

Optimal Power Quality Meters Placement with Consideration of Single Line and Meter Loss Contingencies

Mohammad Reza Sheibani,^a Abbas Ketabi,^b and Seyyed Mostafa Nosratabadi^c

A
B
S
T
R
A
C
T

Harmonic state estimation (HSE) is the process of assigning a value to an unknown system state harmonic variable based on measurements from that system according to some criteria. Determining the best harmonic meters places in the system helps to increase the accuracy of the HSE. In this paper, a methodology is presented for optimal placement of power quality (PQ) meters in a power system. The PQ meters results are used to estimate the unknown harmonic variables. Mean square errors of estimated total harmonic distortions in normal condition is selected as the cost function, while single line and meter loss contingencies are also considered by formulating a multi-objective optimization exercise. To achieve this, seeker optimization algorithm (SOA) based on Pareto optimum method has been proposed here. Simulation are performed on an IEEE 14-bus test system. The simulation results demonstrate the effectiveness of the proposed methodology for harmonic state estimation and optimal meter placement.

ARTICLE INFO

Keywords:

Harmonic State Estimation (HSE)
Power Quality (PQ) Meters
Seeker Optimization Algorithm (SOA)
Pareto Optimum Method

Article history:

Received May. 22, 2018
Accepted June. 20, 2018

I. INTRODUCTION

Existence of harmonic pollutions in power systems contribute to problems such as equipment overheating and interference with communication circuits and as such should be studied carefully^{1,2}.

The direct harmonic measurements of all the system state variables are not economically feasible because harmonic measurements are complex and expensive. Harmonic state estimation (HSE) is a tool for reduction of needful measurement in system. A limited number of measuring devices are installed in the system for HSE, the data from which could be used to estimate reasonably the required variables elsewhere³⁻⁶. The quality of the HSE results depend on the number and locations of meters, hence meters placement is very important for the increase of HSE accuracy⁷⁻¹⁰.

Placement of meters for HSE in normal condition operation of power systems is studied in recent years by several researchers. In¹¹, a sequential technique is presented for optimal placement of sensors for HSE, based on the minimum variance approach. In this method, generation and data are required at each harmonic order for all buses. Ref.¹² proposes a time consuming meters placement methodology based on the analysis of system error covariance. In¹³, a technique is proposed for observability analysis in order to determine the minimum number of needful meters for HSE. Ref.¹⁴ offers a method of optimal meters placement based on the minimum condition number. Ref.¹⁵ suggests a harmonic source location method by using impedance network approach. Ref.¹⁶, presents a new algorithm that uses minimum variance criterion and a sequential method for optimal meters placement, singular value decomposition method for observability analysis and finally weighted least square method for harmonic estimation. In¹⁷, binary particle swarm optimization is used to find the optimal locations of harmonic measurement devices to collect harmonic data. The optimal placement of PMUs is carried out in¹⁸, using genetic algorithm (GA) to locate non linear loads for placing the harmonic mitigation devices. In¹⁹, an efficient methodology to locate the harmonic sources and their injection levels has been proposed. The binary particle swarm optimization algorithm has been proposed for optimal placement of PMUs to get the harmonic data.

The disadvantages of these approaches include not considering contingencies such as single line outage and power quality (PQ) meter outage as well as lack of clarity on the nature of different cases for accurate HSE.

In this study, some contingencies are considered in the PQ meters placement. The network line and PQ meters outage are modeled in the proposed approach. A Pareto multi-objective optimization method based on the SOA algorithm is used to determine the best position of the PQ meters. Application of multi-objective approach provides the ability of determining the best PQ meters position in normal and contingency conditions. Several case studies are considered to verify the proposed

^a Corresponding Author: m.sheibani@ec.iut.ac.ir, Department of Electrical and Computer Engineering, Isfahan University of technology, Isfahan, Iran

^b Department of Electrical Engineering, University of Kashan, Kashan, Iran

^c Department of Electrical Engineering, Sirjan University of Technology, Sirjan, Iran

<http://dx.doi.org/10.22111/ieco.2018.25226.1043>

Nomenclature**A. Indexes**

h	Harmonic order index
i, j	Index of bus number
k	Index of bus number which consists of PQ meter
r	Index of line

B. Variables

V_{hj}	The voltage vector of the measured and unknown nodes
$THD_i^{\text{estimated}}$	The estimated THD of the voltage in bus i

C. Constants

I_{hi}	the vector of the measured injected currents
$y_h(i, j)$	The element of the admittance matrix for each harmonic order

σ_{hi}^2	The i^{th} measurement variance
m	Number of used PQ meters
n	Number of buses
THD_1^{actual}	The calculated THD of the voltage in bus i (at monitored buses)
N_{line}	Number of network line

D. Acronyms

HSE	Harmonic state estimation
PQ	Power Quality
SOA	Seeker optimization algorithm
GA	Genetic algorithm
WLS	Weighted least squares
SVD	Singular value decomposition

method.

The organization of the rest of the paper is as follows: In Section II, the proposed method for HSE is formulated. Then the principle of proposed procedure for PQ meters placement is introduced in Section III. The used SOAs and Pareto optimum method are explained in Section IV. Simulation results are demonstrated in Section V and Section VI concludes the paper.

II. HARMONIC STATE ESTIMATION

HSE is an effective method to find the complete harmonic information by the limited number of PQ meters and to identify the system state for each harmonic order^{20,21}. PQ meters are the useful tools for measuring the magnitude and phase angle of harmonic voltages and injected currents in monitored buses.

