A HYBRID MECHANISM OF PSO AND RES FOR OPTIMIZED PMU PLACEMENT

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Abstract— With the growing ultimatum of electrical power, Quality of Service (QoS) and continuity of supply has been the utmost primacy for all major power utility sectors across the world, prior to the global market strategy. Smart Grid is predominantly proposed as the quantum leap in harnessing communication and information technologies to enhance grid reliability, and to enable integration of various smart grid resources such as renewable energy, demand response, electric storage and electric transportation. In order to prevent the prevalent blackouts, implementation of state-of-the-art technologies, such as a state estimation of the transmission network, is required to achieve better controllability, higher reliability and stability of the power system. The Phasor Measurement Unit (PMU) is a device that is employed to detect the voltage and current waveform that is synchronised with a clocking signal obtained continuously from the global positioning system. Measurements of phasors of current and voltage are an important factor which is required in modern power system. Usually supervisory Control and Data Acquisition systems are utilized for the same but in recent years PMU's has gained significant importance. In this research work, we have designed a new Optimized PMU placement mechanism using Reduced Exhaustive Search (RES) and Particle Swarm Optimization (PSO). The proposed algorithm for optimal placement of the PMU's is applied at the IEEE 39 bus system keeping the whole system completely observable.

Keywords— *Power system, phasor measurement unit, pmu, scada, transmission grid, PSO, RES.*

I. INTRODUCTION

Power utilities are facing increasing number of threats of securityof operation due to over stressed power network in competitive power market scenario. State estimation is a tool which provides the real-time state of the system. It is an integral part of energy management system (EMS) for security analysis and other power system applications. Pre-requisite of state estimation is that the system must be fully observable from the available measurements. Before introduction of synchro-phasor technology, state estimation was relying on SCADA systems. Superiority of PMU measurements over SCADA measurements are that PMU provides the phase angle measurement directly and all the measurements are time synchronized. PMU provides voltage phasor of the bus where it is installed and current phasors of all the branches incident to that bus. Direct measurement of all the system states is possible by placing PMUs in all buses of a network without running any state estimator. The PMU and its associated communication system are costly and the voltage phasor of the incident buses to PMU installed bus can be obtained with the help of branch parameter and branch current phasor. If the network is observable through optimally placed PMU, a linear state estimator provides system states in a single iteration. The main objective of optimal PMU placement is to determine the minimal number of PMUs to be installed at strategic locations so that the entire power system becomes completely observable for state estimation. Some of the important contributions in PMU placement area are bisecting search and simulated annealing based method, non-dominated sorting based genetic algorithm approach, simulated annealing based graph theoretic approach, integer programming (IP) based approach. Random selection of PMU placement sets makes bisecting search approach computationally less efficient. The IP approach uses linear programming (LP) solver and branch and bound algorithm. Branching involves development of subproblem of the original problem and bound involves enumeration of the subproblem through linear programming. The process requires use of LP solver in every iteration which again depends on the size of the system and thus the method is computationally intensive. For benchmarking of global optimal solution the exhaustive binary search method is suitable but computational burden is heavy for large size networks. In a phased installation scheme of PMUs is proposed such that the final placement will be optimal. RES and PSO method is proposed to obtain minimum number of PMU for complete observability of power system. A non-dominated sorting based differential evolution algorithm is proposed for multi-objective optimization of PMU placement problem. In a metaheuristic based iterative local search method is proposed to find the optimal solution where an initial PMU placement is considered which makes the system fully observable. PMU

