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Bashian, Amir; Assili, Mohsen; Anvari-Moghaddam, Amjad

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Optimal Placement of PMUs and Related Sensor-based Communication Infrastructures for Full Observability of Distribution Networks

Amir Bashian
Department of Power Engineering
Shahrood University of Technology
Shahrood, Iran
Amir.bashian@gmail.com

Mohsen Assili
Department of Power Engineering
Shahrood University of Technology
Shahrood, Iran
m.assili@ieee.org

Amjad Anvari-Moghaddam
Department of Energy Technology
Aalborg University
Aalborg, Denmark
aam@et.aau.dk

***Abstract*— optimal installation of measurement units is an important issue in distribution systems. Phasor measurement units (PMUs) are used widely in wide area measurement system (WAMS). Transferring the measured data to the control center by a proper communication system is a key part of WAMS. In this paper, energy harvesting sensor nodes (EHSNs) are used as a communication infrastructure for connection of PMUs. The low cost and simple infrastructure of this system enable not only the full observability of communication system but also ensures adequate reliability levels. In the proposed model, the main objective is to minimize the number of EHSNs and PMUs considering the effect of conventional measurements and zero-injection buses with respect to the observability of the power system and communication network. A binary genetic algorithm is used for solving the proposed optimization problem. The proposed method is implemented on a sample 11 node and the IEEE 34 node test feeder to show the effectiveness of the method in the distribution network.**

Keywords*— *Power system observability, phasor measurement unit, energy harvesting sensor node, communication observability.

I. Introduction

In distribution networks, all measurable values, such as nodal voltages and line currents, are not always available. In distribution networks, remote terminal unit (RTU) and automatic meter reading (AMR) are used in supervisory control and data acquisition (SCADA) process to monitor the distribution system variables.

Wide area measurement system (WAMS) has been developed to modify the defects of the SCADA system. Some of the defects of a SCADA system are lack of simultaneous measuring and inability to measure the voltage and current angle [1]. PMU is the main part of WAMS. In fact, by measuring the voltage and current angles and increasing the sampling rate and simultaneous measurement capability, the previously mentioned disadvantages could be eliminated [2]. The first step in state estimation is observability analysis [3]. Therefore, the number of measurement devices, their proper position, the type of communication infrastructure, and the reliable transmission of measured data to the control center are important [4].

In recent years, many methods have been developed to optimize the PMU placement with respect to the observability of the system. The aim of these methods is reduction of WAMS cost. Global optimal solution for optimal PMU placement (OPP) is obtained by integrating the communication cost with power system cost. In fact, the cost of communication system is considerable compared to PMU placement cost [5]. Therefore, some recent researches tried to consider the mentioned cost associated with PMU placement cost. In [6], optimal PMU-communication link placement has been proposed and showed that co-optimal placement of PMUs and communication infrastructure could end to an optimal result. In [7] the authors added optimal placement of phasor data concentrator (PDC) to the objective. In [8] the effect of zero-injection buses (ZIBs) and bandwidth cost included into the OPP problem.

In most of the recent works, it is assumed that the communication system is based on conventional optical fiber cables. The major infrastructure and high investment cost of optical fiber cables are the main problem of installing this equipment. As an alternative, wireless sensors can be effectively used to yield a low-cost communication system with simple infrastructure [9]. The main motivation of implementing these sensors into the power system is to decrease the communication cost and to simplify communication infrastructures. In [10], optimal PMU and related communication infrastructure using hybrid wireless sensor respect to reliability constraint is presented. The results showed that using the proposed method, the communication infrastructure cost is much lower than the conventional fiber-link optic communication infrastructure.

Most conventional wireless sensors are powered by batteries. Maximization of battery lifetime and minimization of energy consumption has been given a bunch of attention recently [11]. Considering the importance of secure and continued data transmission, some types of wireless sensors with higher reliability and more lifetime have been developed in recent years. Energy harvesting sensor nodes (EHSN) can be used to solve the lifetime problem of battery-based sensors [12].

In this paper, the OPP together with the optimal placement of communication links using EHSN is proposed. The objective function includes minimization of the total number of PMUs and

EHSNs considering the ZIB and conventional measurement effect with respect to the power system and communication network observability. A binary-coded genetic algorithm is accordingly used for solving the proposed optimization problem.

