Optimal Placement of Micro-Phasor Measurement Units and Power Flow Measurements to Monitor Distribution Network

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Abstract

Distribution network monitoring is essential for the reliable and secure operation of the distribution network. The micro-phasor measurement unit (μPMU) is the most advanced measurement device to monitor the distribution network. It provides high precision and high accuracy synchronized measurements of the voltage and current phasors as well as amplitudes. Due to its high installation cost, however, we propose the combinational monitoring system with the $\mu PMUs$ and Power Flow Measurements (PFMs) to minimize the installation cost while guaranteeing the observability of the whole system. The Nonlinear Programming method is applied to obtain the optimal solution for the proposed combinational system, so we obtain the minimum number of $\mu PMUs$ and PFMs, and their placements in the distribution network. By simulations using IEEE 13, 34 and 37 bus test feeders, it is confirmed that the proposed method obtains the optimal solution compared to the other monitoring system only with μPMUs.

Keywords

nonlinear programming; optimal placement of $\mu PMUs$ and PFMs; distribution network.

1. INTRODUCTION

The complexity of distribution network due to the interactions of Distributed Energy Resources (DERs) and demand-side management (DSM) including renewable generation, electrical vehicle charging, and customer participation in the power market has increased variability uncertainty on the distribution network [Primadianto et al, 2017], [Wu et al, 2018]. The complexity makes some changes in the distribution network such as bidirectional power flows and voltage profile issues. These complexities have raised the need for more continuous monitoring of distribution network to maintain the reliability and resiliency on the network [Chen et al, 2016].

Traditionally, the distribution system is controlled by conventional Supervisory Control and Data Acquisition (SCADA) systems. The SCADA system receives the data from conventional measurements installed in different locations of power network [Dong et al, 2017]. These conventional measurements record unsynchronized voltage and current magnitude, real and reactive power flows with the low accuracy of $\pm 0.5\%$. SCADA systems have a low resolution of 1Hz which is not sufficient to monitor the dynamic states of the network [Blas et al, 2018]. The small changes in states are invisible to SCADA technology because of its low precision. Therefore, the advanced metering device of high accuracy and high precision is needed for monitoring distribution network applications.

The advanced Phasor Measurement Units (PMUs) were developed for monitoring transmission networks. They can provide synchronized voltage and current phasors (magnitude and phase angle) with high accuracy of $\pm 1^0$ and the reporting rate of 30 samples per second at 60Hz [Jain et al, 2018]. Currently, PMU has been mainly deployed in transmission network due to its high cost and the distribution applications are much more complicated than the transmission applications, the voltage angle differences are small in distribution circuit [Arghandeh, 2016]. Therefore, the distribution networks require high precision and high accuracy rate.

Micro-Phasor Measurement Unit (μPMU) was developed for monitoring, protection, and control distribution network applications. Thus, it can alleviate the problems of complex interactions of DERs by providing synchronized voltage and current phasors with high precision and high accuracy at widely different locations with real-time monitoring of distribution network; a micro-Global Positioning System (μGPS) receiver is used for time stamping the data in order to have the same time reference across all μPMUs; μPMU has angle accuracy of $\pm 0.01^0$ and its amplitude accuracy is $\pm 0.05\%$ [Chakrabarti et al, 2008], [Jain et al, 2017], [Chen et al 2015]. It has a high sampling rate of 120 samples per second at 60Hz.

The μPMUs provide the voltage and current phasors information in real-time with high resolution and precision, and enable the visibility of distribution network [Mohsenian-Rad, 2018]. The μPMU placement problem has been studied in recent works of literature to find the optimal μPMU placement in distribution networks [Wu et al, 2018], [Mabaning et al, 2017], [Tahabilder et al, 2017]. The previously reported works have conducted on optimal PMU placement with the existing flow measurements, consideration of the zero injection buses and contingencies in transmission systems [Almunif et al, 2017], [Chakrabarti et al, 2009], [Emaili et al, 2013]. The joint placement of phasor and

Power Flow Measurements (PFMs) was recently reported in [Kavasseri et al, 2011], they focused on the system observability when there is a fault in the power system. The entire system observability means that all the bus voltage phasors and the line current phasors for a given power system network should be known [Maji et al, 2015].