The Phasor Measurement Unit (PMU) is a device that is employed to detect the voltage and current waveform that is synchronised with a clocking signal obtained continuously from the global positioning system (GPS). Integrating with the GPS receiver, the base station is able to receive the synchronous data from each PMU in real time. The location of malfunction circuits or transmission lines can be immediately identified if phase differences between different PMUs are detected [8]. Phase angle between the voltage phase and current phase as the basic measuring function of PMU has been utilized to monitor the condition of power networks. Theoretically, the active (real) power flow in a distribution line is proportional to the sine of the angle difference between voltages at the two terminals of the line. In which case, the angle difference was deemed as a special consideration to manage and operate the power network [9]. In the early 1980s, novel phase angle measurement equipment was introduced. The communication channel, which was based on LORAN-C, GOES satellite transmissions and the HBG radio transmissions in Europe was utilized to maintain the reference signal in synchronization. Researchers established the local phase angle with respect to the time reference for resolving zero crossing of the phase voltage. The phase voltage was referred to the common reference signal and the phase angle difference between two sets of phasor measurements was computed. However, the best-achieved time reference from the communication channels mentioned above only provided measurement accuracy in the order of 40 microseconds. As a consequence of this, these devices could not offer high precision to realize power network measurements in time synchronization [2].

The global positioning system (GPS), which was invented and deployed by the U.S. Department of Defense in 1993, was introduced to the next generation of phase measurement devices called the Phasor Measurement Unit (PMU). The GPS consists of space satellites, control stations and user equipment. A total of twenty-four satellites orbit at a height of a million miles from the earth, and transmit the high frequency signals to the control stations to provide the precise message of the time and orbital information. As a result, the users can achieve 24-hour continuous real-time information-processing that is synchronized to the international standard time. In addition, the GPS provides high precision timing, ranging from 1 nanosecond to 10 nanoseconds. At the same time, the GPS receiver can supply a unique pulse signal in one second intervals, which is known as 1 pulse per second (PPS). Therefore, the issue of unsynchronized standard time in the power grid was solved by installing or embedding the GPS receivers into various devices in arbitrary positions, such as in the high voltage sub-station and transmission towers [5].

Apparently, the implementation of the GPS technology into the power network is a perfect idea as it allows for accuracy and reliability of clock synchronization. For instance, the accuracy of the GPS timing pulse is better than 1 microsecond, which for a 50 Hz system corresponds to About 0.02 degrees. In comparison with the previous methods, it offers several advantages, such as clock synchronization with high Accuracy in the nanoseconds range, extensional usage range, and no special demand for a communication channel; there is also less chance of the device being influenced by weather conditions and/or geography.

II. PHASOR MEASUREMENTS

Phasor is a fundamental concept in Electrical Engineering that represents a sinusoidal signal represented by the quantity of its magnitude and phase with respect to a reference. In the figure of sinusoidal waveform as depicted in Fig. 1, the distance between the sinusoidal peak of signal and the time reference (E.g. time = 0) is defined as a phase angle .

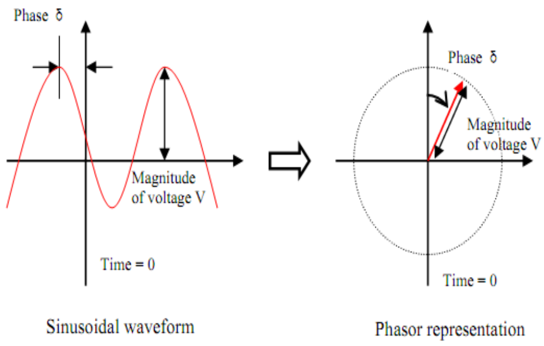

Figure 1. Sinusoidal waveform and its phasor representation.

Phasor technology including the Phasor Measurement Unit (PMU) is a valuable measurement technology in the power system for monitoring the condition of transmission and distribution networks. As shown in Figure 2, the pharos of the 50Hz component is obtained based on the digitally-sampled analog voltage waveform that is synchronized with the clocking signal from the GPS receiver in distributed locations (#1 and #2). The time reference is titled as a 'common reference' signal and it helps to synchronies the different waveforms at all different sites. The amplitude difference between Signal #1 and Signal #2 in Fig. 2 is due to the signal attenuation on the overhead transmission line.