The rest of this paper is organized as follows. A brief introduction of the wireless sensor networks and also the WAMS structure is defined in section II. The optimal problem formulation and the proposed optimization method are presented in section III. The numerical study and simulation results are carried out in section IV while section V concludes the paper.

II. Problem and Components Definition

In this paper, for data transferring among PMUs, wireless sensor network is utilized. Wireless sensor network is a network that includes a series of components called sensor nodes. Each node has special capabilities such as environmental conditions measuring, storing and processing information as well as wireless communications with adjacent nodes. Each sensor node in the network has two functions; one sends the collected information by the sensor itself and the other sends received information from the adjacent nodes to the destination node in the role of the router [13]. Accordingly, most wireless sensor networks are multimode or hybrid networks.

Generally, there are three levels in WAMS: data acquisition, data transferring and data processing. In this paper, for the first level, the phasor measurement unit (PMU) is utilized. In the second level, a wireless sensor-based CI is used. The EHSNs are used for delivering data to the control center. It is assumed that the location of the control center is determined and fixed. In fact, instead of the conventional communication infrastructure such as optic fiber links, the EHSNs are used for communication infrastructure. The provided data by the measurement system and CI can be processed in the third level according to the requirements of the system operator. In the next section, the formulation of the proposed method is presented.

III. Problem Formulation

In this paper, optimal PMU placement and related sensor-based wireless communication system are considered. The goal is to minimize the number of measurement devices and related communication system considering multiple constraints. To achieve this aim, modeling of the power system and CI components is necessary. In this regard, OPP problem is initially defined and formulated mathematically. Then, the effect of zero-injection buses and conventional measurement on the OPP problem is considered. In the next step, the communication system structure is introduced. Then, the observability analysis of wireless sensor-based CI is considered. Finally, the proposed solution method based on a binary-coded genetic algorithm is defined.

A. Optimal PMU Placement

The general objective for optimizing the placement of PMUs in the power network is to use the least number of measuring devices that corresponds to the minimum cost considering the full observability of the network. A power grid is fully observable if all systems buses (i.e., nodes) can be observed. Generally, the presence of a PMU in a bus is adequate for observability of all adjacent buses.

If the number of network buses is equal to N, then the matrix of the nodes will be N×N, which is formed as follow:

$$A_{N\times N}(i,j)=\begin{cases}1 & \text{i=j}\\ 1 & \text{if bus i and j are connected}\\ 0 & \text{otherwise}\end{cases} \tag{1}$$

Moreover, the existence of a PMU in a bus can be represented mathematically as:

$$x_i=\begin{cases}1 & \text{if a PMU is installed at bus i}\\ 0 & \text{otherwise}\end{cases} \tag{2}$$

Accordingly, the optimal PMU placement problem can be defined as follows:

$$Min\ \sum_{i=1}^{n} C_i x_i \tag{3}$$

$$s.t.\ f_i \geq 1 \tag{4}$$

Where, C_i is the cost of purchasing and installing PMU at bus i and f_i is the observability function at the bus i.

$$C=[C_1, C_2, ..., C_N] \tag{5}$$

$$f_i=\sum_{j\in I} A_{i,j} X_j \quad \forall i\in I \tag{6}$$

Where I is the set of buses.

B. Effect of ZIBs and Conventional measurement

The zero-injection buses (ZIBs) and conventional measurements can affect and decrease the needed PMU numbers to make the system fully observable. In this paper, the power flow measurement (PFM) is chosen as a conventional measurement. There is no injection in a ZIB. To consider the effect of ZIBs and PFM, a seven-node test system is used in Fig. 1.

