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An Examined Binary Grey Wolf Optimization Technique for the Best Phasor Measurement Unit Placement on Weak Buses

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Abstract: *Accurate and efficient monitoring is necessary to build a dependable and stable electrical system. Phasor Measurement Units (PMUs), which supply the synchronized data required by modern power grids, have developed into handy tools for real-time monitoring, boosting PMU effectiveness, and lowering installation costs; nonetheless, PMU placement must be done correctly. This study uses Binary Grey Wolf Optimization (BGWO), a metaheuristic-based optimization technique, to arrange PMUs in a power system on weak buses. Observing what is correct and efficient is necessary to build a dependable and stable electrical system. Phasor Measurement Units (PMUs), which supply the synchronized data required by modern power grids, have developed into extremely useful tools for real-time monitoring, boosting PMU effectiveness, and lowering installation costs; nonetheless, PMU placement must be done correctly. This work uses Binary Grey Wolf Optimization, a metaheuristic-based optimization technique. The social structure and hunting habits of grey wolves served as inspiration for the development of this improved version of the Grey Wolf Optimization algorithm. It is used to solve optimization problems by imitating the hunting techniques and leadership structure of grey wolves in the wild. regarding the best location for PMUs on weak buses. By using this technique, the power system's monitoring and control capabilities are improved by finding the ideal site for PMUs. This study aims to find the minimum number of PMUs required for full system observability to reduce the total investment in monitoring equipment and to guarantee that weak buses are adequately covered. To create an objective function, redundancy, cost, and system observability are combined. After that, BGWO is used to perfect the function, producing a series of binary decisions that show where the buses are located for PMU installations. As the algorithm iteratively becomes better, it eventually reaches the best placement. The acquired results are compared with heuristic approaches and standard optimization techniques to show the benefits of BGWO in terms of processing efficiency and solution quality. This study advances smart grid technology and the efficient management of electrical networks by supporting the development of new instruments for the best placement of PMUs. The application of the BG O technique to PMU placement has the potential to significantly improve the performance and reliability of the power system.*

Keywords—phasor measurement unit, buses, binary grey wolf optimization, meta-heuristic

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I. INTRODUCTION

The operation, regulation, and monitoring of these enormously complex and man-made networks—the electrical energy design—now face additional challenges because of the reorganization of power systems and the growing electricity demand. To maintain stability and the integrity of the network, the deployment of a Supervisory Control and Data Acquisition device is being considered. Generally, synchronous data sets are not supported by SCADA systems. These systems also have modest sampling rates. As a result, the data from the

SCADA network indicates that the system is in a semi-stable state, and the command base employees are not equipped to understand the dynamic nature of the system's features [1]. Due to the shortcomings of the SCADA system, the wide-area measurement system (WAMS) was created, allowing for precise data assessment [2]. The Phasor Measurement Unit is the core part of a WAMS. By watching the voltage and current angles, increasing the sample rate, and enabling simultaneous measurement, the shortcomings could be addressed [3]. The primary aims of the electricity utility are to deliver electricity while safeguarding the system continuously and repeatedly against serious malfunctions and outages. Power network analysis is used to achieve the power of supply identification. It's critical to find the issue as soon as possible to prevent it from getting worse and having a detrimental effect on how the framework and its components work. The complexity of the massive organization is the source of fluctuations, flaws, power outages, and unpredictable conduct in the electricity source [4]. The ability of PMUs to track the electrical system instantaneously led to the development of these devices in WAMS. However, electricity framework observability cannot be achieved solely by the deployment of PMUs; rather, an essential part of WAMS is the infrastructure for communication (IC), which must be effectively developed and put into operation to gather data from PMUs and send it to the command centre. The PMU is the brain of the system; it provides information such as voltages and phase angle evaluations. An added aim is to estimate the status of the system using synchro-phasor technology to decide the best number of PMUs to install in the system for power system analysis and system economic advantages [5]. PMUs for online power system monitoring make it easier to create such devices in a WAMS, but to achieve full observability, the communication system's observability must also be examined (8). PMU is a more sophisticated kind of SCADA that is used to synchronize time to calculate voltage and current. Its main purpose was to guarantee the observability of the complete power system. The advantage of the PMU is that it can evaluate the voltage and current coming from connected buses and note their magnitudes and slopes. They were used in many countries, and techniques for phasor measurement, PMU installation costs, synchronization, PMU and WAMS application, model validation, and parameter identification were used. It also plays a big part in the WAMS and has the improved function of monitoring [6]. Power networks are becoming more and more complicated because of the expansion of the power grid and the use of new technologies. Dynamic state estimation (DSE) algorithms that can accurately predict the dynamic states of the power network in real-time, including voltage magnitudes, phase angles, and rate of change of frequency using PMU, are necessary to ensure the stability, dependability, and effectiveness of these networks. These algorithms must be able to handle varying loads, shifting network circumstances, and contingencies. To find the best locations for PMU installations in the power network that will maximize their observability and controllability, several factors must be considered, including the topology of the network, critical buses, redundancy, and financial constraints. To help decision-makers improve the stability and reliability of the grid, the positioning strategy should ensure that the network can be seen under a range of operational conditions and enable real-time monitoring and control. It should also create a system for real-time monitoring and control that uses the PMU data and DSE outputs. Control systems for fault detection, voltage regulation, and adaptive protection schemes must be created to do this. Redundancy should be considered in the best placement design to ensure data availability in the case of PMU failures or communication interruptions. Backup locations must be chosen for critical measures.

