 21,28,29, 30	10	8,12,14,15,1 6,19, 20,22,23,26
Channel Limits 4	10	8,13,15,1 6,22, 23,24,25, 27,28	9	13,16,18,19, 20,25 26,29,30
Channel Limits 5	10	6,7,8,9, 10,11,15, 18,19,28	9	8,10,16, 17,20,22, 26,29,30

VIII. CONCLUSION

The optimal placement of PMU is implemented using Binary Particle Swarm Optimization (BPSO) and Binary Artificial Bee colony (BABC) algorithms. Basic connectivity of standard bus systems along with the considerations like ZIB, critical buses and redundancy for any PMU loss are taken. On comparing the simulated results, BABC approach gives optimal and efficient trace for PMU placement in fast and reliable mode.

The optimal PMU placement given with channel limitations gives a realistic approach in power grids. Optimally placed PMUs ensures observability and plays a prominent role in power system phasor control.

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