The used method for HSE in the present work is based on the weighted least squares (WLS) estimation. The real and imaginary parts of voltages in each harmonic

are considered as the state variables. Minimization the sum of the squares of the difference between the measured and estimated values, weighted by the variance of their corresponding meter errors is the objective of this method^{22,23}. The target of HSE is minimization of below objective function:

$$J_h = \sum_{i \in k} \frac{(\text{Real}(A))^2 + (\text{Imag}(A))^2}{\sigma_{hi}^2} \quad (1)$$

where

$$A = I_{hi} - \sum_{j=1}^n y_{h(i,j)} V_{hj}$$

σ_{hi}^2 is the i^{th} measurement variance reflecting the expected corresponding meters accuracy²³. The harmonic voltages and injected harmonic currents are known only in the buses equipped with PQ meters. I_{hi} and V_{hj} s can be obtained by the PQ meters data. Eq. (1) in conjunction with the improved SOA algorithm is used to estimate the voltages of the buses without PQ meter.

III. PLACEMENT OF PQ METERS

The quality of the outputs of the HSE is related to the number and positions of the PQ meters. However, due to considerable installation cost of PQ meters, only a limited number of buses are equipped with PQ meters. Therefore, at first we should determine the minimum number of PQ meters. Then the locations of the PQ meters are determined. In this work, an optimization algorithm is proposed for PQ meters placement in normal and uncertain conditions of the power system.

A. Placement without Contingency

A power system is considered as normal when all PQ meters and lines operate as designed. In such condition, a new method is proposed here to determine the optimal number and location of PQ meters for an accurate HSE. This method is based on minimizing the Mean Square Error of the estimated Total Harmonic Deviation (THD) in the system^{24,25} calculated as follow:

$$THD_i = \frac{\sqrt{\sum_{h=2}^{\infty} |V_{hi}|^2}}{|V_{1i}|} \quad (2)$$

where $|V|$ is the amplitude of voltage.

The objective function of the PQ meters placement in normal condition is:

$$OF_{\text{normal}} = \frac{\sum_{i \in k} (THD_i^{\text{actual}} - THD_i^{\text{estimated}})^2}{m} \quad (3)$$

B. Placement with Considering of Congestion

HSE should be able to accommodate all types of contingencies (such as single line/PQ meter outage), otherwise the estimations results may become incorrect. Hence, the objective function has to consider both normal and contingency conditions for PQ meters placement. Two types of contingencies considered in this study are as follows:

1. Considering a PQ meter Outage

In order to take the single PQ meter loss into account, an additional term is added to the normal objective function as follows:

$$\min \begin{matrix} f_1 = OF_{\text{normal}} \\ f_2 = OF_{\text{s.m.c}} \end{matrix} \quad (4)$$

where

$$OF_{\text{s.m.c}} = \left(\frac{\sum_{i \in k} OF_{\text{normal}}^{\text{i}^{\text{th}} \text{lost meter}}}{m} \right)$$

and $OF_{\text{normal}}^{\text{i}^{\text{th}} \text{lost meter}}$ is the OF_{normal} for the i^{th} PQ meter loss. Hence, to obtain f_2 , with a loss meter, OF_{normal} is evaluated using the existing meters.

2. Considering of a Line Outage

Single line contingency happens frequently and therefore should be considered in the PQ meters placement. When the link between two adjacent buses is disconnected, single line contingency occurs where this event leads to reduction of estimations accuracy. In the proposed objective function to considering the line contingency, the mean of objective functions at single line outage ($OF_{\text{s.l.c}}$), is added to the objective function in normal condition (OF_{normal}). Hence,

$$\min \begin{matrix} f_1 = OF_{\text{normal}} \\ f_2 = OF_{\text{s.l.c}} \end{matrix} \quad (5)$$

where

$$OF_{\text{s.l.c}} = \left(\frac{\sum_{r=1}^{N_{\text{Line}}} OF_{\text{normal}}^{\text{r}^{\text{th}} \text{lost line}}}{N_{\text{Line}}} \right)$$

$OF_{\text{normal}}^{\text{r}^{\text{th}} \text{lost line}}$ is the OF_{normal} for the r^{th} line outage. Similar to the previous case, to obtain f_2 , with a loss line, OF_{normal} is calculated with the new topology. A combination of Pareto method and SOA algorithm is employed to solve the multi-objective functions in Eq. (4) and Eq. (5).

IV. INTRODUCTION OF SOA BASED ON PARETO OPTIMUM METHOD

In this study, SOA is employed for HSE and PQ meter placement optimization. SOA is a relatively new intelligent algorithm that is a population-based heuristic stochastic search method^{26,27}. The details and formulations of used SOA can be found in²³. The results of simulations in^{26,27} indicate the robustness of this algorithm, in rapid convergence in reaching the global optimum. The algorithm has the additional advantage of being easy to understand, simple to implement so that it can be used for a wide variety of design and optimization tasks.

The Pareto optimum method is used for selection of the most appropriate solution amongst the spectrum of solutions of defined Multi-objective optimization problems for PQ meters placement^{28,29}. The workflow for the proposed strategy using SOA algorithm based on Pareto method is shown in Fig. 1. At first, the positions of seekers are determined and the population is randomly divided to subpopulations. Then, the real and imaginary parts of the voltages in all buses are calculated using Eq. (1). The sub functions of major objective function related to the initial population are evaluated using Eq. (4)

and Eq. (5) in step 3. Then a set of first solutions consist of the best positions of the personal, neighborhood, and population are selected using the Pareto optimum method, in order to obtain the non dominated answers. Next, population is updated with SOA. The process is then repeated for the preset maximum number of iterations ($Iter_{max}$). Finally, the best solution is identified amongst the Pareto optimum set depending on the user preference and appropriate constraints.