Different methods for monitoring distribution network using μPMU were carried out for determining the minimum number of μPMUs and their locations which can be installed in the network such that the system is completely observable. Even if their optimal number can monitor the system, the installation cost is still high for full observability. Due to its high installation cost in the distribution network, our contribution in this paper, we propose a combinational monitoring system with μPMUs and PFMs to minimize the installation costs while ensuring observability of the entire system for the normal operating condition. This method is for a new distribution network monitoring system to minimize the number of μPMUs and PFMs, and also the overall installation cost. The joint optimal placement of μPMU and PFM is formulated as nonlinear programming which can be solved using Sequential Quadratic Programming (SQP).

This paper is organized as follows. Section 2 explains the μPMU and PFM in the distribution network, and Section 3 represents the optimization problem formulation and the algorithm applied for the proposed method, the simulation results and discussions are shown in Section 4. Section 5 concludes the paper.

2. μPMU AND PFM IN DISTRIBUTION NETWORKS

The μPMU measures the voltage magnitude and phase angle at the installed bus, and current phasors of lines incident to that bus; the voltage phasors of adjacent buses to that bus can be determined using line parameters and ohm's law. Therefore, all neighboring buses to that bus installed μPMU are observable [Tawfik et al, 2017]. If a bus i is directly or indirectly observable through a μPMU, the adjacent bus j to bus i can be observable through a PFM installed on line $i-j$ [Kavasseri et al, 2011], refer to figure 1.

Fig. 1. Power Flow measurement installed on line *i-j*

The PFM measures the real P_{ij} and reactive power Q_{ij} flows of the line installed, the voltage magnitude at bus j, v_j , is determined using the parameter of line. Therefore, $v_j = v_i - z_{ij}I_{ij}$, I_{ij} is obtained from the relation $v_i I_{ij}^* = P_{ij} + Q_{ij}$, where z_{ij} is the line impedance, I_{ij} is the line current, I_{ij}^* is the conjugate of line current.

3. μPMU AND PFM PLACEMENT

3.1. Nonlinear Programming Formulation

The objective function of the combinational monitoring system with the μPMUs and PFMs is to minimize the number of μPMUs and PFMs, and to determine their installation locations subject to the whole system observability. In this paper, nonlinear programming is used to determine the optimal number of µPMUs and PFMs, and their locations to make the whole system observable. For N-bus and M-line system, the nonlinear programming formulation for optimal μPMUs and PFMs is as follows,

$$\underset{x,y}{\text{Minimize}} \sum_{i \in N} c_i x_i + \sum_{i,j \in M} p_{ij} y_{ij} \tag{1}$$

$$\text{Subject to } x_i + \sum_{j \in N(i)} x_j + \sum_{j \in N(i)} \sum_{k \in N(j) \setminus i} y_{ij} x_k \geq 1, \quad i \in N \tag{2}$$

where N and M represent the sets of buses and lines, respectively. The element in M is composed of two connected buses (i, j). Binary decision variables x_i for μPMU installation and y_{ij} for PFM installation are defined as:

$$x_i = \begin{cases} 1, \text{ if a } \mu\text{PMU is installed at bus } i \\ 0, \text{ otherwise,} \end{cases} \tag{3}$$

and

$$y_{ij} = \begin{cases} 1, \text{ if a PFM is installed on line } i-j \\ 0, \text{ otherwise,} \end{cases} \tag{4}$$

respectively.

The vector $\boldsymbol{x}$ and $\boldsymbol{y}$ are the placement vectors presented as binary vectors for N bus system and M line respectively. The costs of μPMU installed at bus i and PFM installed on line $i-j$ are represented as c_i and p_{ij}, respectively. Let $N(i)$ denote set of all buses adjacent to bus i. Equations (1) and (2) represent the objective function and the observability constraint, respectively.

