PMU Optimal Placement for Fault Detection in Wide Area Monitoring Systems based on the Drone Squadron Optimization

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Abstract: Wide area monitoring systems require the integration of new technologies that provide real time synchronized phase angle measurements. The Phasor measurement units (PMUs) are the most advanced devices to achieve this task so far. The objective of this work is to find the minimum number and optimal placement of PMUs in some standardized IEEE systems. The relatively new drone squadron optimization (DSO) technique is used to solve this problem. Next, fault location is studied based on the measurements collected from these PMUs. The simulations are carried out using MATLAB SIMULINK. The results show that it is possible to achieve the observability of the overall system; however, more PMUs are needed to locate the faults.

Keywords: PMU, WAMS, PMU placement, Faults, Drone Squadron Optimization.

1. INTRODUCTION

Smart Grid utilities and research institutions are looking for the best solution for PMU placement, for both the observability and fault location in wide area monitoring systems. In modern energy management system, state estimation (SE), observability and fault location are becoming crucial applications. Conventional state estimators use a set of measurements; bus voltage, real and reactive power flows, and injections, in order to estimate the bus voltage phasors in the system. These measurements were obtained, in the near past, only through the supervisory control and data acquisition (SCADA) system, which gathers the real time measurements from the remote terminal units (RTUs) installed in substations [1].

PMUs became the measurement technique of the best choice in electric power systems for Wide Area Monitoring System (WAMS) [2]. They provide positive sequence voltage and current measurements synchronized with accuracy of a microsecond. The deployment of this device can improve performances of power system protection, monitoring, and control systems [2][3].

With the increased interest in the development and deployment of Smart Grid, researches are leaning on the use of PMU to replace the old fault detection and observability solutions due to its great value in power system dynamic monitoring, potential applications in system modeling and validation and system wide protection and control [3]. Phasor Measurement units (PMUs) can offer accurate node voltage and current phasors referring to the same time-space coordinate. They can enhance many applications such as state estimation and bad data detection [4], stability control[5], remedial action schemes [6], and disturbance monitoring [7].

PMU is a monitoring device that assures advanced protection, analysis and control in power systems. A PMU placed at a given bus is capable of measuring the voltage phasor of the bus as well as the phasor currents for all lines incident to that bus. Then, uses synchronization signals from the global positioning system (GPS) satellites and provides the phasors of voltage and currents measured at a given substation. In other words, PMUs are used for monitoring the stability throughout the Smart Grid system. They provide the precise description necessary to minimize and control power outages and avoid cascading blackouts.

As the PMUs become more and more affordable, their utilization is increasing not only for substation applications but also at control centers for Energy Management System (EMS) applications[8]. These devices are also necessary when dealing with wide disturbances that often cause blackouts in power system networks, for power system state estimation and for network protection and control.

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However, considering the high cost of PMUs, it is not possible to place one in each bus to make the entire system observable. As a result, the problem of optimal PMU placement (OPP) appeared to find where and how many PMUs should be implemented to a power system to achieve its full observability at minimum number of PMUs [9][10], [11]. Using the data provided by PMUs installed in some appropriate bus nodes of a power network, one can construct a new type of measuring system to improve the observability and the precision of the power system state estimator. The observability depends on the type, the number and the geographic distribution of measurements [2].Several researches have been conducted to reduce the number of PMUs used.

The Optimal PMU Placement (OPP) observability problem concerns the determination of the minimum number of PMUs *n*, and their optimal placement set*S(n)*, necessary to assure the observability of the entire power system. The authors in [1], present a state of the art of the optimization methods applied to the optimal PMU placement for observability problem . They proposed taxonomy of Optimal PMU Placement (OPP) methods describing a large number of works devoted to this topic. According to them, methodologies for optimal PMU placement problems are classified into two categories: mathematical and heuristic algorithms. Several works are listed in paper [1] as mathematical algorithms which use the Linear Integer Programming (ILP) or Integer Nonlinear programming. A voltage stability based contingency ranking method is carried out in [12] to present few critical contingencies considered in the optimal PMU placement problem . A hybrid two-stage PMU placement technique is proposed in [13] which uses an ILP based approach to guarantee the system topological observability. A description of an optimal PMU placement for the overall network observability is presented in [14] taking into consideration the PMU failures and network contingencies that give rise to both topology changes and bad data measured by PMUs.

A new formulation for PMU placement is developed in [15] based on ILP, the work considers the necessity of the network observability under all possible arrangements of lines connections at complex buses. The authors take also into consideration the cases of the lines outage and PMUs failure probability.

