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Optimal Placement of Phasor Measurement Units for enhancing Observability of Power Systems by Using Genetic Algorithm

M. Afroozeh
Dept. of Engineering
Payam Golpaygan Institute
Golpaygan, Iran
mahdiafroozeh@gmail.com

AA. Ghadimi
Dept. of Engineering
University of Arak
Arak, Iran
aa.ghadimi@gmail.com

Abstract— With the increasing expansion of power grid in the recent years, the need for new monitoring and controlling systems for better control and exploitation of power systems, is felt more than ever. In the meantime, the use of synchronous phasor measurement units (PMU) has recently attracted the attention and interest of the researchers and designers of power grids. These units, by measuring the voltage and current phasor with high-speed, provide the conditions for accurate and real-time observability of the system. The important point here is that the necessary condition for the full observability of the power system is the optimal placement of these units in the power grid. In this paper, the primary objective is the optimal placement of the PMU units in a conventional power grid by using genetic algorithms to enhance the observability of the system; then, in the end, by comparing the results obtained from the proposed method with other conventional methods, the efficiency of the model is assessed.

Keywords— Genetic algorithm, Optimal placement, PMU, Smart grid protection.

I. INTRODUCTION

Conventional systems like SCADA / EMS do not have the capability of simultaneous sampling, for this reason they are not able to present voltage and current phasor values. Slow sampling and low accuracy of these systems that present the values of voltage, current, active and reactive power about every 10 seconds, are not suitable for many applications [1]. On the other hand, in addition to the above problems, after the data collection, for determining the state of the system, state estimation algorithm should be implemented, which is a non-linear and time-consuming process. But in the case of PMUs, the situation is different, these system provide the voltage and current phasor to the system with variable rate from 1 to 60 samples per second and high accuracy that the mechanism of implementation of this action by using the recursive discrete Fourier transform algorithm has been presented in the following part. These data provide the possibility of linear state estimation that is much more quickly [2]. PMU devices are used in WAMS and can be supplement for common SCADA / EMS for increasing stability and monitoring of the system. IEEE-1394 standard has determined the formats of the data that are used by the PMU [3]. In general, in order to use the PMU devices for observability of the power system, it is necessary to install and set up these units at certain points in the grid and while having minimum required number of them, the highest observability should be achieved for the system. In fact, the considered issue is an optimization problem that in several articles and researches, various algorithms have been used to find the best answer. Linear Programming Algorithm (ILP) [4], Particle Swarm Optimization Algorithm (PSO) [5] and Imperialist Competitive Algorithm (ICA) [6] are among the most popular functional algorithms in this field; among these, the genetic algorithm (GA) provides one of the best responses to such issues that have high numbers of variables and high-speed responding capability. In this paper, genetic optimization method for optimal placement of phasor measurement units will be carried out in such a way that their number will be the least and observability of the system will be preserved. In the next section, the modus operandi of phasor measurement unit and the method of its measurement have been described. Then the applications of PMU will be mentioned. In the later part, briefly some explanation will be provided about the optimization techniques and in more

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details, about the genetic algorithm. Next the problem and optimization method of PMU places through genetic algorithms will be discussed. Then the simulation results will be presented and analyzed. At the end, there will be a summary and conclusion.

II. THE METHOD OF MEASURING PHASOR BY PMU

Devices of PMU are sampled according to the data and by using the Discrete Fourier Transform (DFT) with the help of (1) calculate the phasor of x (t) signal, which is sampling of reference signal at the time of $t = \tau$ [2].

$$X = \frac{1}{\sqrt{2}} \frac{2}{N} (X_c - jX_s) \tag{1}$$

Where N is the number of samples in a period of nominal fundamental frequency:

$$X_c = \sum_{k=1}^{N} \chi_k \cos k\theta \tag{2}$$

$$X_S = \sum_{k=1}^{N} \chi_k \sin k\theta \tag{3}$$

And θ is sampling angle corresponding to τ and it is defined as follows [5]:

$$\theta = \frac{2\pi}{N} = 2\pi f_0 \tau \tag{4}$$

Typical sampling rate, for most applications of measuring and relaying, is12 times more than the frequency of power system.

Equation 1, which was introduced for the Discrete Fourier Transform, was a non-recursive relationship; in practice, the following recursive equation is used for calculating the phasor of time-variable. Suppose that X^r is the phasor obtained from the set of samples of $x\{k = r, r+1, ..., N+r-1\}$.In this case, when a new sample is obtained, set of new samples are shown as $x\{k = r, r+1, ..., N+r\}$,in this case, the updated phasor will be obtained by using equation 5 [1]:

$$X^{r+1} = X^r + \frac{1}{\sqrt{2}} \frac{2}{N} (\chi_{N+r} - \chi_r) e^{-jr\theta} \tag{5}$$

Recursive calculation method with sliding sampling window is faster than non-recursive method and it needs two samples at each stages. If $x(t)$ possesses transient changes, sliding window will track the changes in amplitude and phase with a delay that this delay depends on the rate of the sampling time.