The network observability is represented by nonlinear inequality constraints. The solution for optimal μPMU and PFM placement is obtained by changing the initial values to random numbers, one and zero. Then, we start from different initial $\boldsymbol{x}$ and $\boldsymbol{y}$. The solution of their optimal placement is obtained when x_i and y_{ij} are equal to one or zero. The nonlinear constraints are solved by the sequential quadratic programming algorithm.

3.2. Application Example

This section shows an example of the nonlinear programming formulation using the IEEE 13-bus test feeder shown in Fig. 2. The IEEE 13-bus test feeder has a switch connecting bus 7 and bus 8, and the switch is considered as closed at the normal operating condition.

$$\underset{x,y}{\text{Minimize}} \sum_{i\in N} c_i x_i + \sum_{i,j\in M} p_{ij}\, y_{ij}$$

$$\text{Subject to } x_i + \sum_{j\in N(i)} x_j + \sum_{j\in N(i)} \sum_{k\in N(j)\setminus i} y_{ij}\, x_k \geq 1$$

$i \in N$, where $N = \{1,2,3,4,5,6,7,9,10,11,12,13\}$.

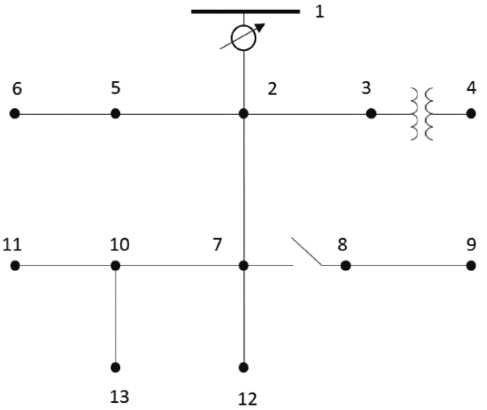

Fig. 2. IEEE 13-bus test feeder

Let F_i denotes the observability constraint at bus i. The constraint $F_i \geq 1$ means that each bus should be observed at least once by μPMU or PFM. It can be formed as bellow:

$$\begin{aligned}
F_1 &= x_1 + x_2 + y_{1\,2}(x_3 + x_5 + x_7) \geq 1\\
F_2 &= x_1 + x_2 + x_3 + x_5 + x_7 + y_{2\,3}\, x_4 + y_{2\,5}\, x_6\\
&\quad + y_{2\,7}(x_9 + x_{10} + x_{12}) \geq 1\\
F_3 &= x_2 + x_3 + x_4 + y_{2\,3}\,(x_1 + x_5 + x_7) \geq 1\\
F_4 &= x_3 + x_4 + y_{3\,4} x_2 \geq 1\\
F_5 &= x_2 + x_5 + x_6 + y_{2\,5}\,(x_1 + x_3 + x_7) \geq 1\\
F_6 &= x_5 + x_6 + y_{56}\, x_2 \geq 1\\
F_7 &= x_2 + x_7 + x_9 + x_{10} + x_{12} + y_{2\,7}\,(x_1 + x_3 + x_5)\\
&\quad + y_{7\,10}\,(x_{11} + x_{13}) \geq 1\\
F_9 &= x_7 + x_9 + y_{7\,9}(x_2 + x_{10} + x_{12}) \geq 1\\
F_{10} &= x_7 + x_{10} + x_{11} + x_{13} + y_{7\,10}\,(x_2 + x_9\\
&\quad + x_{12}) \geq 1\\
F_{11} &= x_{10} + x_{11} + y_{10\,11}\,(x_7 + x_{13}) \geq 1\\
F_{12} &= x_7 + x_{12} + y_{7\,12}\,(x_2 + x_9 + x_{10}) \geq 1\\
F_{13} &= x_{10} + x_{13} + y_{10\,13}\,(x_7 + x_{11}) \geq 1
\end{aligned}$$

The optimal placement for the IEEE-13-bus test feeder is that μPMUs are installed on buses 2 and 7, and PFMs are installed on line 3-4, 5-6, 10-11 and 10-13.