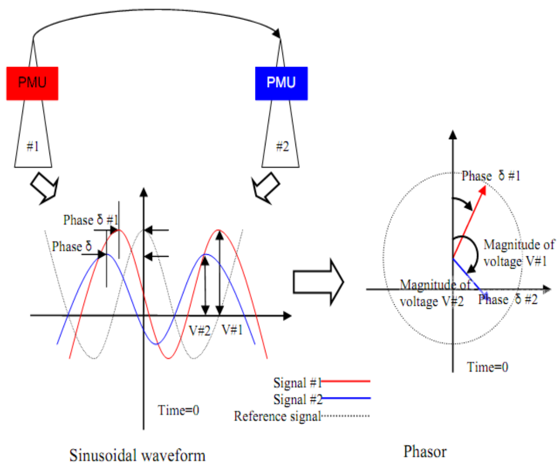

Figure 2. Signals received by PMU's

With the invention of the Phasor Measurement Unit (PMU), the phase angle was first directly measured. A PMU is a digital device that can provide synchronized voltage and current phasor measurements. Phase angles at the different sites can be determined when the measurements are synchronized to a common time source [15]. The Global Positioning Satellite (GPS) is capable to provide the common time signal of the order of 1 microsecond, which can obtain highly accurate PMU voltage and current phasors. Fig 3 provides the function blocks of a PMU. The analog inputs include voltages and currents obtained from the secondary windings of the voltage and current transformers. The anti-aliasing filter is used to attenuate the frequencies that are higher than Nyquist frequency. The phaselocked Oscillator converts GPS 1 purse per second into a sequence of high speed timing purses that will be used in waveform sampling. The A/D converter can convert the analog voltage and current signals to digital signals, which are imported into phasor microprocessor to execute the Discrete Fourier Transform (DFT) phasor calculations. The computed string of phasors is assembled in a phasor data concentrator (PDC) and this phasor stream is then transmitted to the modems [13].

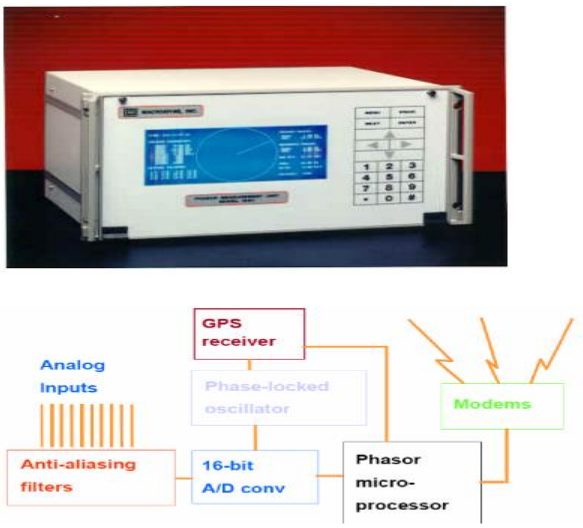

Figure 3. Phasor Measurement Unit (PMU) and its function block diagram.

In recent years, PMUs are gradually applied in the monitoring and control of power systems for improving network observability and state estimation accuracy. PMUs sample synchronously at selected locations throughout the power system. This provides a system-wide snapshot of the electrical system through the use of GPS receiver-clocks. The GPS not only provides time tagging for all the measurements but also ensures that all phase angle measurements are synchronized to the same time as well.The Phasor Measurement Unit embeds the Global Positioning System (GPS) receiver clocks to achieve the synchronising of sampled signals at nominated locations of the entire power network. In the real-life system, the PMU receives the voltage and current waveforms as inputs, which are derived from standard Current Transformer (CT) and Potential Transformer (PT). The input signals are isolated, filtered and sampled at an effective rate of 48 samples per cycle of the fundamental frequency [15].