A. *State estimation and location allocation problem for state estimation*

State estimation is one of the most important challenges in monitoring of the power grid; estimators of the state, according to the available measurements and information about the network topology, calculate the values of phasors of bus voltage of the system.

B. *Registering and finding the place of error*

PMU devices installed on the grid provide the possibility of having access to data of terminals of 2 sides of line. Due to the synchronization of these data, there is the possibility of accurate placement of error.

C. *Correction of the system model*

In power systems of PMUs for studying the grid computer models are used. By recording the behavior of system, in the face of various events that occur as a result of turbulence in the system and comparing it with behavior of the simulation, the system model can be optimized and it can be made closer to the actual model.

D. *Anticipation of transient and dynamic instability*

Stability analysis of power systems are done offline, measurement of synchronous phasors make the stability analysis and prediction of stability possible in Real-Time form that in this paper they have been studied in detail [7].

E. *Adaptive relaying*

At the present time, adaptive relaying uses the information that has been obtained from stability simulations for different logical states. Out-of-step relays reveal the power fluctuation with the help of the change of apparent impedance observed by distance relay. The problem with this method is that the actual situation, with regard to the power fluctuation, is different from conditions that have been used in stability simulation. PMUs can be used in these cases and dynamic data with respect to fluctuations can provide power [1].

F. *Widespread protection of the grid*

Protection of the system at large-scale is carried out for protecting system against general power outages or similar events. In this context, PMU is also used widely.

G. *Thermal line monitoring*

For thermal line monitoring, PMU should be installed on both sides of the line.

III. Optimization methods

A. Introduction to optimization

Optimization is a process that is followed to make something better. Thought, idea or plan that is proposed by a scientist or an engineer, becomes better during the process of optimization [4]. During the optimization initial conditions are analyzed with different methods and the obtained data are used for improving an idea or method. Optimization is a mathematical tool that is used for finding answers to numerous questions about the way of solving different problems. The issue that is raised in optimization is to find the best solution for a problem. The term, the best, implies that there is more than one answer to a problem that of course all of them are not of the same value. Definition of the best answer is dependent on the problem under study, solving method and the amount of permissible error. So, the way of formulating the problem has a direct impact on the method of the defining the best answer. Some of the problems have certain answers; the best player in a field of sport, the longest day of the year and the response of an ordinary differential equation are among the examples that can be cited as two or minimum one simple issues. In contrast, some of the issues have multiple maximum answers that are known as optimum points or extremum and probably the best answer would be a relative concept.

B. Genetic optimization algorithm

Genetic algorithms use Darwin's principle of natural selection to find the best formula for the prediction or adaption of the pattern. The reason of the popularity of the genetic algorithms is that their results are more significant. The final formula will be visible to the user and to provide a confidence level for the results, conventional statistical techniques can be applied on these formulas. In short, it is said that genetic algorithm is a programming technology that uses genetic evolution as a problem-solving model. Genetic algorithm is a searching technology in the engineering sciences for finding the optimal solution and search issues. Genetic algorithms are one of evolutionary algorithms that have been stimulated by biological sciences such as inheritance, mutation, sudden selection, natural selection and combination.

IV. The optimal placement of PMU in power system

In general, observability of the power systems means the calculation of grid variables to estimate the state of the system and if the data required for estimating the state were not available then the grid would not be observable. Grid variables are usually considered as phasor voltage of buses. This is done by the analyst of observability of the system and if the system was not observable corrective action such as adding auxiliary measurements will be performed.

A. Methods of analyzing observability

In general, observability of the power systems means the calculation of grid variables to estimate the state of the system and if the data required for estimating the state were not available then the grid would not be observable. Grid variables are usually considered as phasor voltage of buses. In general, observability can be divided numerically and topologically.