4. SIMULATION RESULTS

In this paper, the nonlinear programming algorithm is applied for various IEEE standard test feeders to find the optimum number of μPMUs and PFMs, and their locations such that the whole system is observable.

The optimization problems are solved using fmincon function in MATLAB using sequential quadratic programming solver for nonlinear programming. The test systems used to show the effectiveness of the proposed method using IEEE 13, 34 and 37 bus test feeders which are shown in figures 2, 3 and 4, respectively.

The cost of μPMU is higher than the cost of PFM. For simplicity, we assume that c_i and p_{ij} are uniform. The installation cost of μPMU with 16GB at bus is \$6,890 and the cost of PFM is approximately \$300 [elspec-ltd], [alibaba].

The simulation results for testing the proposed method on three test systems are shown in Table 1. It is shown that the IEEE 13 bus test feeder is completely observable by installing 2 μPMUs at buses and 4 PFMs on lines; the IEEE 34 bus test feeder is fully observable by installing 7 μPMUs at buses and 11 PFMs on lines, and IEEE 37 bus test feeder is entirely observable by installing 7 μPMUs at buses and 9 PFMs on lines.

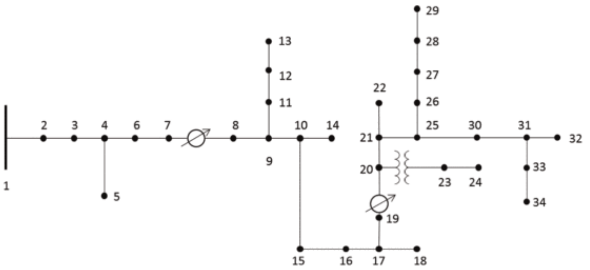

Fig. 3. IEEE 34 bus test feeder

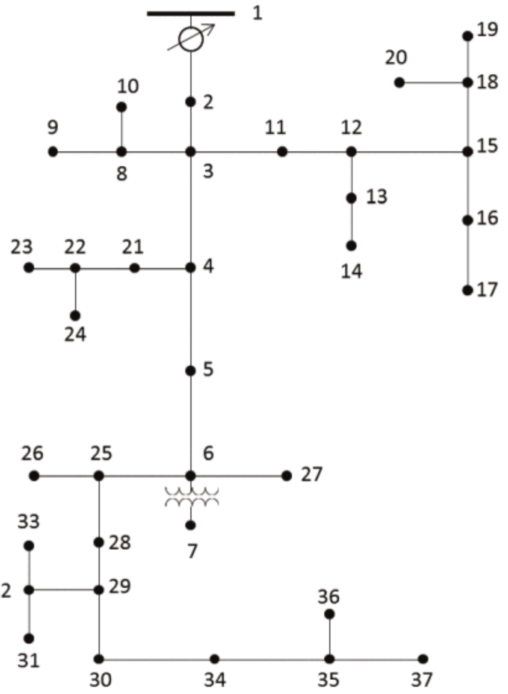

Fig. 4. IEEE 37 bus test feeder

Test feeder	**μPMUs**		**PFMs**	
	Number of μPMUs	**Location of μPMUs**	**Number of PFMs**	**Locations of PFMs**
IEEE 13 bus	2	2,7	4	3-4, 5-6, 10-11, 10-13
IEEE 34 bus	7	3, 9, 12, 16, 20, 27, 31	11	1-2, 4-5, 4-6, 7-8, 10-14, 17-18, 21-22, 23-24, 28-29, 25-30, 33-34
IEEE 37 bus	7	3, 6, 13, 15, 22, 32, 35	9	1-2, 8-10, 8-10, 16-17, 18-19, 18-20, 25-26, 25-28, 30-34