The approach for solving the optimal PMU placement for system observability is the Heuristic algorithms. A new methodology based on Genetic Algorithm considering the Zero-Injection buses is presented in [16] to ensure the system observability.

Critical bus constrained optimal PMU location is presented in [17], where Zero Injection Bus (ZIB) is considered for the complete system observability. The authors propose to indentify the critical buses that are joined to the ZIB, in order to dictate the true state of the system. Binary Integer Programming (BIP) is used to minimize the objective function designed under bus constraints for optimal PMU allocation and takes into consideration both ZIB and critical buses. The authors in [18] present a multi-objective probabilistic model, this method optimizes both the number of PMU, used for the observability, for its minimum and the maximum of system redundancy.

Two types of observability analysis are presented in [19]: numerical and topological observability. This paper studied a topology transformation method that implies a merging between a ZIB with one of its incident buses. The authors solved the problem of the right incident bus choice by proposing three rules to assure the right selection of the bus to be merged with the ZIB as well as the right PMU placement. An ILP based method is proposed in [20] under voltage stability and intensely islanding to ensure the system full observability. An additional objective is proposed which consists in a rise in the reliability of the system.

Another objective of Optimal PMU Placement in Wide Area Monitoring Systems (WAMs) is the fault location. Several researches are conducted for this purpose. According to [21] fault location observability is the ability to locate exactly the fault in a network, using devices as PMUs. The fault location procedure is categorized into impedance-based, traveling wave-based, high frequency components, knowledge-based [22], and artificial intelligence-based methods [23]. Where impedance based fault location can be classified into single-ended, double-ended and multi-ended methods [24].

In paper [24], a new algorithm for fault location on transmission lines is presented, such that faults on all lines of the network can be diagnosed and located regardless of their locations. To achieve that, a PMU placement algorithm is utilized to find the requisite data for impedance-based fault location occurring at any fault line in the network system. Then, another algorithm is proposed to figure out the voltage and current values of the fault line for fault location.

A method for fault location based on a minimum number of PMUs, and using integer linear programming framework is presented in [25]. The authors of [26] , add to the objective of finding the minimum number of PMUs another objective which consists of obtaining a redundant measurement i.e. none of the placed measurements are critical and each bus is measured by at least a pre-determined number of measurement devices. One bus spaced strategy is proposed in [27], [28] to achieve the minimum PMU placement for observability and fault location. Authors of [29] studied at first the normal condition state ,no PMU failure or line outage. They defined an optimal measurement set to achieve full network observability. Then, they considered

contingency conditions, by making modifications in the normal condition states. Binary Particle Swarm Optimization was used to find the minimum number of PMUs as well as their optimal placement.

In this wok, the problem of finding the minimum number of PMUs to achieve the observability and fault detection in wide area monitoring system is presented. Drone Squadron Optimization (DSO) technique is proposed to find the optimal PMU placement to assure the observability and fault detection and location in Wide Area Monitoring Systems.

2. MATHEMATICAL FORMULATION

2.1. Problem Formulation

The typical Optimal PMU Placement problem concerns the determination of the minimum number of PMUs, *n*, and the optimal location set, *S(n)* , of the *n* PMUs, ensuring that the entire power system remains a single observable island. This model can be generalized to include additional constraints or contingencies. The objective function is formulated as follows [19]:

For an n-bus system, the PMU placement problem can be formulated as follows:

$$\text{Objective function: } J = Min\sum_{i=1}^{n} x_i \qquad (1)$$

$$\text{such that: } f(X) \geq \hat{i}$$

Where X is a binary decision variable vector, whose entries are defined as:

$$x_i = \begin{cases} 1 & if\ Bus\ i\ has\ a\ PMU \\ 0 & otherwise \end{cases} \qquad (2)$$

f (X) is a vector function, whose entries are non-zero if the corresponding bus voltage is solvable using the given measurement set and zero otherwise.

îis a vector whose entries are all ones.

2.2. Constraints

In order to form the constraint set, the binary connectivity matrix A, whose entries are defined as below, will be formed first.

$$A_{k,m} = \begin{cases} 1 & if \quad k = m \\ 1 & if \quad k \text{ and } m \text{ are connected} \\ 0 & if \quad \text{otherwise} \end{cases} \qquad (3)$$

Based on the acknowledgement that by placing a PMU on one bus, the voltage phasors of this bus and its neighboring buses can be calculated, we can get

$$f = A \times X \qquad (4)$$

Constraint functions defined by equation (3) ensure full network observability while minimizing the total number of the PMUs.

The procedure for building the constraint equations (vector function *f (X)*) will be presented for four possible cases:

- No PMU measurements or conventional(flow and injection) measurements exist
- Only flow measurements exist,
- Both flow and injection measurements (they may be zero injections or measured injections) exist or
- PMU measurements and conventional flow or injection measurements exist.