To fully observe the Power grid network and minimize cost analysis, the study aims to provide an overview of the creation of an algorithm for the best positioning of the PMU device on the weak buses. The goal of the project is to develop novel PMU placement strategies that will improve the observability, accuracy, and financial viability of PMU-based monitoring systems. By creating an algorithm for the best location of the PMU device on the weak buses for full power grid network observation and cost analysis minimization, it is possible to develop an algorithm for dynamic state estimation and optimal PMU device placement for comprehensive power grid network observation.

A. Phasors Measurement Unity (PMU)

A PMU is an electronic device that measures and analyzes electrical quantities in the power system, including phase angle, frequency, voltage, and current. The challenges can be successfully overcome by using a newly designed PMU, which can deliver up to 120 time-tagged observations per second. However, those PMUs must have the necessary features connected to the distribution system's vulnerability factors. The IEEE defines a PMU as "a tool that generates coordinated phasors, frequency, and rate of change of frequency (ROCOF), and infers a time-matching signal from both voltage and current signals [8]." The power system needs to work efficiently and dependably, and the PMU can provide very correct and synchronized measurements of these quantities in real-time [9]. By obtaining readings from instrument transformers (CTs and PTs) and transmitting them to nearby PDCs via an aliasing mixer, PMUs can obtain and calculate the analogue signal spectrum as needed. Following the GPS receiver signal, data are then transferred through an analog-to-digital converter in the central processor unit to obtain the proper digital signal. Here, the signals' phase and size are calculated, and data time is synchronized by a random sampling clock [10]. PMU technology provides phasor information both size and phase angle in real-time. The reports gathered by PMUs are incredibly correct, enabling technicians to pinpoint the precise sequence of events that have caused outages and failures that may have led to the catastrophic malfunction of the electrical system. One of the biggest advantages of PMU technologies is that information transmission speed is no longer a crucial factor in the use of this data since all PMU observations with the same timestamp are used to infer the state of the electrical network at the instant described by the timestamping [11]. Phasor and its visual interpretation: Assume that phi, the phase angle in radians, is a sensory quantity that represents the signal's angular frequency in radians per second.

$x(t) = Re\left\{Xe^{j(\omega t+\varphi)}\right\}$ (2)

The sinusoid of Equation. (1) is represented by a complex number $X*$ known as phasor representation open presentation$(t) = \left(\frac{X}{\sqrt{2}}\right)e^{j\emptyset} = \frac{X}{\sqrt{2}}(\cos\emptyset + \sin\emptyset)$ (3)