Table 1. Number of μPMU and PFM, and their placement locations

Test Feeder	**Proposed method**				**Ref. [Chen et al, 2016]**		**Ref. [Xuebing et al, 2016]**		**Ref. [Tahabilder et al, 2017]**	
	μPMUs		PFMs		μPMUs		μPMUs		μPMUs	
	number	Cost ($)	number	Cost ($)	number	Cost ($)	number	Cost ($)	number	Cost ($)
IEEE 13 bus	2	13,780	4	1,200	5	34,350	5	34,350	5	34,350
	Total cost ($)		**14,980**							
IEEE 34 bus	7	48,230	11	3,300	12	82,680	12	82,680	12	82,680
	Total cost ($)		**51,530**							
IEEE 37 bus	7	48,230	9	2,700	12	82,680	12	82,680	12	82,680
	Total cost ($)		**50,930**							

Table 2. Comparison between the total costs of μPMUs and PFMs obtained by the proposed method and the total costs of μPMUs obtained by monitoring systems only with μPMUs

The obtained results with the proposed method for the test systems mentioned above have been compared with other monitoring systems solely with μPMUs. The comparison between the proposed method and other methods only with μPMUs is shown in Table 2. It is shown that the number of μPMUs have been greatly reduced for each test system with the proposed method due to the power flow measurements while ensuring the observability of the entire system. Thus, the proposed method obtains the minimum number of μPMUs and PFMs to observe the whole system compared to other monitoring systems only with μPMUs. As shown in Table 2, the total installation cost of each test feeder with the proposed method is very reduced compared to the installation cost with the only μPMU. The installation costs for IEEE 13, 34 and 37 bus test feeders 56.4%, 37.7% and 38.4% are reduced respectively with the proposed method compared to the other systems that use only with μPMUs. Therefore, it is confirmed that the proposed method gives a better solution in terms of installation cost.

5. CONCLUSION

Micro-Phasor Measurement Units (μPMUs) are used at the power distribution level for measuring the voltage and current phasors for monitoring, diagnostic and control distribution network applications. Due to the high installation cost of μPMU, in this paper, we present a proposed method of the combinational monitoring system with optimal placement of μPMU and PFM for full system observability. A nonlinear programming algorithm is applied to solve the optimal μPMU and PFM placement problem using Sequential Quadratic Programming Solver.

Simulation results for IEEE 13, 34 and 37 bus test feeders are compared with other μPMU placement schemes which only considers μPMU. The proposed method is more economical than other schemes. The installation costs by the proposed scheme for IEEE 13, 34 and 37 bus test feeders are reduced by 56.4%, 37.7% and 38.4%, respectively.

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References

Almunif A. and Fan L., 2017, Mixed integer linear programming and nonlinear programming for optimal PMU placement, *2017 North American Power Symposium (NAPS)*, Morgantown, WV, 2017: p1-6.

Arghandeh Reza, 2016, Micro-Synchrophasors for Power Distribution Monitoring, a Technology Review, arXiv:1605.02813v1 [cs.SY] 10 May 2016.

Azizi S., Gharehpetian G. B. and Dobakhshari A. S., 2013, Optimal integration of phasor measurement units in power systems considering conventional measurements, *IEEE Transactions on Smart Grid*, 2013: p1113-1121.

Blas L. L. F., Bundoc P. E. D. C., Melchor K. C. L. and Orillaza J. R. C., 2018, Micro-synchrophasors for event detection in an electric power system simulator, *2018 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, Singapore, 2018: p178-183.

Chakrabarti S. and Kyriakides E., 2008, Optimal placement of phasor measurement units for power system observability, *IEEE Transactions on Power Systems*, 2008: p1433-1440.

Chakrabarti S., Kyriakides E. and Eliades D. G., 2009, Placement of synchronized measurements for power system observability, *IEEE Transactions on Power Delivery*, 2009: p12-19.

Chen X., Chen T., Tseng K. J., Sun Y. and Amaratunga G., 2016, Hybrid approach based on global search algorithm for optimal placement of μPMU in distribution networks, *2016 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, Melbourne, VIC, 2016: p559-563.

Chen X., Tseng K. J. and Amaratunga G., 2015, State estimation for distribution systems using micro-synchrophasors, *2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Brisbane, QLD, 2015: p1-5.

