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Optimal Placement of PMUsWith ConsideringNumber of Optimal Channel Measurement and APO Index

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ABSTRACT

This paper presents an optimization model for the calculation of the minimum number of phasor measurement units in complete observability electrical power networks. Since the phasor measurement units with more route measurements have higher costs, investigation the weight matrix is recommended. In conditions in which matrices with the same weight are available, in order to select the optimum result, calculation of average probability of observability index is suggested. The solution method represented in this paper is simulated in MATLAB© software environment on 9 bus IEEE standard network using linear integer programming. The results indicate the optimum placement of phasor measurement units with less cost and efficient average probability of observability index in this issue.

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INTRODUCTION

State estimators are among the most basic components of energy management systems. They calculate system's state variables such as voltages and relative angles buses by means of solving nonlinear equations regarding to measurements which are sent by the system[1]. By converting conventional nonlinear state estimation equations of network to linear equations and also without the use of sophisticated calculations to solve them [2,4], phasor measurement units (PMU) improve the speed of control, protection and management systems which utilize the state estimation results [2]. In this case, the most important issues are optimal allocation of these measuring devices in terms of perfect placement and number for observability of the entire system with minimum the required cost in power systems. However the cost of installation and operation of PMU is not always the same in different situations. For example, that PMU installed on the bus which is connected to a large number of branches and includes higher measurement paths, has the higher weight (i.e:cost) than other PMUs [3].

In the reference [5], in order to obtain a complete set of solutions with ILP method the placement has been proposed. Also it is used in the reference [4] for a sample network using particle swarm optimization (PSO) to PMU placement with considering the weight matrix in normal state. It worth mentioning that in these references, no argument is posted related to comparison and ranking of responses. In the reference [6] by the use of mixed integer programming (MIP) and the assist of average probability of observability index, PMU is implemented in the network.

In this paper, according to the more optimal answer of ILP method, due to the needs of power companies to have the optimal technical and economical choice, a complete set of placements with minimum number of PMUs by taking the specified weight matrix into consideration and also the average probability of observability (APO) the result set has been compared.

In this regard, in the next section the analysis of observability based on the phasor measurement units is presented. In the section 3 by the use of introduction of a result set, PMU placement is formulated. In the section 4 investigation of the effect of weight matrix (W) in PMU placement is discussed while in the section 5 APO index is introduced in order to select the best result. Finally, the results of simulation of the PMU placement -

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taking into account the effect of weighting matrix and average probability of observability - is presented in the section 6.

Observability of power system by PMU:

The observability of a power system is defined as the calculation of system variables in order to estimate system state [4]. PMU installed on a certain bus is able to measure the voltage phasor of that bus. It is also able to measure current phasor of the all branches connected to it. As a result, the voltage magnitude and phase angle of the neighboring bus can be computed using voltage drop equations. Thus the buses monitored by a PMU are directly observable whereas the neighboring buses connected to the PMU are indirectly observable. The other buses which are not associated with the PMU buses are unobservable [1].

The formulationof optimal placement of phasor measurement units:

Problem of optimal PMU placement is one where the objective is to minimize the number of PMUs utilized while preserving the system observability.

For this purpose, it is sufficient to know the system topology (interconnection method buses and lines) and the type of system buses. The system bus connections are displayed using a system connectivity matrix[2]. This matrix shows the interconnection of buses by transmission lines. Here, denoting A as the connectivity matrix and N as the number of system buses, A forms a n × n matrix with the entries defined as equation (1)[1,7,8]:

$$A_{n\times n}(i,j) = \begin{cases} 1 & i = j \\ 1 & \text{if buses i and j are connected} \\ 1 & \text{otherwise} \end{cases} \quad (1)$$

The discrete nature of the optimal PMU placement problem requires the vector X to be defined as equation (2) such that its elements show installationstatus ofa PMU on each bus[4]:

$$[x]_i = x_i = \begin{cases} 1 \text{ if PMU is installeat bus i} \\ 0 \ \text{ otherwise} \end{cases} \quad (2)$$

The formulation of the optimal placement of PMU in a system with n buses is presented as equation (3)[2,6,7,9,10]:

$$\min \sum_{i=0}^{n} \boldsymbol{w_i x_i} \qquad s.t \quad y = Ax \geq b \quad (3)$$

In which w is the matrix of installation cost of the PMUs at a bus, and in normal placement state is considered equal to the n×n matrix. According to the target which is the observability of all system buses, the matrix b is defined as equation (4)[5,7,8]:

$$b_{n\times 1} = [1\ 1\ 1 \ldots 11]^T \quad (4)$$

Binding to existence of a unique solution for PMU placement - according to the lack of same communication facilities for all buses and introduction of observability indices - is not favorable for enhancement reliability of the problem. It necessitates a complete set of solutions in order to achieve a flexible choice.