A. Parameter Setting of Used SOAs for Proposed Method

If M harmonic orders exist in the system, $M + 1$ SOAs are needed (M number of SOAs for HSE and one SOA for PQ meters placement) for determination of the number and place of PQ meters by proposed method. In HSE problem, the number of state variables is two times that of the buses number, since HSE estimates both the real and imaginary parts of the non-monitored bus voltages. In the placement problem the number of state variables is equal to bus numbers. To indicate the absence or presence of meter in a bus, we assign 0 or 1 values, respectively to the state variables. In the proposed SOA, the population is randomly categorized into 3 subpopulations to search is done over several different domains.

In HSE problem the upper and lower bounds are considered as follows:

$$\begin{aligned} V_{max} &= 1.05 \times V^{nominal} \\ V_{min} &= 0.95 \times V^{nominal} \end{aligned}$$

These quantities are determined based on the setting properties of the protective devices. In this paper, it is supposed that the overvoltage and under voltage relays are set to 105% and 95% of nominal voltage, respectively. Standard deviation (σ) of used PQ meters in HSE is assumed 0.01 pu and. The minimum and maximum membership degrees in SOAs and $iter_{max}$ are considered 0.0111, 0.97 and 75, respectively. As it is shown in Fig. 1, in each iteration some places are suggested, then HSE is done for those places.

V. TEST SYSTEM AND RESULTS

The IEEE 14-bus test system shown in Fig. 2 is chosen to verify the ability of the proposed method for HSE and PQ meters placement in normal and uncertain conditions³⁰. Simulations results show that by considering four harmonic loads connected at buses 4, 5, 7 and 13, the present harmonic orders in this network are 5th, 7th, 11th, 13th, 17th and 19th. The simulations and optimization are done in MATLAB software.

A. Harmonic state estimation

In this section, to showing the ability of used method for HSE, 4 PQ meters are installed in buses 7, 9, 10 and 14. Singular value decomposition (SVD) method shows

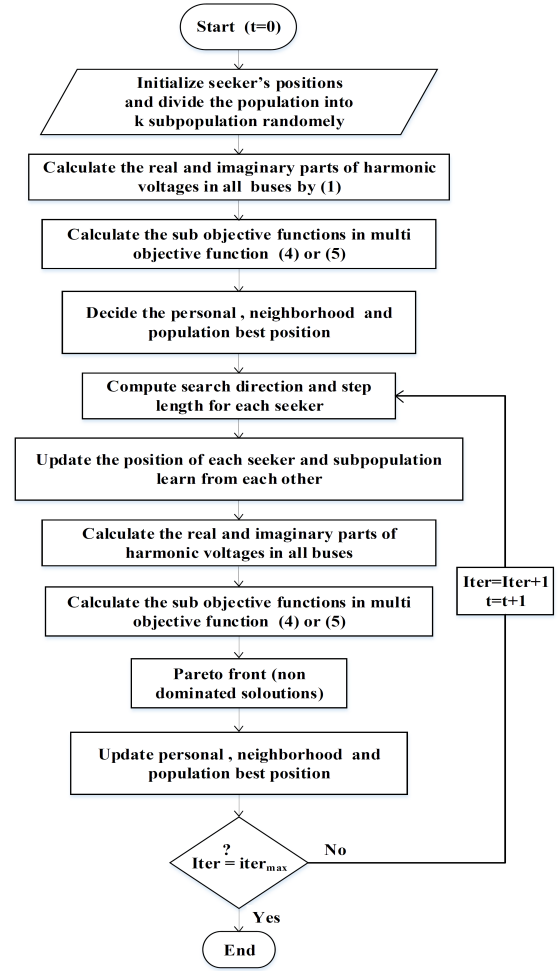


FIG. 1. Proposed flowchart of used SOA for placement of PQ meters.

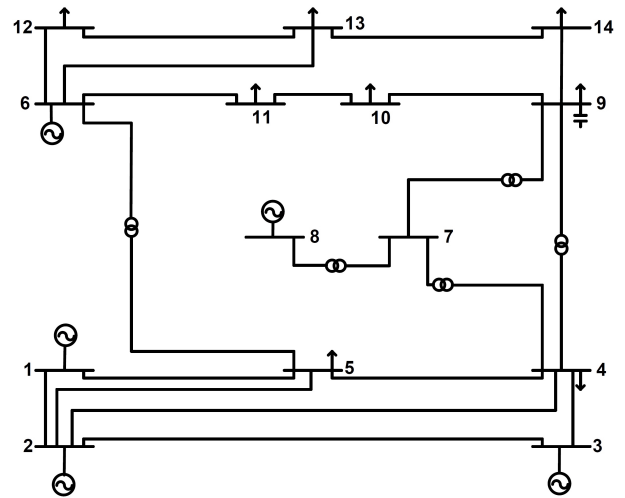


FIG. 2. The IEEE 14-bus system.