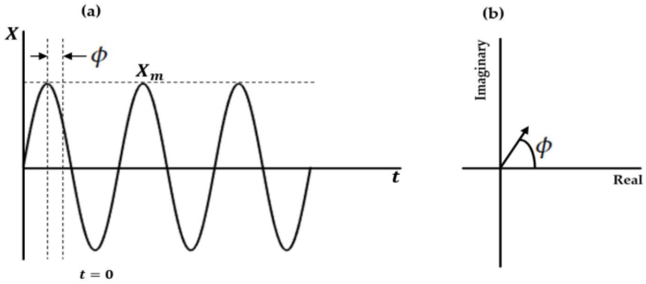


Fig.1(**a**) Sinusoidal waveform; (**b**) phasor representation

III. PMU MEASUREMENTS

PMU-based SE, which uses correct time-tagged voltage and current synchro-phasor measurements that are updated every cycle, is expected to be used by future EMSs. PMUs are thought to measure phase angles of busbar voltages, branch current synchro-phasors, and busbar voltage synchro-phasors.

Each phase and size angle synchro-phasor independent estimation error has a zero mean and a defined deviation, according to a Gaussian distribution. It is believed that the estimated size and phase angle of each voltage or current synchro-phasor are not correct approximations of their actual values [12].

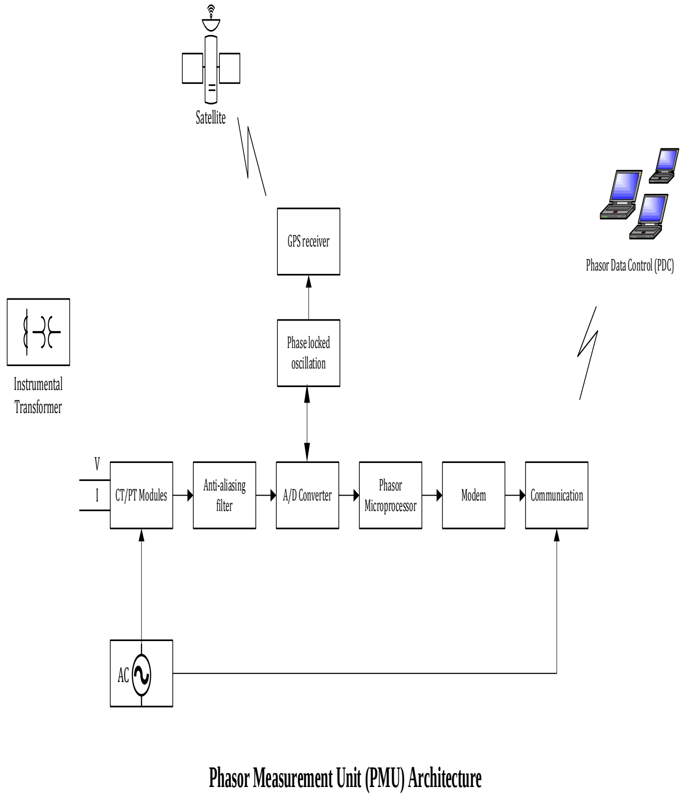


Fig. 2

Current Transformer (CT)

The high primary current of a power system is converted to a low, standardized secondary current suitable for measurement and protection devices by an instrument transformer or CT. The primary winding of a CT is linked in series with the power conductor carrying the current to be measured, while the secondary winding is connected to protection or measurement devices. CTs provide a reduced, proportionate current output that faithfully stands for the primary current. By keeping the present waveform's phase link, they offer correct readings. Common uses for CTs are as follows: • • Current measurement for energy, watt, and ammeter meters; • Current inputs for safety relays to detect faults and overcurrent conditions.