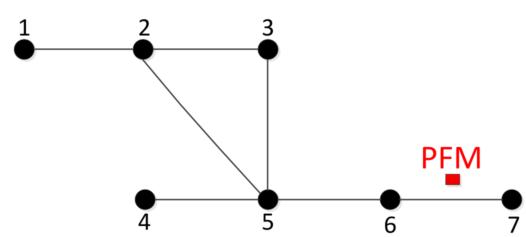

Figure 1. Seven-node test system

In this test system, if none of the nodes are ZIBs and also there is no PFM, at least three PMUs are needed for full observability of the network. The needed PMUs can be placed on nodes 2, 5 and 7. Now, suppose that there is a PFM between nodes 6 and 7, and also node 2 is a ZIB node. A ZIB and its adjacent buses are called a set of zero injection bus (SOZIB) [14]. Observability of N – 1 buses from SOZIB is adequate for full observability of a SOZIB. For more simplicity, the SOZIB will be shown with U. In Fig. 1, the SOZIB can be realized as follow:

$$U_2 = \{1,2,3,5\} \quad (7)$$

With a PMU in node 5, the nodes 2, 3,4,5,6 are observable. With regard to the ZIB effect, out of the four nodes 1, 2, 3, and 5 of the U_2, three nodes are observable. Therefore, all of the nodes in U_2 are observable.

The ZIB effect can be added to the objective function with a linear inequality as follow:

$$f_1 + f_2 + f_3 + f_5 \geq 3 \quad (8)$$

For the power flow measurement (PFM), similar to the ZIBs, a set of PFM associated nodes can be generated. It is called set of power flow measurement buses (SOPFM) and shown with V. observability of N-1 nodes of a SOPFM is adequate for full observability of a SOPFM. For Fig. 1, the SOPFM is as follow:

$$V_1 = \{6,7\} \quad (9)$$

In fact the observability equations for this PFM can be written as:

$$f_6 + f_7 \geq 1 \quad (10)$$

In this case, with a PMU in node 5, the node 6 is observable. So, f_6=1 and (10) is satisfied and there is no need to any PMU for observability of the test system. Therefore, using the ZIBs and PFM, the needed PMU for full observability of the network is equal to 1. We know that without considering these effects, the needed PMU was 3. Equations (8) and (10) should be added to the initial equations that obtained from (3)-(4).

In general, considering the ZIBs effect and conventional measurements, (3)-(4) can be modified as follow:

$$Min \sum_{i=1}^{n} C_i x_i \quad (11)$$

$$s.t. f_i \geq 1 \;\; \forall i \notin U \cup V \quad (12)$$

$$\sum_{k \in U_i} f_k \geq |U| - 1 \;\; \forall i \in Z \quad (13)$$

$$\sum_{k \in V_i} f_k \geq 1 \;\; \forall i \in CM \quad (14)$$

Where Z is the set of zero injection buses and CM is the set of conventional measurements.

C. Communication System

As mentioned before, wireless sensor network is used as a means of communication in this research. Most conventional wireless sensors are battery driven. EHSN can be used to solve the lifetime problem of battery-based sensors. EHSN can harvest energy from the environmental source such as vibration, solar energy, and wind. New EHSNs technologies can be driven by both battery and energy harvesters at the same time. So the lifetime of these sensors is greatly prolonged. Moreover, the cost of this communication system is relatively lower than the PMU cost which makes it a suitable choice especially in cases where the project budget is limited.

In this paper, the connection of PMUs is performed using EHSNs. As illustrated in Fig. 2, the connection among PMUs should be made through EHSNs. Thus, the minimum number of sensors to the control center must be found subject to the observability constraint of CI.

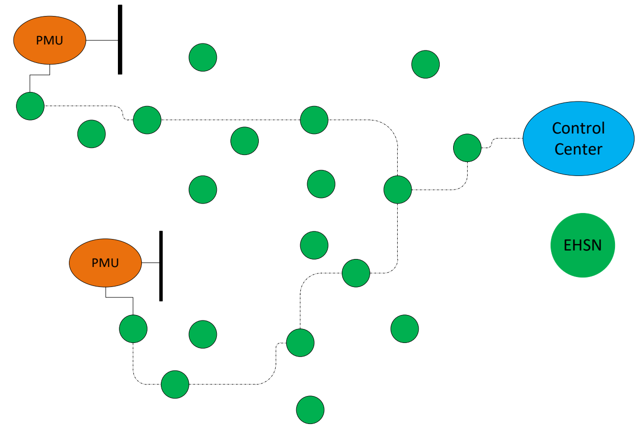

Figure 2. Communication system

D. Communication System Observability

In wireless communication systems, similar to the PMUs placement, the observability analysis has to be done to be sure that wireless sensors can communicate with each other and to the control center. By definition, a node in communication system is observable if there is a connection between that node and the reference node. The reference node is a node that the data should be ultimately delivered to. The reference node in this research is the control center. The communication observability equations are presented in [10]. As a result, the communication matrix (CM) can be used for observability analysis of communication system. Matrix CM shows the connectivity of the nodes to the control center. If the control center is in area *S* and the set of all communication nodes be *Z*, for complete observability of communication system (15) should be met.