Dong Q., J. Sun, Wu Q. and Liu Y., 2017, A method for filtering low-frequency disturbance in PMU data before coordinated usage in SCADA, *IEEE Transactions on Power Systems*, 2017: p2810-2816.

Esmaili M., Gharani K. and Shayanfar H. A., 2013, Redundant observability PMU placement in the presence of flow measurements considering contingencies, *IEEE Transactions on Power Systems*, 2013, p. 3765-3773.

Fadiran J. I., Chowdhury S. and Chowdhury S. P., 2012, Optimal placement of phasor and conventional measurements for power system state estimation and fault observability, *2012 IEEE International Conference on Power System Technology (POWERCON)*, Auckland, 2012: p1-6.

https://www.alibaba.com, retrieved 19.03.2019.

https://www.elspec-ltd.com, retrieved 19.03.2019.

Jain A., Bhullar S., 2018, Micro-phasor measurement units (μPMUs) and its applications in smart distribution systems, Springer Proceeding Book by India Smart Grid Forum (ISGF) Compendium of Technical Papers, Lecture Notes in Electrical Engineering 487, New Delhi, 2018.

Kavasseri R. and Srinivasan S. K., 2011, Joint placement of phasor and conventional power flow measurements for fault observability of power systems, *IET Generation, Transmission & Distribution*, 2011: p1019-1024.

Liao A. L., Stewart E. M. and Kara E. C., 2016, Micro-synchrophasor data for diagnosis of transmission and distribution level events, *2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, Dallas, TX, 2016: p1-5.

Mabaning A. A. G., Orillaza J. R. C. and von Meier A., 2017, Optimal pmu placement for distribution networks, *2017 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, Auckland, 2017: p1-6.

Maji T. K. and Acharjee P., 2015, Multiple solutions of optimal PMU placement using exponential binary PSO algorithm, *2015 Annual IEEE India Conference (INDICON)*, New Delhi, 2015, pp. 1-6.

Mohsenian-Rad H., Stewart E. and Cortez E., 2018, Distribution Synchrophasors: Pairing big data with analytics to create actionable information, *IEEE Power and Energy Magazine*, 2018: p26-34.

Nan X. and Beng G. H., 2013, Optimal PMU placement with local redundancy of conventional measurements, *2013 IEEE Computational Intelligence Applications in Smart Grid (CIASG)*, Singapore, 2013: p1-5.

Primadianto A. and Lu C., 2017, A Review on distribution system state estimation, *IEEE Transactions on Power Systems*, 2017: p3875-3883.

Sun Y., Chen X., Yang S., Rusli, Tseng K. J. and Amaratunga G., 2017, Micro-PMU based monitoring system for active distribution networks, *2017 IEEE 12th International Conference on Power Electronics and Drive Systems (PEDS)*, Honolulu, HI, 2017: p518-522.

Tahabilder A., Ghosh P. K., Chatterjee S. and Rahman N., 2017, Distribution system monitoring by using micro-PMU in graph-theoretic way, *2017 4th International Conference on Advances in Electrical Engineering (ICAEE)*, Dhaka, 2017: p159-163.

Tawfik A. S., Abdallah E. N. and Youssef K. H., 2017, Optimal placement of phasor measurement units using binary bat algorithm, *2017 Nineteenth International Middle East Power Systems Conference (MEPCON)*, Cairo, 2017: p559-564.

Von Meier A., Stewart E., McEachern A., Andersen M. and Mehrmanesh L., 2017, Precision micro-synchrophasors for distribution systems: A summary of applications, *IEEE Transactions on Smart Grid*, 2017: p2926-2936.

Wu, Z.; Du, X.; Gu, W.; Ling, P.; Liu, J.; Fang, C., 2018, Optimal micro-PMU placement using mutual information theory in distribution networks, *Energies*, 2018.

Xuebing Chen, Tengpeng Chen, King Jet Tseng, Sun Yuhao and Amaratunga G., 2016, Customized optimal μPMU placement method for distribution networks, *2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Xian, 2016: p135-140.