So if the $x_{s1} = [x_{s1,1} \ \ x_{s1,2} \ \cdots \ x_{s1,n}]^T$ is an optimum solution for m PMUs, to obtain the w optimum solutions and to avoid repetition of same answers, $A_{n\times n}$matrix and $b_{n\times 1}$ vector will be modified in the form of equation (5):

$$A_{(n+w)\times n} = \begin{bmatrix} & A_{n\times n} \cdots & & \\ -x_{s1,1} & -x_{s1,2} & \cdots & -x_{s1,n} \\ -x_{s2,1} & -x_{s2,1} & \cdots & -x_{s2,n} \\ \vdots & & & \vdots \\ -x_{sw,1} & -x_{sw,2} & \cdots & -x_{sw,n} \end{bmatrix}_{(n+w)\times n} \quad (5)$$

$$b_{(n+w)\times 1} = [1 \ \ 1 \ldots 1 \ -(m-1) \ldots -(m-1)]^T_{1\times(n+w)}$$

As a result,the optimal placement of phasor measurement unitis calculated to obtain a complete set of the results as equation (6):

$$\min \sum_{i=1}^{n} w_i\, x_i$$
$$\text{subjectto: } A_{(n+w)\times n} \times nX_{n\times 1} \geq b_{(n+w)\times 1} \quad (6)$$
$$X_{n\times 1} = [x_1 x_2 \ldots x_n]^T$$
$$x_i \in \{0,1\}$$

In this equation The A matrix and b vector will be modified at each iteration. Repetition will stop if the number PMUs is larger than m which is the number of optimal PMUs calculated in the first iteration.

Optimal Placement of PMU Considering the Influence Number of Channels Measurement:

The weight matrix in the equation (1) is related to the number of branches connected to each bus. The PMU installed on the bus which is connected to a larger number of branches and includes higher measurement directions has higher weights (cost) than the other PMUs. Condition (7) represents the relation between the bus cost and the number of connected branches[11]:

$$\mathrm{w} = \begin{cases} 1 & \text{if } \mathrm{NUM_j} < 3 \\ 1.5 & \text{if } \mathrm{NUM_j} \geq 3 \end{cases} \tag{7}$$

Here NUMj is the number of branches connected to bus j. In this regard, if the number of connected branches to bus j is less than 3 then the weight of j bus will be equal to one where as if the number is equal to or greater than 3, the weight of j bus will be equal to 1.5.

Average probability of observability index:

Since it is possible to get multiple answers in the investigation of results set for optimal PMU placement, a condition which is the probability of an observation (PO) is added to the problem to simultaneously satisfy the constraints observable systems and also to check bus. With this bond issue, the complex answers can be ranked in terms of their values in the observable rating.

Thus we considered the average probability of observability as system index, which provides a quantitative perspective on the observability of power system for operator.

The probability of observability of the bus I is calculated from equation (8):

$$PO_i = 1 - \prod_{j \epsilon I} \left(1 - \mu_j A_{ij}\right); \forall i \tag{8}$$

Whereu_j is a binary variable representing the installed PMU at the bus j. A_{ij} is a constant value representing the probability of observability of bus i as a result of the PMU installed at bus j . This value is mathematically defined as equation (9):

$$A_{ij} = a_{ij} A_j^{v_m} A_j^{PMU} A_j^{Link} A_{ij}^{c_m} A_{ij}^{Line}; \ \forall i, \forall j \tag{7}$$

In which $A_j^{v_m}$ and$A_{ij}^{c_m}$ are the availability of PMU voltage measurementat bus j and the availability of PMU current measurementat lineij respectively. These values could be calculated interms of the availability of potential transformers (PTs) and currenttransformers (CTs). Note that three-phase measurementsare required for each phasor calculation [1]. A_j^{PMU} andA_j^{Link} are the probability of successful operation of the PMU at bus j and its communication link, respectively. Also, A_{ij}^{Link} representsthe availability of lineij . In (9), $A_{ii}^{Line} = A_{ii}^{c_m} = 1; \ \forall i$and a_{ij} is the binary connectivity parameter defined as (10):

$$a_{ij} = \begin{cases} 1 & i = j \\ 1 & if\ buses\ i\ and\ j\ are\ connected \\ 0 & otherwise \end{cases} \tag{10}$$

The system index is defined as the average value of bus indices as equation (11)[12]:

$$APO = \frac{1}{Nb} \sum_{i \in I} PO_i \tag{11}$$

In which N_b and i are the number of system busesand a set of buses respectively.The averagefunction employed is used to maintain the APO between zero and one. Definitely the answer with higher APO is selected as the optimum solution. If for any reason such as restrictions on telecommunications, PMU cannot be installed in some buses of the set, the next answer set in rank of APO size is selected as the optimum solution.