The phasor microprocessor, as shown in Fig. 3, uses the recursive Discrete Fourier Transform (DFT) algorithm to calculate the local positive sequence, fundamental frequency and voltage and current phasors from the sampled data. The resultant time-tagged phasors are immediately available for local or remote applications via the standard communications ports. With these PMUs installed of a power system, a network is created, visible to the operators. The simplest form of phasor network consists of two nodes; one Phasor Measurement Unit (PMU) at node 1 that communicates with one Phasor Data Concentrator (PDC) at node 2. A PDC forms a node in a system where phasor data from a number of PMUs or PDCs is correlated and fed out as a single stream to other applications. The PDC correlates phasor data by time-tag to create a system wide measurement set. Typically, many PMUs located at various key substations gather data in real-time and they are connected to a PDC at the utility center where the data is aggregated [18] [21]. A personal computer, connected to the output of the PDC provides the users with software, such as RTDMS that calculates and displays locally measured frequencies, primary voltages, currents, MWs and MVARs for system operators. Additionally, many PDCs belonging to different utilities can also be connected to a common central PDC (SuperPDC) to aggregate data across the utilities to provide an interconnection-wide snapshot. A SuperPDC should have the capability to do both and it is possible if it is fast enough. The obvious problem of locally storing all the data would be the need to employ large disk drives and have a system in place to regularly transfer full disk phasor data to DVD for permanent storage. A rate of 30 or 60 samples per second fills up a disk drive very quickly. By operating interrelated software of the PMU, the users are capable of monitoring the phasors across the whole transmission network for any abnormal events. The phasor data provides information of pre-fault or post-fault conditions. Therefore, the operators in the central control room can sequentially and continuously acquire and calculate the values of phasor.

III. PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Dr. Ebehart and Dr. Kennedy in 1995, inspired by social behavior of bird flocking or fish schooling. PSO shares many similarities with evolutionary computation techniques such as Genetic Algorithms (GA). The system is initialized with a population of random solutions and searches for optima by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles. The detailed information will be given in following sections. Compared to GA, the advantages of PSO are that PSO is easy to implement and there are few parameters to adjust. PSO has been successfully applied in many areas: function optimization, artificial neural network training, fuzzy system control, other areas where GA can be applied. The term "Artificial Intelligence" (AI) is used to describe research into human-made systems that possess some of the essential properties of life. AI includes two-folded research topic.AI studies how computational techniques can help when studying biological phenomena.AI studies how biological techniques can help out with computational problems. The focus of this report is on the second topic. Actually, there are already lots of computational techniques inspired by biological systems. For example, artificial neural network is a simplified model of human brain; genetic algorithm is inspired by the human evolution. Here we discuss another type of biological system - social system, more specifically, the collective behaviors of simple individuals interacting with their environment and each other. Someone called it as swarm intelligence. All of the simulations utilized local processes, such as those modeled by cellular automata, and might underlie the unpredictable group dynamics of social behavior. Some popular examples are bees and birds. Both of the simulations were created to interpret the movement of organisms in a bird flock or fish school. These simulations are normally used in computer animation or computer aided design. There are two popular swarm inspired methods in computational intelligence areas: Ant colony optimization (ACO) and particle swarm optimization (PSO). ACO was inspired by the behaviors of ants and has many successful applications in discrete optimization problems. The particle swarm concept originated as a simulation of simplified social system. The original intent was to graphically simulate the choreography of bird of a bird block or fish school. However, it was found that particle swarm model could be used as an optimizer. PSO simulates the behavior so bird flocking.

$$V_i^{(u+1)}=w*V_i^{(u)}+C_1*rand()*(pbest_i-P_i^{(u)})+C_2*rand()*(gbest_i-P_i^{(u)})$$

$$P_i^{(u+1)}=P_i^{(u)}+V_i^{(u+1)}$$

In the above equation, The term rand ( )*($pbest_i-p_i^{(u)}$) is called particle memory influence. The term rand ( )*($gbest_i-P_i^{(u)}$) is called swarm influence. $V_i^{(u)}$ which is the velocity of i^{th} particle at iteration 'u' must lie in the range $V_{min}\leq V_i^{(u)}\leq V_{max}$

IV. PSO BASED CLUSTER FORMATION

Input: Connectivity details of the given bus system

1: Create binary table for the given buses as

For i = 1 to number of bus

For j = 1 to number of bus

If bus (i) connect to bus (j)

Matrix element represent as 1

Else

Matrix element represent as 0

End If

End For

End For

2: D= Sum (f(x))

3: L = max (d)

4: Calculate the bus connection for Lth bus and place PMU on that bus

5: Update the binary table by eliminating the bus from binary table

6: Initialize particles

7: Position of particles = 'x' and 'y' coordinating points of bus location.