TABLE I. Estimations relative errors (%) of real part of harmonic voltages by SOA

Bus	Harmonic order					
	5	7	11	13	17	19
1	1.02	0.97	1.37	0.89	0.91	1.12
2	0.65	2.04	1.42	0.73	0.93	1.02
3	2.14	0.51	0.83	1.27	2.41	0.78
4	0	0	0	0	0	0
5	0.29	1.02	0.91	1.31	0.98	0.51
6	1.23	0.65	0.98	1.03	0.81	1.02
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	1.03	1.01	0.38	1.89	0.71	2.12
14	0	0	0	0	0	0

that the buses 1, 2, 3, 5, 6 and 13 are unobservable. Tables I and II demonstrate the relative estimating errors of HSE outputs. Table III shows the actual and estimated values of THD and relative errors. As shown in Tables I-III, estimation errors for the monitored buses are zero since the harmonic voltage values are available. It is worth noting that estimation results for observable buses (4, 8, 11, 12) are very accurate and the estimations of unobservable buses are in the acceptable range, which is one of the advantages of the used method.

For comparison, GA is also employed in HSE which the estimation results and their relative errors are demonstrated in Table IV. Comparing Tables III and IV, superior performance of SOA is represented by the smaller errors. The complete results of HSE can be found in²³. In the next section, it is shown that the estimation results are improved when PQ meters are suitably placed.

B. Optimal PQ meters placement

As mentioned in Section III, PQ meters placement is based on minimizing the MSE of estimated THDs. Here, two cases are considered for placement of different number of PQ meters in normal and uncertain conditions.

1. Placement in normal condition

In normal condition, the PQ meters placement would not require the Pareto method since the optimization becomes a single objective exercise. In this case, using Eq. (3) and the expressed SOA algorithm in Section IV, the minimum number of PQ meters and their best position is determined. Table V shows the results of placement for 7, 6, 5, 4 and 3 PQ meters numbers.

Second column of this table shows the best places to install the PQ meters. This table also shows the minimum number of PQ meters for a pre-determined accuracy in the required HSE. For example, if user accepts a maxi-

TABLE II. Estimations relative errors (%) of imaginary part of harmonic voltages by SOA

Bus	Harmonic order					
	5	7	11	13	17	19
1	0.87	1.04	0.56	1.67	0.54	1.25
2	1.12	0.67	1.04	1.11	0.76	0.39
3	0.91	1.83	0.76	0.65	1.92	2.12
4	0	0	0	0	0	0
5	0.48	2.04	1.26	0.74	0.91	1.74
6	1.43	0.76	0.45	1.06	2.54	1.54
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	1.65	0.91	1.12	0.76	1.54	1.31
14	0	0	0	0	0	0

TABLE III. Actual and estimated THD (%) and estimation errors by SOA

Bus	Actual THD%	Estimated THD%	Relative Error%
1	1.782	1.761	1.178
2	1.983	1.9227	3.041
3	2.401	2.3081	3.869
4	3.7612	3.7612	0
5	6.7331	6.6172	1.721
6	1.9882	1.9287	2.993
7	5.5211	5.5211	0
8	1.3321	1.3321	0
9	2.1536	2.1536	0
10	2.2972	2.2972	0
11	1.5231	1.5231	0
12	3.2326	3.2326	0
13	7.5662	7.2313	4.426
14	2.6433	2.6433	0

TABLE IV. Estimation results by GA algorithm

Bus	Actual THD%	Estimated THD%	Relative Error%
1	1.782	1.6861	5.381
2	1.983	1.8522	6.594
3	2.401	2.2176	7.639
4	3.7612	3.7612	0
5	6.7331	6.4011	4.931
6	1.9882	1.8817	5.359
7	5.5211	5.5211	0
8	1.3321	1.3321	0
9	2.1536	2.1536	0
10	2.2972	2.2972	0
11	1.5231	1.5231	0
12	3.2326	3.2326	0
13	7.5662	7.0144	7.293
14	2.6433	2.6433	0

TABLE V. Result of placement of PQ meters in normal condition

Number of PQ meters	Position of PQ meters	OF ^{min}
7	3,4,5,7,11,12,14	0
6	3,4,7,10,11,14	3.1×10^{-11}
5	3,4,5,10,11	5.4×10^{-8}
4	1,5,10,11	2.9×10^{-7}
3	6,11,12	6.1×10^{-7}

TABLE VI. Actual and estimated THD (%) and estimation errors for 4 PQ meters after placement

Bus	Actual THD%	Estimated THD%	Relative Error%
1	1.782	1.782	0
2	1.983	1.983	0
3	2.401	2.356	1.89
4	3.7612	3.7612	0
5	6.7331	6.7331	0
6	1.9882	1.9882	0
7	5.5211	5.464	1.038
8	1.3321	1.3052	2.021
9	2.1536	2.1536	0
10	2.2972	2.2972	0
11	1.5231	1.5231	0
12	3.2326	3.2063	0.814
13	7.5662	7.4001	2.195
14	2.6433	2.5965	1.769

TABLE VII. Result of placement of PQ meters in single meter contingency for 5 PQ meters (Fig. 6)