Zero Injection Bus

A Zero Injection Bus (ZIB) is a bus which has no load or no generator or no measurement device. The sum of current flowing to a ZIB, is zero. Zero injection bus are the buses from which no current is being injected into the system. The ZIB and its connected buses are defined as a set of SOZIB (set of zero injection bus and its adjacent buses). If ZIB are also modeled in the PMU placement problem, the total number of PMU's can be further [32].

3. DRONE SQUADRON OPTIMIZATION

3.1. Underlying Priniples

The DSO algorithm has been derived from simulating artifact self-adaptive behavior of drone while exploring a given region. Unlike other computational algorithms, DSO is not inspired from a natural phenomenon. The algorithmic operation of DSO is based on following two major aspects [33]:

(i) The semi-autonomous drones that fly over the region to explore it (formation of the team)

(ii) The command center that processes the retrieved data & updates the drones' firmware (calculation of the lowest fitness value).

The initial generation in DSO-algorithm is saved into an array with a dimension of $\left(n_p \times \dim\right)$ called coordinates. Here, n_p &dim are population size & dimension of the control variable, respectively. The DSO-algorithm mainly comprises: (i) drone squadron with the different team & (ii) a command center to control the drone position while exploring and computing firmware for adjusting the drone locations. In DSO, the firmware is any set of distinct rules or configurations set by the users to evolve the population.

3.2. Mathematical representation

The DSO working principles consist of five major operations that can be described mathematically as:

- Command Center

This is the most important and intelligent part in the DSO algorithm. The command center generates and provides the orders to the drones to scan the region. In DSO, scanning a region corresponds to the calculation of fitness function. The command center modifies the firmware (distinct mechanism used to improve the search agents) to update the drone positions [33].

- The firmware

To modify the position of the search agents, the firmware is updated in DSO based on equation (5) [33].

$$\begin{cases} P = departure + offset(); \\ TC = calculate(P); \end{cases} \quad (5)$$

Where P is the perturbation model calculated using (6); "*departure*" is the solution point in the search area; *offset* is a function that returns the actual perturbation movement; TC are trial coordinates. The '*departure* coordinate' & '*offset* function' are calculated by using (6) [33].

$$\begin{cases} P_1 = \overrightarrow{GBC} + \left(c_1 \times \left(\overrightarrow{GBC} - \overrightarrow{CBC_{drone}}\right)\right) \\ P_2 = \overrightarrow{CBC_{drone}} + \left(G(0,1) \times \left(\sqrt{U(0,1)_{\dim}} + \overrightarrow{CBC_{drone}}\right)\right) \end{cases} \quad (6)$$

Where $GBC \,\&\, CBC$ are global best coordinate & current best coordinates, respectively; c_1 is user defined function; $G(0,1) \,\&\, U(0,1)$ are Gaussian & uniform distribution functions, respectively. In (6), the 1st part in either equation is representing '*departure*' and second part is '*offset*'.

- Drone Movement

The drone uses an autonomous system to calculate the target position, move to it, and gather the information that is to be sent to command center. at this step, DSO generates the target position of each drone in each team called 'team coordinator' $\left(TmC_{team,drone}\right)$. After each drone runs the perturbation step & generates trial coordinates $\left(TC_{drone}\right)$, it performs either recombination with best coordinates found so far to generate TmC or no recombination at all. Finally the drone is allowed to move within some boundary. The violation of boundary conditions are adjusted using equation (7) [33]. In (7), '$\max \,\&\, min$' are the maximum & minimum limits of control variable, respectively.

$$violation_{team} = \sum_{i=1}^{n_p} \sum_{j=1}^{\dim} \begin{cases} \left| TmC_{team,drone,j} - \max_j \right| \\ \left| min_j - TmC_{team,drone,j} \right| \end{cases} \quad (7)$$

- Firmware Update

The command center measures the quality of team by taking: (i) the fitness function value, & (ii) the degree of out-of-bound coordinates. To update the firmware, (8) is employed with *violation* [33].

$$\begin{aligned} &for\, i = 1 : t\,(no.of\ team) \\ &\quad TeamQuality = Rank_i + violation_i; \\ &end \end{aligned} \quad (8)$$

- Local Stagnation Detection

The drone may generate the same coordinates while exploring a specific region. In (9), convergence avoidance mechanism has been suggested to avoid local stagnation. For more exploration in DSO to detect local stagnation, (9) is employed [33]:

$$\begin{aligned} &if \\ &\quad f\left(TmOFV_{drone,best}\right) < f\left(CBOFV_{drone}\right) or\, U(0,1) < P_{aw} \\ &\quad CBC_{drone} \xleftarrow{update} TmC_{drone,best} \\ &end \end{aligned} \quad (9)$$

where $U(0,1)$ is randomly selected number between $(0,1)$ through uniform distribution; P_{aw} is probability of acceptance of a worst output.