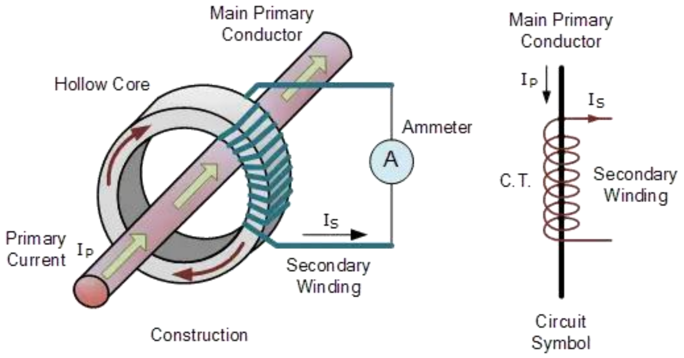


Fig. 3

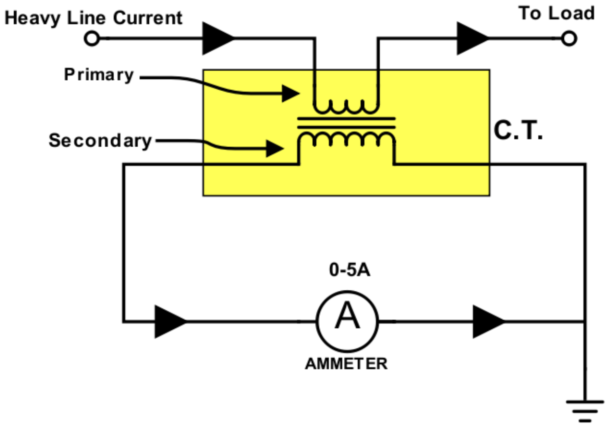


Fig. 4

Potential Transformer (PT):

A PT, also known as a voltage transformer (VT), is another type of instrument transformer that is used to step down a high primary voltage in a power system to a smaller, standardized secondary value. While a PT's primary winding is connected to power lines, its secondary winding is attached to voltage detection or protection devices. PTs produce a proportional, lowered voltage output that accurately stands for the original voltage level. Furthermore, they keep the phase relationship, which is necessary for correct measurements.

PTs are often used in the following applications: • Voltage measurement for power quality analyzers and voltmeters.

•input voltage for control systems and protection relays.

When it comes to PMUs, CTs and PTs give precise current and voltage readings. For phasor estimation and real-time power system state monitoring, these measurements are essential. PMUs use synchronized measurements taken from several places within the electrical grid to calculate phasors, which display the size and phase angle of voltage and current waveforms. These phasor data are critical for assessing the stability of the power system, detecting faults, and keeping an eye on grid activities.

In conclusion, CTs are used to measure current in power systems, while PTs are used to check voltage. They are essential components for the correct protection and monitoring of the power system, especially when PMUs are being used for real-time data collection and processing.

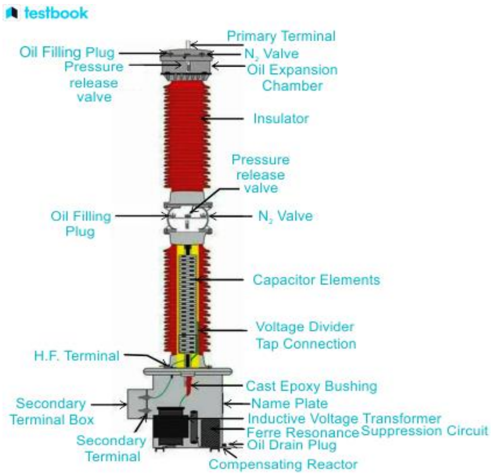


Fig. 5 Potential Transformer Schematic

i. ANTI-ALIASING FILTER

The anti-aliasing layer anti-aliasing filters are available in analogue versions and normally handle the signal before sampling. Applying an anti-aliasing filter before limiting a signal's bandwidth makes it easier to satisfy the Nyquist-Shannon sampling theorem's requirements. The sampling frequency of the signal must be twice as high as its maximum frequency once the sampling operation is complete. If the sampling rate of a signal is less than twice its highest frequency, the data produced from the original signal cannot be recovered. To meet the requirements of the sampling theorem, anti-aliasing filters are used to limit a signal's bandwidth [13].

ii. ANALOGUE /DIGITAL CONVERTER

Analog to digital converters are used to convert sampled signals into the output of anti-aliasing filters. To get a proper spectrum of input signals, these signals must first be acquired and then converted from an analogue to a digital converter. Analogue-to-digital (A/D) converters receive these analogue signals from anti-aliasing filters to begin the digitalization process. The phase lock loop decides a signal's sampling rate after conversion. These signals are then sent to the CPU by the A-to-D converter (ADC). Moreover, a transmission system uses six ADC digits to run the phasor quantities. These numbers are divided into two parts, with a digit given to each half.