Point (left to right)	Position of PQ meters
1	3,8,9,12,13
2	6,7,9,11,12
3	1,2,5,7,13
4	5,8,9,11,14
5	2,3,9,12,14
6	1,3,5,8,11
7	2,5,7,9,12
8(A)	6,8,10,12,13
9(B)	2,6,9,11,12
10(C)	3,4,5,7,12
11	1,7,9,10,12
12	4,6,7,9,12
13	2,7,11,12,14
14	2,5,9,10,13
15	1,5,8,10,12
16	4,7,11,13,14
17	1,5,9,13,14
18	3,8,9,12,13
19	6,7,9,11,12
20	1,2,5,7,13

num objective function of 3×10^{-7} , the number of required meters is 4 and the best places of these meters are 1, 5, 10 and 11. Table VI shows the THDs for 4 meters that their places are showed in Table V. Comparing the results of Tables III and VI, the relative errors of Table

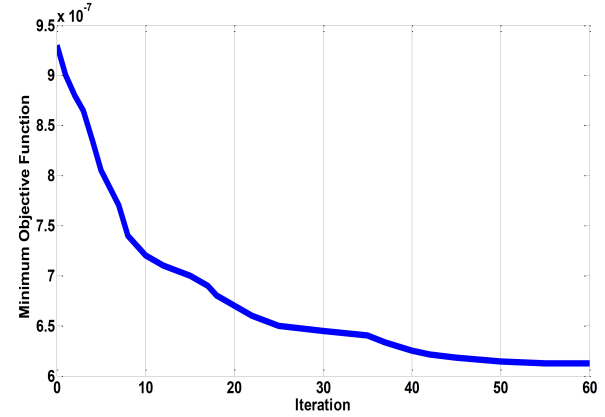


FIG. 3. Convergence rate of SOA algorithm for placement of 3 PQ meters in normal condition.

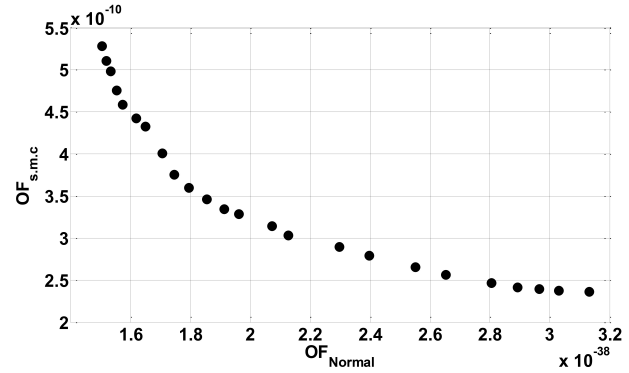


FIG. 4. Pareto optimum results for single PQ meter contingency for 7 PQ meters.

VI are less than Table III. However, the number of used PQ meters to HSE is the same in both cases. Therefore, the errors of HSE in system are reduced by obtaining the best places of PQ meters. Fig. 3 shows the convergence rate of SOA algorithm in PQ meter placement for 3 PQ meter number. Clearly, the convergence rate of SOA in placement problem is acceptable.

2. Placement considering the contingencies

As it is described in Section III, two types of contingencies (single line outage and PQ meter loss) are considered in this study. In placement with uncertainty,

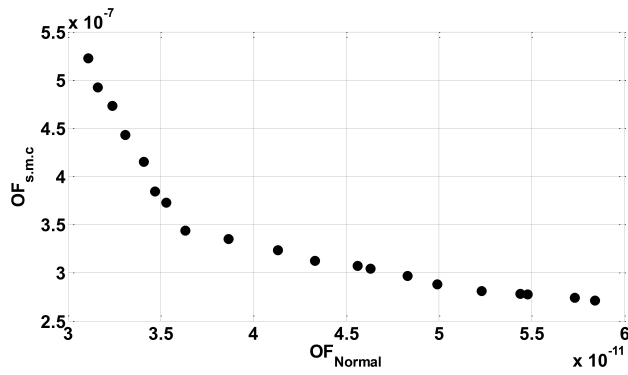


FIG. 5. Pareto optimum results for single PQ meter contingency for 6 PQ meters.

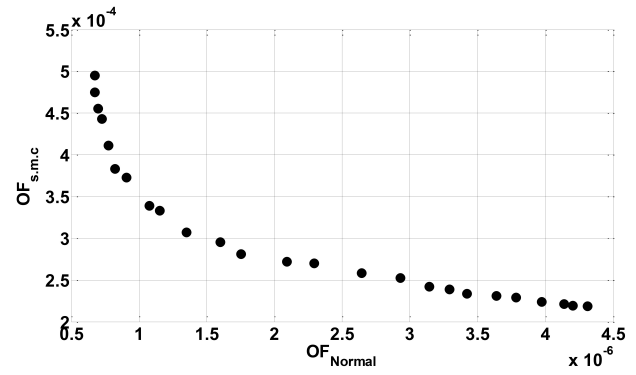


FIG. 8. Pareto optimum results for single PQ meter contingency for 3 PQ meters.

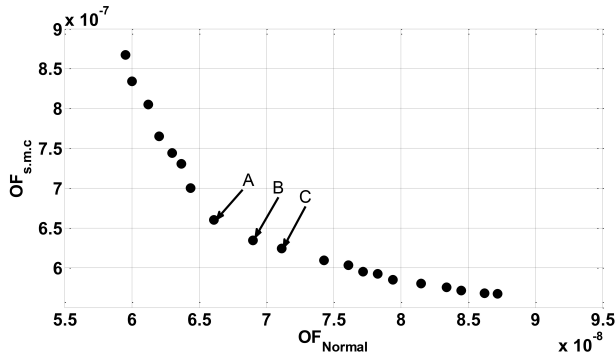


FIG. 6. Pareto optimum results for single PQ meter contingency for 5 PQ meters.