1) Linear model of systems with PMU

In the numerical methods, to get mathematical definition for the observability, a mathematical model should be obtained for the intended power system or its measurements. Linear measurement model, which is used in most of the state estimations, is defined as follows:

$$Z = HX + e \tag{6}$$

In this model, Z vector includes m measurement of voltage and current phasor of the lines; X is N-dimensional state vector, H is fixed Jacobian matrix of measurements and e is a vector of measurement error in the form of $m\times 1$.By analyzing the vector Z to sub-vectors of voltage $M_V \times 1$ and current $M_I \times 1$ (Z_I, Z_V) and analyzing the vector X to measured sub-vectors $N_M \times 1$ and unmeasured sub-vectors $N_C \times 1$ ، (V_C, V_M) the above equation becomes as follows:

$$\begin{bmatrix} Z_V \\ Z_I \end{bmatrix} = \begin{bmatrix} I & 0 \\ Y_{IM} & Y_{IC} \end{bmatrix} \begin{bmatrix} V_M \\ V_C \end{bmatrix} + \begin{bmatrix} e_V \\ e_I \end{bmatrix} \tag{7}$$

In a way that I, the identity matrix, Y_{IM} and Y_{IC}, represents the series impedance and shunt admittance of the network. By disregarding the elements of the shunt, the H matrix is summarized as follows:

$$H = \begin{bmatrix} 1 & 0 \\ M_{IB} Y_{BB} A_{MB}^T & M_{IB} Y_{BB} A_{CB}^T \end{bmatrix} \tag{8}$$

Here, M_{IB} is the Incidence Matrix of measuring branches that includes measurement of phasor of current of branches in the form of $M_I \times b$, Y_{BB} is a diagonal matrix that includes admittance of branches, A_{MB} and A_{CB}, respectively, measured sub-vectors $N_M \times b$ and incidence sub-matrix of nodes and branches in the form of $N_C \times b$. In traditional methods, observability analysis is done by examining the following formula:

$$Rank(H) = 2n - 1 \tag{9}$$

According to equation (9), if the Jacobian matrix is of the complete degree, the grid will be observable and state estimation will be performed [5].

2) Topological analysis method of observability

Another way to check the observability of the network is the topological method. In this method, the observability analysis is according to the following principles:

- Buses that the PMU has been located on them possess obvious voltage phasor. Also the current of the lines, which are connected to the bus with PMU, is also specified.
- If the voltage phasor of a bus and the current of the line that is connected to the mentioned bus are obvious and specified, voltage of the other side bus is also calculable.
- If the voltage of buses of two ends of a line is specified, then the current of that line is computable.
- If the current of all the lines leading to the zero-injection bus, except one, is specified, due to KCL law, phasor of unknown current is calculable.

On the basis of the mentioned principles, voltage phasor of the bus that PMU has been installed on it, as well as the current of all branches that enter into that bus, are measured directly. In this paper, the topological methods been used to analyze observability that has been described in the next section.

V. Definition of the Problem of PMU Placement

A. *Observability in an electrical network*

PMU installed on a bus is able to calculate the voltage phasor of that bus and also current phasor of all branches that are connected to the bus. Therefore by installing PMU at strategic points of the grid, the required data for the observability of the system can be obtained. As mentioned before, two purpose of observability of the grid for state estimation and reducing the number of PMU, are considered as two main objectives [7].

For n bus systems the optimal placement is expressed with the following formula:

$$\begin{aligned} &\min \sum_i^n W_i . X_i \\ &s.t \qquad f(x) \geq \hat{1} \end{aligned} \qquad (10)$$

Where x is a binary variable that is defined as follows:

$$x_i = \begin{cases} 1 & \text{if a PMU is installed at bus i} \\ 0 & otherwise \end{cases} \qquad (۱۱)$$

W_I is the costs of PMU installed at i bus and f (x) is a function that shows constraints of observability of the bus of each grid. In following part we will show that for each bus of $f_i(x) \geq 1$ that bus will be observable. In the proposed scheme, the constraints of observability are investigated in 3 modes: 1- In the first case it is assumed that there is no other common measurement tool other than PMU 2- Using PMU along with the injection measurement (and/or the zero-injection bus) and 3- The use of PMU along with injection measurement and current measurement.

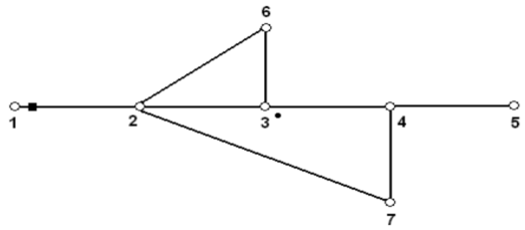

Fig. 1. 7 Bus System

B. *The concept of Zero-Injection Bus*

At this point, we will try to define and clarify the concept of Zero-Injection Bus by mentioning an example. Consider the 7 bus system of the figure 1. Injection measurement may be expressed as the real measurement or as a zero-injection bus, that in both cases it will have the same behavior. In this case, we assume that bus 3, is a zero-injection bus. In this case, we can observe that if the voltage phasor in 3 buses of 4 buses of 2, 3, 4 and 6 are specified, the fourth bus voltage phasor can be calculated by writing KCL in the node 3. Therefore in network topology, the bus that includes injection measurement or zero-injection bus can be combined with one of the adjacent buses. Figure 2 is the same as the previous grid in a case that the buses 3 and 6 are combined together and replaced by a new bus.