iii. **PHASE LOCK OSCILLATION**

A phase-locked oscillator (PLO) or phase-locked loop (PLL) is an electrical control system that generates an output signal whose phase is associated with the phase of an input signal. In many different electrical systems, it commonly carries out tasks like frequency synthesis, clock generation, demodulation, and more. The phase detector, voltage-controlled oscillator, and low-pass filter (LPF) are the main components of a phase-locked oscillator. A phase-locked oscillator's main objective is to keep the input and output signals' phase relationship constant. In many applications—including communication systems, where phase coherence is essential—correct timing and synchronization are essential. In addition, PLLs can be used to multiply and divide frequencies, producing a frequency that is a multiple of or fraction of the input frequency [14].

iv. GLOBAL POSITIONING SYSTEM

The system reaction was carefully tracked by using the Global Positioning System. This provides information on the location of an object in any given area of the earth's surface under different air conditions, together with facts and statistics. GPS plays a crucial role in enhancing the efficacy of wide-area management by providing an efficient path for PMU measurement monitoring. Road mapping and agriculture both receive help from GPS devices [15].

PHASOR MICRO-PROCESSOR

Phasor microprocessors get the information from GPS and the sampled data via a Phase Lock Loop. The voltage and current amplitudes are then optimistically blended after that. Discrete Fourier transform (DFT), a recursive technique, is used to process the data. The phasor microprocessor, which regulates a signal's information and flows across the system, is regarded as the PMU device's brain. Furthermore, the two algorithms—recursive and non-recursive—that are used to find a signal's amplitude, magnitude, and phase angle refer to DFT's parts.

IV. METHOD OF PMU PLACEMENT

Phasor measuring units (PMUs) are needed in modern power systems for monitoring, control, and protection. The concept of optimal PMU placement (OPP) deals with allocating a minimum number of PMUs and their locations to achieve full network observability. To increase measurement redundancy (MR) at the buses and minimize the number of PMUs, this paper presents the binary grey wolf optimization (BGWO) technique. To tackle the OPP problem, several factors are considered, such as the existence of zero injection buses (ZIBs) and single PMU failure. IEEE 9 buses are used for testing these components. Topological techniques: These techniques decide the ideal PMU placement by using the power system's topological structure. Numerical techniques: To decide the ideal P placement, these techniques employ numerical optimization algorithms. Hybrid techniques: These techniques complement placement by combining topological techniques.

$$\min F(z) = \sum_{i=1}^{N} zi + w1(M - AZ)T(M - AM) + w2Nb \quad (4)$$

$$\boldsymbol{A.Z \geq b} \quad (5)$$

To solve the OPP problem of limiting the number of PMUs, this study has considered several practical constraints, such as single PMU loss, effect under zero injection bus (ZIB) consideration, and PMU device channel limit. These factors are considered, either to decrease PMUs or to build a fully observable network in an emergency. Since uncertainty resulting from inevitable events might impact the power system, total observability under a single PMU loss requires that every bus be seen by a minimum of two PMUs. So, the following definition of the modified unit vector can be given [16]

$bn \times 1 = [2\ \ 2\ \ 2\ \ 2 \ldots\ \ldots\ \ldots]$ (6)

Proposed Binary Grey Wolf Optimization (BGWO)

Grey Wolf Optimization (GWO) was initially introduced by Mirjalili et al. in 2014. It is a population-based meta-heuristic approach influenced by the hunting strategies of grey wolves. The membership of grey wolf packs typically ranges from five to twelve. Every group member adheres to the social hierarchy's tiers. The top rank of the hierarchy consists of Alpha (α) wolves. They handle making decisions on hunting as the group's leader. The beta (β) wolves, who support the alpha leader in hunting decisions, make up the second level. Third on the list are the delta (δ) wolves. The three leader wolves in GWO—alpha, beta, and delta—follow the hunting process [17]. The following is the mathematical expression for encircling the prey.

$D = |C'(Xp(t)) - X(t)|$ (7)

$$X(t+1) = \{Xp(t) - A'.D\} \quad (8)$$

where X denotes the position vector of the grey wolf and *Xp denotes* the position vector of the prey
The coefficient vectors A' and C' can be defined as follows:A'=$2ar1 - a$ (9)

$$C' = 2r2 \quad (10)$$

where *r1* and *r2* are two random vectors between 0 and 1 and the value of 'a' decreases linearly from 2 to 0 over the entire iteration. After the encircling process, the omega wolves update their positions based upon positions obtained from the alpha (*α*), beta (*β*), and delta (*δ*) wolves. The updated positions are given as follows:

$X(t+1) = (X1 + X2 + X3)/3$ (11)

where the values of the three best positions of *X1*, *X2*, and *X3* can be calculated as per the following.