4. RESULTS AND DISCUSSIONS

In this work we consider some standardized IEEE bus system: 14, 30 bus systems. PMUs are installed in network system to measure the voltage and current samples from various location points [31]. Table 1 shows the results of the optimization technique used to find the minimal number of PMUs as well as their corresponding bus locations.

Table 1: Optimal PMU placement result.

Test Case	Number of PMUs	PMU location
14 bus system	3	2, 6 and 9
30 bus system	7	3, 5, 10, 12, 18, 23, 27

Validation of the results for the 14-bus system

In this section, the results obtained in table 1 will be used for fault detection. The analysis is done for the 14-bus system. Similar work can be done for the 30-bus system. As shown in table 1, there must be three PMUs to be placed at buses 2, 6 and 9, respectively. Bus 7 is the only zero injection bus. The PMU at bus 2 can not only measure the voltage of bus 2, but also the current of branches 2-1, 2-3, 2-4 and 2-5. Using Ohm's law, the voltage at buses 1, 3, 4 and 5 can be obtained from the branch currents and the voltage at bus 2. Having determined voltage at buses 1, 2, 3, 4, and 5, the current of branches 1-5, 3-4 and 4-5 can be calculated.

Following the same logic, PMU at bus 6 can measure the voltage at bus 6 and the current of branches 6-5, 6-11, 6-12 and 6-13, thus allowing the calculation of the voltage at buses 5, 11, 12, 13 and the current of branch 12-13.

PMU at bus 9 can measure the voltage at bus 9 and the current of branches 9-4, 9-7, 9-10, 9-14 and allow the calculation of the voltage at buses 4, 7, 10, 14, and the current of branches 4-7. As voltage of buses 10, 11, 13, 14 are known, current of branches 10-11 and 13-14 can now also be calculated.

Using the known current of branches 4-7 and 9-7, and the zero injection at bus 7, the current of branch 7-8 can be derived using the Kirchhoff's Current Law. The only remaining unknown voltage at bus 8 can now be calculated by using the voltage at bus 7 and the current of branch 7-8. Thus the entire system becomes observable by placing only three PMUs at buses 2, 6, 9 and by considering the zero injection at bus 7.

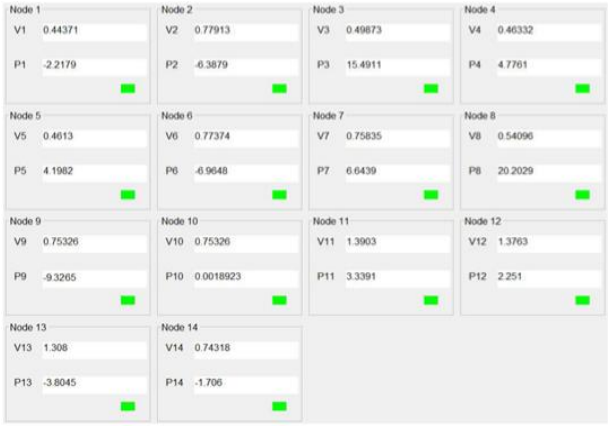

Fig. 1 graphical user interface for IEEE 14 buses.

The PMUs collect phasor data from busses 2,6 and 9 and use a communication way to send them to a Phasor Data Concentrator PDC, in our case we used MATLAB graphical User Interface. Fig. 1 represents the system healthy state as it appears in the control center. Each PMU here measures the voltage phasor of its corresponding bus as well as the current phasors of all lines connected to that bus. This will make the voltage of all adjacent buses observable using KCL rule.

Fault detection using PMUs

In this section, different types of faults are to be induced each time in different location placement. The synchronized fault voltages are monitored by neighboring PMUs installed at indicated busses. These detects the measurements abnormalities either a voltage drop in bus or a current spike between two busses. Based on the calculated fault node injection, fault nodes can be deduced or fault locations in transmission lines can be calculated [31]. Two different faults are studies: Fault in a bus carrying a PMU and a fault in a bus without PMU.

- **Fault in a bus carrying a PMU**

In this case, a fault is induced at bus 2; a bus carrying PMU. Fig. 2 represents the GUI display in this case.