8: Velocity = random (number of buses)

9: Check fitness for given position by using objective function.

10: Minimum (F_Position)

11: Velocity = w * velocity + c1 * (r1 * (Lposition – Position)) +c2 * (r2 * (Gposition – Position))

12: Position = Position + Velocity

13: For k = 1 to iteration

If Present_fitness< Last_fitness

Update fitness value

End If

Update velocity and position.

End For

14: Find maximum (fitness_value), mf = max (fitness)

15: Place PMU on that bus.

16: Update binary table by eliminating the bus from binary table.

17: Loop to Step 6 until binary table gets empty.

18: If the PMU placed at only one bus,

Check the nearest bus and made connection between them and update cluster.

19: End If

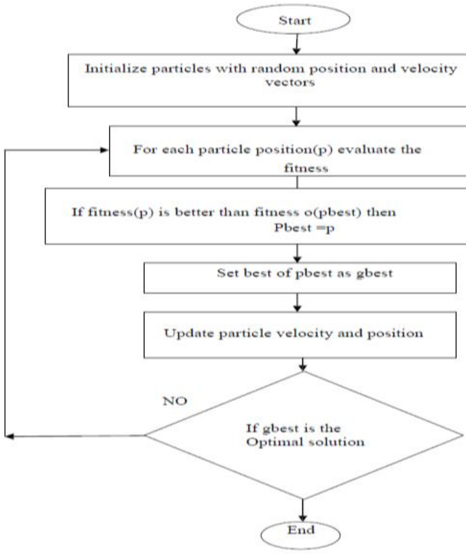

Figure 4. Flowchart

V. ZERO INJECTION BUS

In many cases, zero injection buses (ZIBs) exist in a power system. This may reduce the total number of PMUs needed for complete observability of a given system. A ZIB can be identified if all of the following conditions are satisfied. Zero injection buses are the buses from that no current is passed into the system. Zero injection correspond to the transferring nodes in the system. If zero injection buses are also designed in the

PMU placement problem, the entire number of PMUs are further minimized.

The bus conditions are:

1. There is no connected load or generator.
2. The current injection of the bus is zero.
3. The active and reactive power measurements are zero.

A way of incorporating ZIBs to the OPP calculation is by the modification of the general binary connectivity matrix.

VI. POWER SYSTEM OBSERVABILITY

The main objective of PMU placement is to have complete system observabilty. Reducing the number of PMUs needed for complete observability at the minimum will give the OPP. To achieve the main objective, there are cases that have to be satisfied for the system to be observable.

Case 1. If a PMU is installed on a bus then the phasor voltage of that bus and the phasor currents of all incident branches are known by direct measurement.

Case 2. If the phasor voltage of one terminal of a branch and the phasor current of that branch is known then the voltage phasor of the other terminal of that branch is also known by using circuit laws.

Case 3. If phasor voltages of both ends of a branch are known then the phasor current of that branch is also known by using Ohm's law.

Case 4. If phasor currents of all buses incident to a ZIB are known except for one then the unknown phasor current is also known by using Kirchhoffs Current Law (KCL).

Case 5. If phasor voltages of all buses incident to a ZIB are known then the phasor voltage of that ZIB is also known by using Kirchhoffs Voltage Law (KVL).

Case 6. If phasor currents of all buses incident to a set of incident ZIBs are known except for one then the unknown phasor current of that branch is also known by using KCL.