$$CM_{s,j} = 1 \;\; \forall j \in Z \quad (15)$$

E. Proposed Objective Function

Solving (11)-(14) with an integer linear programming, the optimum number of PMUs respect to the ZIBs and PFMs is obtained. For solving these linear equations, Bintprog solver in MATLAB can be used. After optimal placement of PMUs, the optimum number of EHSNs should be evaluated. Therefore the objective is to find the minimum number of EHSNs with respect to the observability of the communication system. In fact, in the proposed optimal design, the observability of power system is guaranteed by (11)-(14), and then the observability of communication system is checked by (15). The objective function can be written as follow:

$$Min \sum_{i=1}^{N_T} SN_i \quad (16)$$

$$s.t.$$

$$CM_{s,j} = 1 \;\; \forall j \in Z \quad (17)$$

$$SN_i = 1 \;\; \forall i \in Z \quad (18)$$

Where SN is the existence of sensor node in each area, N_T is the total number of meshes, CM is the communication observability matrix, Z is the set of all communication nodes and S is the control center node.

IV. Case Study

This study aims to examine the advantages and feasibility of using wireless sensors as a communication system in WAMS. For the proper testing of the proposed method, a sample 11-node test feeder and the IEEE 34 node test feeder are utilized.

A. Sample 11-Node Test Feeder

1) Optimal Placement Without PFM and ZIB effect

The sample network is illustrated in Fig. 3. Node 4 is chosen as the control center in this case. Without any ZIBs and PFMs, using (11)-(14), the best position of PMUs due to power system observability constraint is obtained. The candidate buses for PMU placement using Bintprog solver in MATLAB are: 3,4,7,8.

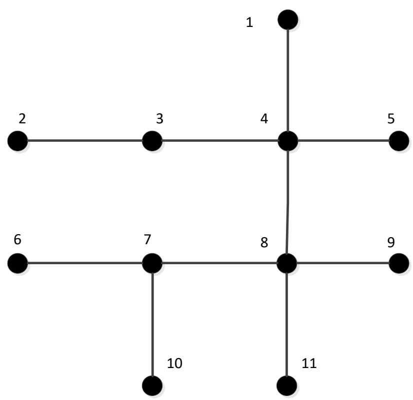

Figure 3. Sample 11-nodes test feeder

It can be seen that by installing 4 PMUs, the 11-node test system is observable. It is assumed that the transmitting range (*tr*) of each EHSN is 150 meters. According to [10], the relationship between the transmitting range (tr) of the wireless sensors and the length of each mesh (d) is as follows:

$$d = \frac{2}{3\sqrt{2}} tr \tag{19}$$

Therefore, if tr=150m, then d=70.17. The length and width of the communication network over that the sensors must be placed are about 1315m and 592m, respectively. So, there are 171 areas in the mesh grid. The initial population is formed according to the position of PMUs. In each area that there is a PMU, an EHSN should be installed. Because the distance of EHSNs is more than the transmission range (*tr*), the router sensors are needed. Therefore, the optimization problem according to (16)-(18) is solved using a genetic algorithm with related parameters as reported in Table 1 where PC is the probability of crossover and PM is the probability of mutation. The results of the optimization problem for this network are shown in Table 2 (case 1). It can be seen that in this case, 4 PMUs and 10 EHSNs are needed to satisfy the observability constraints of power system and communication network.

2) Optimal Placement considering PFM and ZIB effect

Suppose that there is a power flow measurement (PFM) between nodes 2, 3. In this case, with only three PMUs, the network can be observable. The needed PMU and EHSN in this case are listed in table 2 (case 2). It can be seen that the total number of EHSNs is decreased because of the reduction of PMU number.