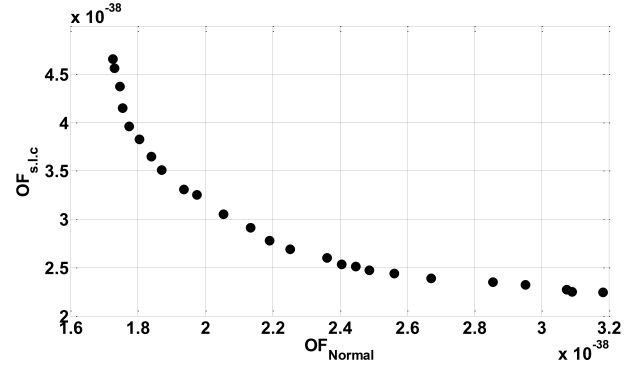


FIG. 9. Pareto optimum results for single line contingency for 7 PQ meters.

Pareto method is used because the optimization problem is multi-objective. Equations (4) and (5) are the multi objective functions for PQ meters placement with single meter and line contingencies, respectively.

Figs. 4-8 show the Pareto optimum results for single PQ meter contingency for 7, 6, 5, 4 and 3 PQ meters number. For instance, if a user accepts a maximum OFnormal of 7.3×10^{-8} and a maximum OFsingle meter

contingency of 6.8×10^{-7} , the number of required meters based on the curves is 5 with points A, B and C (Fig. 6). Table VII shows the best places of PQ meters for each of points in Fig. 6. One of the most important benefits of the proposed method for placement is the ability of the best places selection depends on user selection attending to the importance degree of objective function terms. In this example, if the normal condition is more important

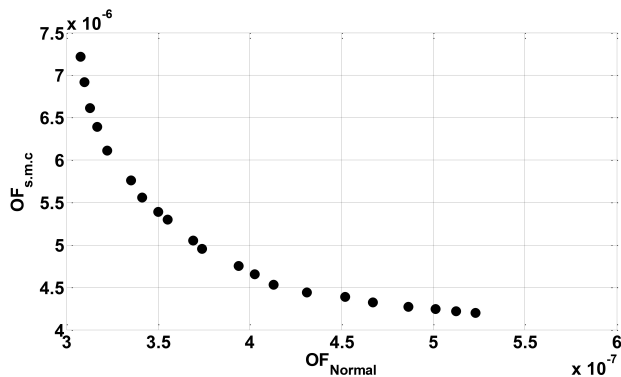


FIG. 7. Pareto optimum results for single PQ meter contingency for 4 PQ meters.

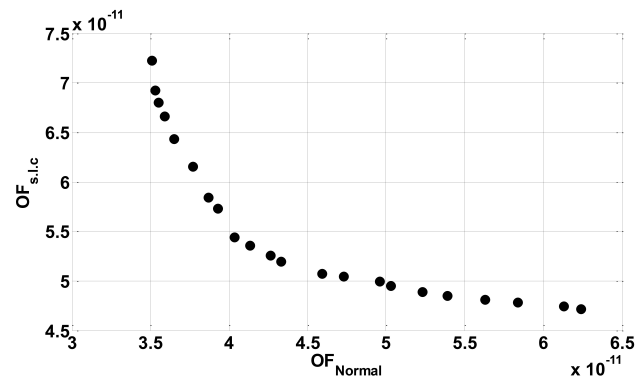


FIG. 10. Pareto optimum results for single line contingency for 6 PQ meters.

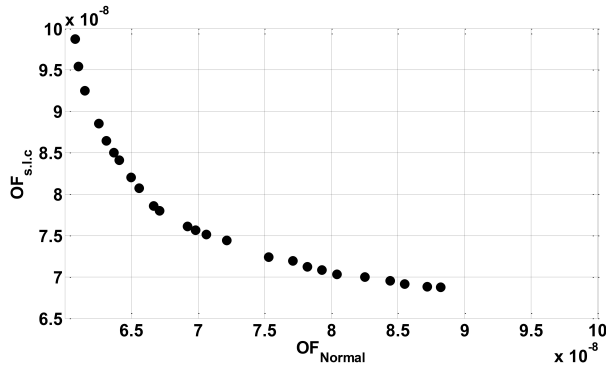


FIG. 11. Pareto optimum results for single line contingency for 5 PQ meters.

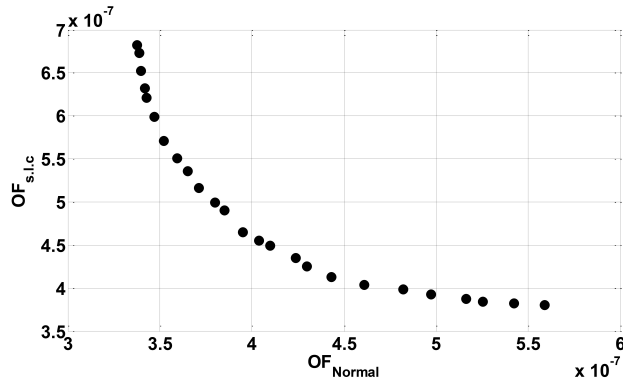


FIG. 12. Pareto optimum results for single line contingency for 4 PQ meters.

than the contingency condition, point A would be more suitable and the best places of these meters are 6, 8, 10, 12 and 13 (Table VII). Conversely, if the contingency condition is more important than the normal condition, point C would be more suitable and the best places of these meters are 3, 4, 5, 7 and 12 (Table VII). Figs. 9-13 show the Pareto optimum results for the single line con-