Case 7. If phasor voltages of all buses incident to a set of incident ZIBs are known then the phasor voltage of that set of incident ZIBs is also known by using KVL

VII. REDUCED EXHAUSTIVE SEARCH

Power systems should have a reliable operation, protection and control. To achieve this, modern power systems require accurate and real-time monitoring devices. Phasor measurement units (PMU)s was developed to provide synchronized voltage and current measurements with their corresponding phase angle measurements in real-time [I). The objective of Optimal PMU placement (OPP) is to have complete system observability with minimum number of PMUs. Complete system observability means that all bus voltages and currents with their phase angles are known or can be computed. OPP can make all buses be directly and indirectly observed. Most of the current methods for OPP give only one solution which gives limited options for the planning of actual PMU placement. It is necessary to know all the possible solutions to have alternatives in special cases that one solution may not be efficient in actual installation. Apart from most of these methods, ES is the most reliable in generating all the possible solutions. The problem with this method is that it requires large number of computations. Because of its exhaustive nature, the execution time for a simulation to finish for large networks may take too long. To overcome this problem, this paper proposes an optimized version of the ES algorithm for OPP. It reduces the search space and the number of computations of the traditional ES thus it is named reduced exhaustive search (RES).

Step 1. Identify the priority constraints by starting from the least number of xi in (2-10) and eliminate all constraints that intersect. Do these on the succeeding constraints in ascending number of Xi for the rest of the set.

Step 2. Reduce the original set of constraints by eliminating all the constraints having a subset .of any of the priority constraints.

Step 3. The number of test PMU s starts at the possible minimum determined by the number needed by Step 1.

Step 4. Candidate solutions are obtained by exhausting all the possible binary permutation of the current number of test PMUs before incrementing. Each solution is created by satisfying first the set of Step 1 before other buses.

Step 5. Record the solutions of Step 4 that satisfy the set of Step 2. If all candidate solutions were exhausted and the recorded set of solutions obtained in this step is not empty then it is the complete set of solutions. Else, increment the test number of PMUs and perform Step 4.

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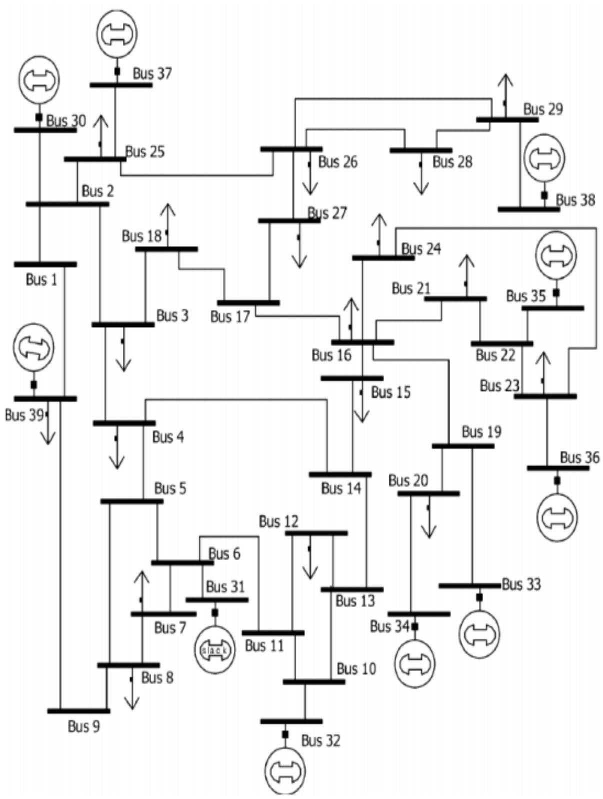

Figure 5. IEEE 39 Bus system

Let f be the sum of all PMUs installed on the system.

$$f(x_1, \ldots, x_9) = \sum_{i=1}^{9} x_i$$

$$f(x_1, \ldots, x_9)_{minimum}$$

$$b = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}^T$$

$$\begin{cases} 1, if\ i = j \\ a(i,j) = 1\ if\ bus\ i\ and\ j\ are\ connected \\ 0, otherwise \end{cases}$$

IEEE bus systems are used by researchers to implement new ideas and concepts. This technical note describes the details of the IEEE 39-bus system. The system consists of loads, capacitor banks, generators. The IEEE contains 39 buses in total and there are 12 zero-injection buses located at bus 1, 2, 5, 6, 9, 10, 11, 13, 14, 18, 19 and 22 as shown in Table 1. An identical procedure is applied to the IEEE 39-bus system and the final results are tabulated in Table 1.