Simulation results of PMU placement:

In this section, to evaluate the potential of the mentioned method, in the first stage, the set of placements with minimum number of PMU for network observability is calculated taking into account the weight matrix for 9 bus IEEE standard network. For the purpose of simulation in this paper, the algorithm of integer linear programming in MATLAB software environment is used. In the second stage using APO indices, the results of the first stage has been compared.

First stage) full observability of network considering the effect of the weight matrix (w):

At this stage, to investigate the effect of the weight matrix in optimal placement of Phasor measurement unit, according to (7), it is necessary to specify the number of branches connected to each bus in the case study network diagram and use it in equation (3). In order to clarify the effect of weight matrix, the possible answers with minimum number of PMU using the equations (5)-(6), and the W matrix using equation (7) is calculated. The result with lower weight matrix is selected as the optimal response. Table (5) shows the result set for placement problem considering the matrix of weights for the 9 bus IEEE network. As it is shown, the most appropriate answer is the one in which W (cost) is lower. Also W does not affect the minimum number of PMUs.

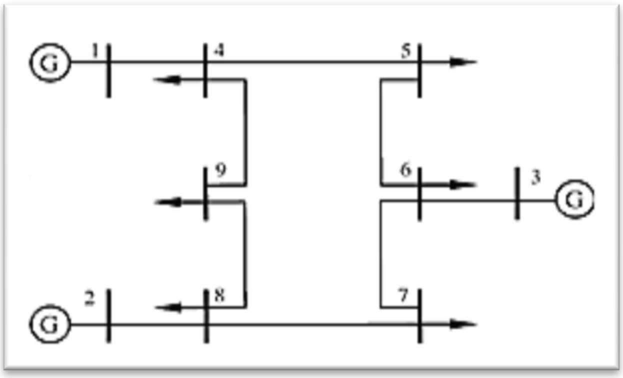

Fig. 1: IEEE 9-bus network diagram.

Table 1: Results set of PMU placement considering the weight matrix for the IEEE 9-bus network.

Number of PMUs	Row of answer	PMU location	Cost (W)
3	1	1,6,8	4
	2	3,4,8	4
	3	2,4,6	4

Second stage) APO investigation to compare sets of PMU placement results considering the weight matrix

In this stage, based on reliability and availability of transmission lines of IEEE 9-bus [12] using relations (8) to (11) and data from tables (2) and (3), APO index have been compared to the first stage results (table1).

Table 2: Reliability information 9-bus IEEE networks.

Parameter	Values	Parameter	Values
A_i^{PMU}	0.99549768	A_{ij}^{Cm}	$(0.99958447)^3$
A_i^{Vm}	$(0.9985447)^3$	A_i^{Link}	0.999

Table 3: Reliability information 9,5 and 7 bus IEEE network with availability of transmission lines 9 bus IEEE.

Parameter	Values	Parameter	Values
A_{1-4}^{Line}	0.9907	A_{6-7}^{Line}	0.9976
A_{2-8}^{Line}	0.9965	A_{7-8}^{Line}	0.9944
A_{3-6}^{Line}	0.9942	A_{8-9}^{Line}	0.9954
A_{4-5}^{Line}	0.9952	A_{4-6}^{Line}	0.9945
A_{4-9}^{Line}	0.9943	A_{9-10}^{Line}	0.9936
A_{5-6}^{Line}	0.9905	–	–

Table 4: Investigation of APO index in compared solution of PMU placement, with the weight matrix on an IEEE 9-bus network.

Row	PMU location	W	APO
1	4,6,8	4	0.9909
2	2,4,6	4	0.9876
3	1,6,8	4	0.9869
4	3,4,8	4	0.9874

As it can be seen, despite the same number of PMUs, changing the location of the PMUs changes APO values that affect the observability likelihood.

According to result table (3), despite the equal number of answers and equal w to other results, answer row 1 is the best location for PMU installation in 9 bus IEEE network because of the higher APO index in the direction of full observability network.

Similarly, results set can be ranked according to the minimum matrix weights and the magnitude of APO index so that if there is a limitation on installation of an answer row, it is possible to have a better choice among all answers. So after the answer row 1, the ranking for selection of optimal placement are answer row 2, row answer 4 and row answer 3 respectively.

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Conclusions:

In this paper, the result set of placement of phasor measurement unit with minimum number for the purpose of complete observability of 9bus IEEE network by taking the weight matrix into account is calculated. The selection of the optimum solution is carried out using minimum amount of this matrix as a priority. Since it is possible to have several equal W values in the answer set, average probability of observability is used in order to select the best solution in such a way that the higher values of this index means the more optimum answer. In this way, possible solutions with the minimum number for 9bus IEEE network is ranked. It should be noted that with location change of PMU, there is a possibility of change in weight matrix and probability of observability.

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