$X1 = |X_{\alpha} - A'_1(D_{\alpha})|$ (12)
$X2 = |X_{\beta} - A'_2(D_{\beta})|$ (13)
$X3 = |X_{\delta} - A'_3(D_{\delta})|$ (14)

The alpha (*Dα*), beta (*Dβ*), and delta (*Dδ*) positions can be updated as follows.

$D_{\alpha} = |C'_1 X\alpha - X|$ (15)
$D_{\beta} = |C'_2 X_{\beta} - X|$ (16)
$D\delta = |C'_3 X_{\delta} - X|$ (17)

Below is a discussion of the technique's detailed descriptions.

Step 1: Using the bus and line data from the IEEE test bus systems, obtain the connection matrix (A).

Step 2: Randomly initialize the parameters a, A', and C', as well as the maximum number of iterations (max_iter) for the grey wolf population.

Step 3: Initialize PMU positions in the system at random.

Step 4: Determine the value of the goal function for each Xα solution in the population.

Step 5: Update Xα, Xβ, and Xδ, the top three searching agents.
Compute X1, X2, and X3 in Step 6.
Step 7: Adjust each Wolf pack's location.
Step 8: Carry out steps 3 through 6 again, up to the maximum number of iterations. Xα is ultimately chosen as the best option.

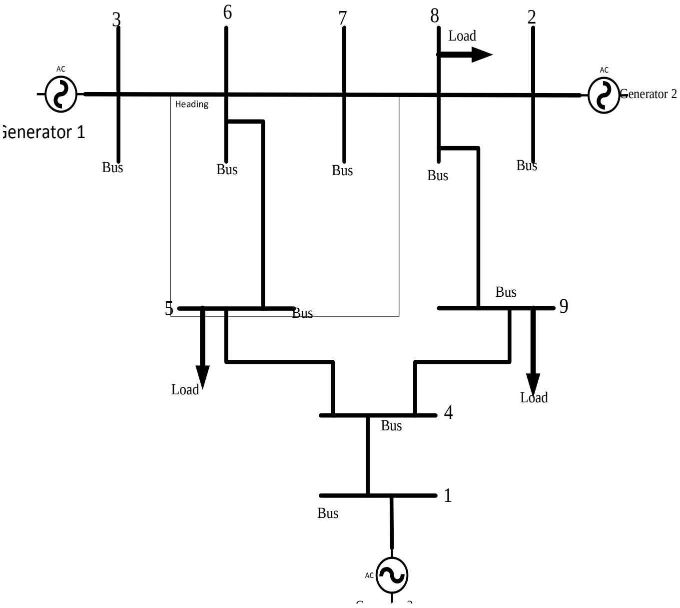
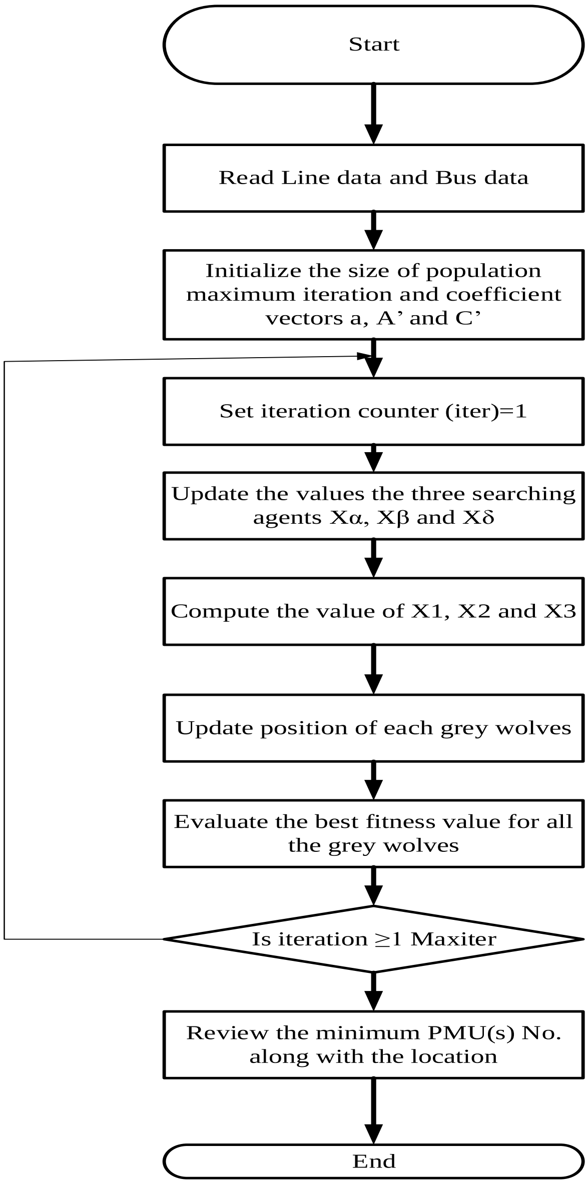