TABLE I. Parameters of Genetic Algorithm for Optimization Process in 11-Node Test Feeder

Network	**Population size**	P_C	P_M
Sample 11 node	100	0.8	0.3
IEEE 34 node	150	0.75	0.35

TABLE II. Optimization Problem Results

Case	**node # (PMU is installed)**	**node # (EHSN is installed)**	**Area # (EHSN is installed)**
1	3,4,7,8	3,4,7,8	40,58,76,94,112,130
2	4,7,8	4,7,8	58,68,92,121

B. IEEE 34-Node Test Feeder

The IEEE 34-node test feeder is depicted in Fig. 4. In this network, the control center is located in node 2. The genetic algorithm parameters are listed in Table 1. For more simplicity, the nodes are numbered from 1 to 34. The candidate buses for PMU placement and EHSN position without PFM and ZIB effect (case 1) and considering PFM (between nodes 18 and 34) and also ZIB (nodes 22 and 24) in case 2 are listed in Table 3. It can be seen that in the second case and with considering the PFM and ZIB effect, the total number of PMU and EHSN are decreased.

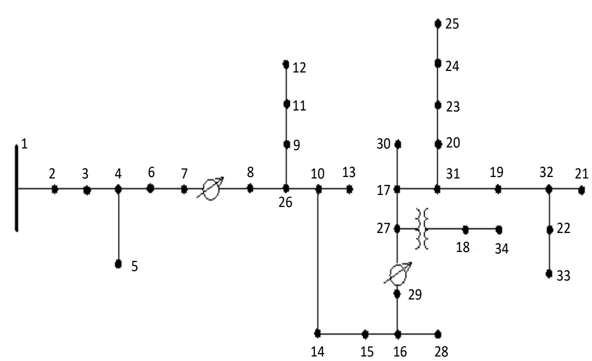

Figure 4. IEEE 34-nodes test feeder

In order to have an economic view about the proposed sensor-based CI, the total system cost is estimated. To this end, it is assumed that the price of each PMU is about \$40,000 [7] and the price of each EHSN is about \$120. Moreover, the cost of related communication infrastructure for each router node and is assumed to be \$150. Therefore the price of each EHSN and related infrastructure in PMU buses and in router nodes are regulated as \$120 and \$270, respectively.

TABLE III. OPTIMIZATION PROBLEM RESULTS

Case	node # (PMU is installed)	node # (EHSN is installed)	Area # (EHSN is installed)
1	2,4,7,10,11,16,18,20,22,24,30,32	2,4,7,10,11,16,18,20,22,24,30,32	24,32,48,55,77,89,99,107,123,130,157,159,165,191,195,208,225,251,263,268,277,283,310,315,319,328,341,351,362,394,401,416,426,437,461,464,472,501
2	2,4,7,10,11,16,17,23,31,32	2,4,7,10,11,16,17,23,31,32	24,32,46,53,75,90,103,119,159,173,188,199,222,241,260,272,281,301,315,321,334,358,387,410,423,435,462,477,502

The costs of test systems are calculated in Table 4. The results of case study showed that considering the effect of ZIBs and CMs, can decrease the cost of the communication system and PMU installation.

TABLE IV. NETWORK COST

Network	PMU cost (in USD)	EHSN cost (in USD)	EHSN cost (router) (in USD)	Total Cost (in USD)
Sample 11-node (case 1)	160,000	480	1,620	162.100
Sample 11-node (case 2)	120,000	360	1,080	121,440
IEEE 34-node (case 1)	480,000	1,440	10,260	491,700
IEEE 34-node (case 2)	400,000	1,200	7,830	409,030

The communication cost in this infrastructure is much lower than the PMU installation. For example, in the 34 node test system (case 1), the PMU placement cost is $480,000. However, the communication infrastructure cost is $11700. The results of [7] show that the optic fiber cables cost is considerable compared to PMU cost. However, modification of this communication system should be done in future works and may lead to increasing the system cost.

V. CONCLUSION

A wireless sensor network communication model for connection of PMUs in wide area measurement system was presented in this paper. In this model, the observability of power system and communication infrastructure were the major constraints. The energy harvesting sensor nodes were used for data transferring. The motivation of this research was realized as reduction of communication cost and introducing a simple infrastructure for communication system compared to conventional systems. The simulation results showed that this communication system can decrease the infrastructure cost.

This model should be modified in future works. The capability of wireless sensor for proper data transferring is an important issue that should be considered. Also, the probabilistic model of this new communication system will be further analyzed in future endeavors.

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