Table 1. Identification of ZIB

System	39
Number of Branches	46
Number of Zero Injection Buses	12
Location Of Zero Injection Buses	1,2,5,6,9,10,11,13,14,18,19,22

When we applied particle swarm optimization on the IEEE 39-bus system, total 10 PMU are required to make the system fully observable. The PMU's should be placed at 16,2,6,26,3,8,10,13,19,22 to make the system observable.

Table 2. Location of PMU using PSO

System	PMU Placement using PSO
39 bus	16,2,6,26,3,8,10,13,19,22

When RES (Reduced exhaustive search) is applied along with PSO, then there is reduction in required number of PMU. The hybrid mechanism has reduced the PMU's to only 5. The location of PMU's is 9, 17,20,23,29.

Table 3 Location of PMU using PSO and RES

System	PMU Placement using PSO and RES
39 bus	9,17,20,23,29

By analyzing the results, it has been found that we are able to reduce the PMU using the proposed mechanism. In comparison with the two proposed methods, the solution of a hybrid approach based on the particle swarm optimization and reduced exhaustive search, which is simulated in Matlab environment, has a lower value in IEEE39-Bus system in comparison with the existing system. Thus, installing a PMU in specified locations will obtain a reliable and stable solution to lead to the network being fully observable.

Table 4. Processing time in seconds

S.NO.	Existing work	PROPOSED
1	10.066019	2.940321
2	10.017514	2.885542
3	9.969499	2.903665
4	9.968113	2.736444
5	9.902928	2.762543
6	9.967776	3.155304
7	9.979594	2.941935
8	9.948776	2.97453
9	9.997233	2.975517
10	10.028435	2.984844

Table 4 demonstrates the different processing time for the existing work and the proposed work. Multiple number of experiments have been conducted and the results have been analyzed. From the values, it is visible that the processing time has been significantly reduced in the proposed work.

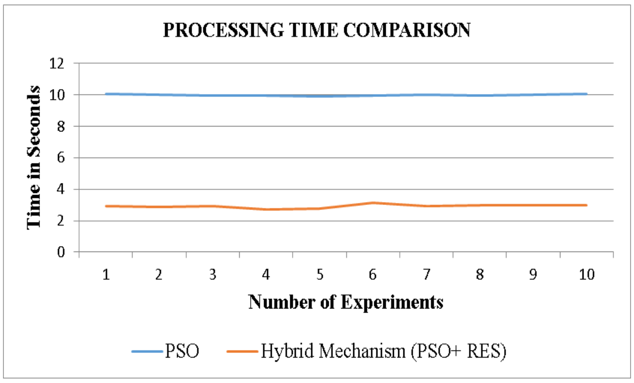

Figure 6. Processing time comparison

X-axis implies the processing time in seconds and y-axis number of experiments. Plots are shown using PSO and hybrid mechanism of PSO and RES. The proposed method overcomes the limitation of PSO successfully and is very versatile to use for any other search purpose. From the Plotted curve it can be easily understand that, original PSO is taking longer time than the proposed mechanism. The proposed algorithm can overcome this deficiency and far quicker than the original PSO.

VIII. CONCLUSIONS

Due to the increasing development of power networks, their control systems and protection requirements are becoming complex. In recent years, the theory of synchronized phase angle measurement has verified that it brings a deep-seated advantage for the network real-time protection. Furthermore, along with the device of Phasor Measurement unit, these applications will enhance, in reality, the power system monitoring, control and protection. In this thesis, we have aimed to ensure that the number of PMUs required for supervising the power network is minimal. If the premise is network observability, installation with less PMUs can be transferred in combinational optimization problems. Two varied combination algorithms have been introduced, separately which are named as PSO (Public swarm optimization) and RES (reduced exhaustive search). To summarize, by researching the hybrid algorithm, it has been found that both algorithms are able to deal successfully with the problem of optimal PMU placement. In the future, the Optimal Placement Algorithm should be implemented into real networks, owing to the absence of information in the models of IEEE standard bus. Accordingly, this is the way to ascertain that the selected locations of PMUs qualify to guard the entire system against any information being lost in the transmission line.

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