Fig. 7 IEEE 9 BUS NETWORK

Objective Function: Min $\sum_{i=1}^{9} Yi$
Subject to:
F(Y)= A.Y
$Bus1$: $Y1 + Y4 \geq 1$ (18)
$Bus2$: $Y2 + Y8 \geq 1$ (19)
$Bus3$: $Y3 + Y6 \geq 1$ (20)
$Bus4$: $Y1 + Y4 + Y5 + Y6 \geq 1$ (21)
$Bus5$: $Y4 + Y5 \geq 1$ (22)
$Bus6$: $Y3 + Y5 + Y6 + Y7 \geq 1$ (23)
$Bus7$: $Y6 + Y7 + Y8 \geq 1$ (24)
$Bus8$: $Y2 + Y7 + Y8 + Y9 \geq 1$ (25)
$Bus9$: $Y4 + Y8 + Y9 \geq 1$ (26)

$$\begin{array}{ccccccccc} 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \end{array} \begin{array}{c} Y1 \\ Y2 \\ Y3 \\ Y4 \\ Y5 \\ Y6 \\ Y7 \\ Y8 \\ Y9 \end{array} \geq \begin{array}{c} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{array}$$

{4 6 8}; [0 0 0 1 0 1 0 1 0] Optimal point of placement on the power grid



Flowchart for Binary Grey Wolves Optimization Algorithm

Contribution to this paper

✓ To find the weak busses and prevent their failure, a polarity measurement instrument is utilized.

✓ The goal is to optimize the functions while considering practical operational constraints, like minimizing the number of PMUs by guaranteeing the system's comprehensive observability redundancy index. This will reduce the overall cost of installing PMUs.

The installation of PMU placement in real-world transmission grids was discussed in the study, and the state estimate accuracy was checked to make sure the operation could be utilized to improve the intelligence of the grid. The installation of PMU placement in real-world transmission grids was discussed in the study, and the state estimate accuracy was checked to make sure the operation could be utilized to improve the intelligence of the grid.

V. CONCLUSION

The suggested binary grey wolf optimization strategy has shown to be a potent and successful way to figure out where PMUs should be placed in a power system on weak buses. The method is especially well-suited to handle the discrete character of PMU placement since it can handle binary decision variables. The implementation of the created technique has enhanced the power system's poor bus observability. The system's capacity to track and evaluate state variables, like voltage and phase angles, has been improved by carefully positioning PMUs on these buses. This enhances situational awareness and strengthens power network control. The power system's resilience is increased when PMUs are ideally positioned on weak buses. PMUs' enhanced monitoring capabilities make it possible to identify and react to disruptions more quickly, which enhances the network's overall stability and dependability. Validation activities and comprehensive simulations back up the research conclusions. Tested in a range of scenarios and system settings, the suggested optimization technique has proven to be reliable and applicable in a variety of power system topologies. The optimization method that was developed has applications for planners and operators of power systems. Optimizing the placement of PMUs can result in economical ways to improve observability without sacrificing system performance. There is room for more research, even though the current study has addressed the best location of PMUs on weak buses in a substantial way. Subsequent research endeavours may delve into the incorporation of supplementary variables, such as cybersecurity implications, limits on real-time data, and the influence of communication network topology on PMU positioning.

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