Incidence Matrix A, in this case becomes as follows:

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 \end{bmatrix} \qquad (12)$$

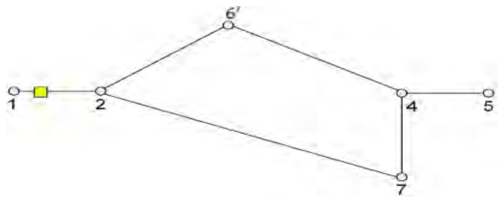

Fig. 2. 7 bus system after the combination of buses 3 and 6

TABLE I. SPECIFICATIONS OF THE STUDIED SYSTEMS

Zero-Injection Buses	Number of branches	System
7	20	IEEE 14 bus
6،9،11،25،28	41	IEEE 30 bus
4،7،11،21،22،24،26،34	78	IEEE 57 bus

VI. RESULTS

In this section by using the proposed method in the standard grid of IEEE (14 bus, 30 bus and 57 bus) PMU placement will be conducted. Basic information of the studied grids at this paper is shown in Table 1. The performed simulations consist of two types of simulation; one group by considering zero-injection buses and another group without considering them. In Table 2, we have presented the results for the three studied grids. Simulations of the standard IEEE systems aimed at finding the number of PMU installed on the buses of systems have been conducted to get the highest observability. Optimization problem to obtain the minimum number of PMU is in such a way to have the observability of the system at the very most.

TABLE II. SIMULATION OF LOCATION ALLOCATION OF PMU IN THE THREE GRIDS

Number of PMU		Number of Zero-Injection Buses	System
Without considering the Zero-Injection Buses	By considering Zero-Injection Buses		
4	3	1	IEEE 14 bus
10	7	5	IEEE 30 bus
17	13	15	IEEE 57 bus

TABLE III. NUMBER OF BUSES OF THE LOCATIONS OF THE PMUS

The location of the PMU		System
Without considering the Zero-Injection Buses	By considering Zero-Injection Buses	
2-7-10-13	2-6-9	IEEE 14 bus
3-5-7-10-11-12-18-19-23-30	2-3-10-12-19-24-27	IEEE 30 bus
1-4-7-9-15-19-22-24-28-32-36-38-39-41-47-50-53	1-4-9-15-20-25-29-32-38-47-50-53-56	IEEE 57 bus

In optimization problems, due to abundance of variables and sometimes high number of unknowns as compared to the equations, usually the solution of the problem is assigned to the optimization algorithms. In this case, the task of the algorithm is to find the best solution to the problem. Accordingly, with a series of basic assumptions, the problems will be solved in many states. Then the optimum solution will be chosen and announced according to the objective function. The results obtained in the proposed method are on the basis of the genetic optimization algorithm and indicate that the optimal solution is obtained for the system. The important point in this method is the rapid converging. Given the increasing importance of speed in solving problems related to the electricity grids, it is considered as a major advantage. In standard network of 57 bus IEEE, as shown in Table 4, the maximum number of repetitions of the search in proposed algorithm is 50 times, which is much less than other methods. The number of repetitions of this method is about 90% lower than the same proposed technique to solve such problems, that this can increase the speed. Considering that installing of PMU is with the aim of creating observability in the system, thus, the related optimization problem is to find the place the minimum number of PMU in lieu of the maximum observability. With this introduction, the issues related to the zero-injection buses are proposed that by this method some information can be obtained about the buses and the installation of PMU in those buses can be ignored. For example, the results of the simulation that are shown in Table 2 indicate that the number of PMU obtained for 57 bus standard networks have declined from 17 to 13 buses.

TABLE IV. SPECIFICATIONS OF PROPOSED GENETIC METHOD

50	The maximum repetition
80	The percentage of inheritance
30	The percentage of mutations
200	Size of the population

VII. CONCLUSION

In this paper, a new method has been presented for optimal placement of PMU and the topological observability by using a genetic based algorithm. This method is also applicable in cases where there are other measuring methods than the conventional measuring method of PMU such as injection and current measurement methods; optimization process follows two goals in this method: (1) reducing the number of required PMUs for observability of the whole system. (2) Also in lieu of considering zero-injection buses, it has been tried to minimize the number of required PMU. Simulation results show that this method present the best answer without the minimum need for repetition and has indicated the excellent performance for various grids.

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