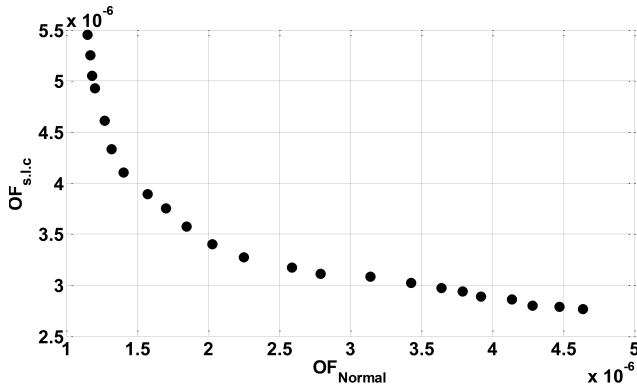


FIG. 13. Pareto optimum results for single line contingency for 3 PQ meters.

tingency for 3, 4, 5, 6 and 7 PQ meters number. Using these curves, the minimum number of meters and their best places at single line contingency can be defined.

C. Future work

In this paper, the PQ meters accuracies are supposed constant. While the meters accuracies are changed during their life time. Thus, consideration of the PQ meters accuracies reduction in the PQ meters placement problem is the issue of the next work of the authors.

VI. CONCLUSION

This paper proposes a methodology to employ SOA algorithm for determining the minimum number of required PQ meters in an HSE. HSE problem is formulated based on WLS method and is solved with SOA algorithm as an optimization exercise. The main impact of the paper is placement of the PQ meters under single meter and line contingencies based on a modified multi-objective Pareto SOA algorithm. By this method, the user is capable of finding the minimum number of meters and their best position by choosing a pre-determined value for the objective function. The simulation results and a comparison with that of a GA application confirm superiority of SOA algorithm and improved HSE accuracy.

REFERENCES

- ¹J. Arrillaga, D. Bradley, and D. Bodger, *Advanced PID control*, New York: John Wiley & Sons, 1985.
- ²L. Ramesh, S. Choudhury, S. Chowdhury, and P. Crossley, "Electrical Power System State Estimation Meter Placement-A Comparative Survey Report," *Electric Power Components and Systems*, Vol. 36, No. 10, pp. 1115-1129, 2008.
- ³C. Madtharad, S. Premrudeepreechacharn, and N. R. Watson, "An optimal measurement placement method for power system harmonic state estimation," *IEEE Transactions on Power Delivery*, Vol. 20, No. 2, pp.1514-1521, 2005.
- ⁴E. Arruda, N. Kagan, and P. Ribeiro, "Harmonic distortion state estimation using an evolutionary strategy," *IEEE Transactions on Power Delivery*, Vol. 25, No. 2, pp. 831-842, 2010.
- ⁵G. Heydt, "Identification of harmonic sources by a state estimation technique," *IEEE Transactions on Power Delivery*, Vol. 4, No. 1, pp. 569-576, 1989.
- ⁶M. Najjar, and G. Heydt, "A hybrid nonlinear-least squares estimation of harmonic signal levels in power systems," *IEEE Transactions on Power Delivery*, Vol. 6, No. 1, pp. 282-288, 1991.
- ⁷A. Kumar, B. Das, and J. Sharma, "Genetic algorithm-based meter placement for static estimation of harmonic sources," *IEEE Transactions on Power Delivery*, Vol. 20, No. 2, pp. 1088-1096, 2005.
- ⁸M. Celik, and E. Liu, "An incremental measurement placement algorithm for state estimation," *IEEE Transaction on Power Systems*, Vol. 10, No. 3, pp. 1698-1703, 1995.
- ⁹M. Hajian, A. Ranjbar, T. Amraee, and B. Mozafari, "Optimal placement of PMUs to maintain network observability using a modified BPSO algorithm," *International Journal of Electrical Power and Energy Systems*, Vol. 33, No. 1, pp.28-34, 2011.
- ¹⁰A. Zonkly, "Optimal meter placement using genetic algorithm to maintain network observability," *Expert Systems with Applications*, Vol. 31, No. 1, pp. 193-198, 2006.