Fig. 2 EEE 14 buses fault detected on bus 2 in a GUI

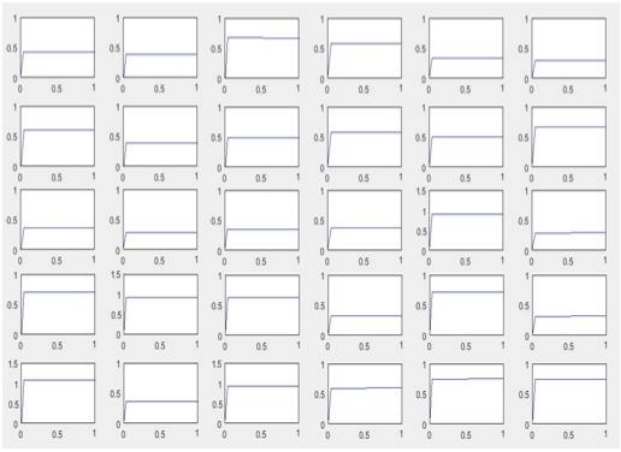

Fig. 3 Healthy state voltage graph

When a fault occurs, the comparison MATLAB program reacts for the voltage difference between the healthy and faulted measurements, and then it detects the fault in the defected bus 2.

Fig. 3 is a graph representation of the fault happening during time period [0.3; 0.5] in bus 2, the changes of voltages are remarkable comparing with the healthy state (fig. 4). During this fault the graph of voltages V in each bus is changed because of the current spike.

- **Fault in a bus without PMU**

In this section, a line to ground fault is induced in the transmission line between buses 12 and 13, both busses do not carry PMU. Fig. 5 shows the voltage change results due to the fault, it is clear that the line fault affects the overall system. However, it is not clear on the location of the fault.

In this example, when a fault occurs in line 12-13, the PMU placed in bus 6 measures the currents from those busses. However, it cannot be clear whether the fault is in one of the PMUs 12 or 13, or that the fault occurs in the line 6-12, 6-13 or 12-13. This implies that the number of PMUs should be increased to find the exact location of the fault.

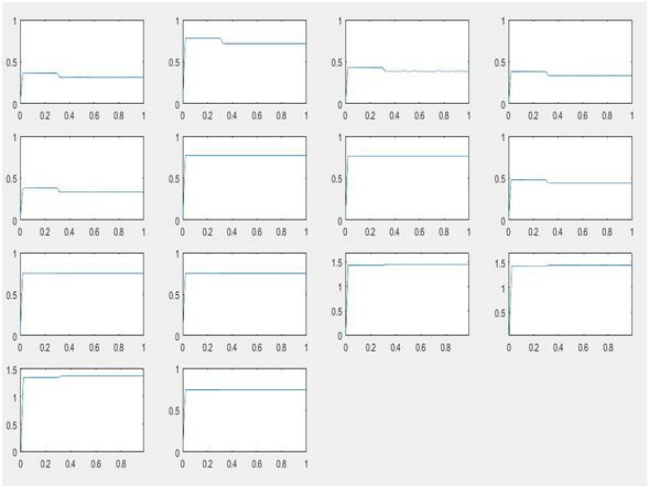

Fig. 4 Unhealthy state voltage graph (Fault in bus 2)

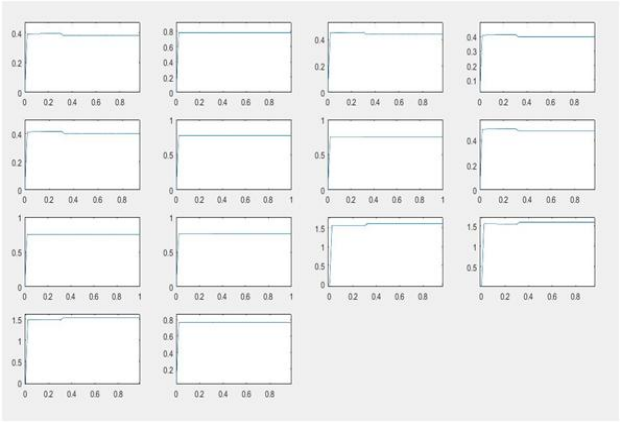

Fig. 5 Unhealthy state voltage graph (fault in line 12-13).

5. CONCLUSIONS

In this work, the use of a minimum number of PMUs to detect and locate faults in a power system has been studied. The purpose is to apply the Drone Squadron optimization to find the appropriate number of PMUs, as well as their corresponding buses. The objective of this optimization is to assure the observability of the system and locate the faulty part of the system. The advantage of this application is to prevent the propagation of the fault to the remaining parts of the power system if any. The results show that the minimum number of PMU can assure the observability of the system however; with this number we cannot find the exact fault location.

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