- ¹¹J. Farach, W. Grady, and A. Arapostathis, "An optimal procedure for placing sensors and estimating the locations of harmonic sources in power system," *IEEE Transactions on Power Delivery*, Vol. 8, No. 3, pp. 1303-1310, 1993.
- ¹²H. Ma, and A. Girgis, "Identification and tracking of harmonic sources in a power system using Kalman filtering," *IEEE Transactions on Power Delivery*, Vol. 11, No. 3, pp. 1659-1665, 1996.
- ¹³N. Watson, J. Arrillaga, and Z. Du, "Modied symbolic observability for harmonic state estimation," *IEEE Proceeding- Generation, Transmission and Distribution*, Vol. 147, No.2, pp. 105-111, 2000.
- ¹⁴M. Shafiee Rad, H. Mokhtari, and H. Karimi "An optimal measurement placement method for power system harmonic state estimation," *International Conference and Exposition on Electrical and Power Engineering, Iasi, Romania*, 2012.
- ¹⁵O. Dag, C. Ucak, and O. Usta, "Harmonic source location and meter placement optimization by impedance network approach," *Electrical Engineering*, Vol. 94, No.1, pp.1-10, 2012.
- ¹⁶M. Shafiee Rad, H. Mokhtari, and H. Karimi, "A new algorithm for optimal measurement placement, observability analysis and harmonic state estimation in power systems," *International Power Electronics, Drive Systems and Technologies Conference, Tehran, Iran*, 2013.
- ¹⁷D. Saxena, S. Bhaumik, and S. N. Singh, "Identification of multiple harmonic sources in power system using optimally placed voltage measurement devices," *IEEE Transactions on Industrial Electronics*, Vol. 61, No.5, pp. 2483-2492, 2014.
- ¹⁸A. Dixit, and M. Kaur, "Harmonic source identification with optimal placement of PMUs," *1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, Delhi, India, 2016.
- ¹⁹A. Dixit, and S. K. Jain, "Genetic algorithm based optimal placement of phasor measurement units for harmonic source identification," *7th India International Conference on Power Electronics (IICPE)*, Patiala, India, 2016.
- ²⁰Z. Du, J. Arrillaga, and N. Watson, "Continuous harmonic state estimation of power systems," *IEEE Proceeding- Generation, Transmission and Distribution*, Vol. 143, No. 4, pp. 329-336, 1996.
- ²¹A. Meliopoulos, F. Zhang, and S. Zelingher, "Power system harmonic state estimation," *IEEE Transactions on Power Delivery*, Vol. 9, No. 3, pp. 1701-1709, 1994.
- ²²J. Grainger, and W. Stevenson, "Power System Analysis," *New York: Mc-Graw-Hill*, 1994.
- ²³A. Ketabi, M. R. Sheibani, and S. M. Nosratabadi, "Power Quality Meters Placement Using Seeker Optimization Algorithm for Harmonic State Estimation," *International Journal of Electrical Power and Energy Systems*, Vol. 43, No.1, pp.141-149, 2012.
- ²⁴A. Ketabi, S. M. Nosratabadi, and M. R. Sheibani, "Optimal PMU Placement Based on Mean Square Error Using Differential Evolution Algorithm," *In: IEEE Proc. of the first Power Quality Conference (PQC 2010)*, Tehran, Iran, pp. 1-6, 2010.
- ²⁵E. Babaei, H. Hosseini, and G. Gharehpetian, "Reduction of THD and low order harmonics with symmetrical output current for single-phase ac/ac matrix converters," *International Journal of Electrical Power and Energy Systems*, Vol. 32, No. 3, pp. 225-235, 2010.
- ²⁶C. Dai, Y. Zhu, and W. Chen, "Seeker optimization algorithm for optimal reactive power dispatch," *IEEE Transactions of Power Systems*, Vol. 24, No. 3, pp. 1218-1231, 2009.
- ²⁷C. Dai, W. Chen, Y. Song, and Y. Zhu, "Seeker optimization algorithm: a novel stochastic search algorithm for global numerical optimization," *Journal of Systems Engineering and Electronics*, Vol. 21, No. 2, pp. 300-311, 2010.
- ²⁸A. Ketabi, S. M. Nosratabadi, and M. R. Sheibani, "Optimal PMU Placement with Uncertainty Using Pareto Method," *Mathematical Problems in Engineering*, Vol. 2012, pp. 1-14, 2012.
- ²⁹W. Zhang, and T. Gao, "A minmax method with adaptive weightings for uniformly spaced Pareto optimum

points," *Computers and Structures*, Vol. 84, No. 28, pp. 1760-1769, 2006.

- ³⁰L. Huaiwei, "Power system Harmonic state estimation and observability analysis via sparsity maximization," *IEEE Transactions of Power Systems*, Vol. 22, No.1, pp.15-23, 2007.



han, Iran. His research interests are power system state estimation, energy storage systems, power system planning and operation, and electricity market.



ble, France, in 2001. He has been with the Department of Electrical Engineering, University of Kashan, Kashan, Iran, since 2001, where he is currently an Associate Professor. He has published over 75 technical papers and four books. His current research interests include power system restoration, smart grids, renewable energy, optimization shape of electric machines, and evolutionary computation.



Professor in the Department of Electrical Engineering, Sirjan University of Technology, Sirjan, Iran. His main area of research interests are power system modeling & operation, electricity markets and smart grids.

Mohammad Reza Sheibani

was born in Tehran, Iran, in 1984. He received the B.Sc. degree in electronic engineering from the Isfahan University of Technology, Isfahan, Iran, in 2008, the M.Sc. degree in electrical engineering from the Kashan University, Kashan, Iran, in 2011. Currently, he is Ph.D. candidate in the Isfahan University of Technology, Isfahan, Iran.

Abbas Ketabi

received the B.Sc. and M.Sc. degrees in electrical engineering from the Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran, in 1994 and 1996, respectively, and the Ph.D. degree in electrical engineering jointly from the Sharif University of Technology and the Institut National Poly-

technique de Grenoble, Grenoble, France, in 2001. He has been with the Department of Electrical Engineering, University of Kashan, Kashan, Iran, since 2001, where he is currently an Associate Professor. He has published over 75 technical papers and four books. His current research interests include power system restoration, smart grids, renewable energy, optimization shape of electric machines, and evolutionary computation.

Seyyed Mostafa Nosratabadi

received the B.Sc. degree from the Shahid Bahonar University of Kerman, Kerman, Iran, in 2008, the M.Sc. degree from the University of Kashan, Kashan, Iran, in 2011, and the Ph.D. degree from University of Isfahan, Isfahan, Iran, in 2016, all in electrical engineering. He is currently an Assistant