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Optimal Placement of Phasor Measurement Units to Maintain Complete Observability Considering Maximum Reliability by Non-dominated Sorting Genetic Algorithm-II (NSGA-II)

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Abstract

Ever-increasing energy demand has led to geographic expansion of transmission lines and their complexity. In addition, higher reliability is expected in the transmission systemsdue to their vital role in power systems. It is very difficult to realize this goal by conventional monitoring and control methods. Thus, phasor measurement units (PMUs) are used to measure system parameters. Although installation of PMUsincreases the observability and system reliability, high installation costs of these devices requireplacing them appropriately in proper positions. In this research, multi-objective placement of PMUs with the aims of improving investment and risk costs in power systems is performed along with observability constraint. Then, PMU placement problem is solved as an optimization problem using Non-dominated Sorting Genetic Algorithm-II (NSGA-II). Finally, the performance of the proposed method is tested on standard IEEE 24-bus test system and Roy Billiton IEEE 31-bus test system.

Keywords: Non-dominated sorting genetic algorithm-II, Phasor measurement unit, Reliability, Roy Billiton IEEE 31-bus test system, standard IEEE 24-bus test system.

1. Introduction

In recent years, with the advancement in communication systems, phasor measurement units (PMUs) have become one of the most influencing devices in wide area monitoring protection and control *(*WAMPC) throughout the power systems. By taking the advantage of powerful signal processing technology and global positioning system (GPS), PMUs could solve the related problems. Considering high costs of installing PMUs and having no appropriate communication infrastructure along with this fact that the installed PMUs on each bus can measure voltage and current phasors in all connected lines, placement of the least number of PMUs for system observability is one of the major aims of related projects in this system [1]. In addition to observability and state estimation, phasor units are used to find fault location in transmission lines [2], real-time transient stability of power system [3], protection in large scale, adaptive relaying, thermal observing of transmission lines and voltage stability [4], [5]. Studies in the field of phasorunits' placement considering parameters such as uncertainty in lines and PMUs [6-12] or multi-objective optimization of phasor units' sitting are reported [13]. In

[8], the effect of one or more phasor units' interruption is studied in detail; while, in [9] and [10], simultaneous interruption of lines and phasor unit is considered.In [11], phasor units' placement considering line interruption is formulated. Authors of [13] proposed an optimal model for PMU by considering controlled islanding of power system where two objectives of minimized installed PMUs and maximized measurement redundancy were pursued.Two standard and practical systems were also used to show the effectiveness of the proposed method. And, in [14], a two-step optimization method is suggested to solve optimum PMU allocation problem. First, minimization model was used to get least number of PMUs for complete observability. Then, the simulated annealing is utilized to get on maximized redundancy. Various standard test systems were used for validation purposes. Azizi et al in [15] discussed optimized PMU placement problem considering single contingencies both on lines and PMUs.

To show their method's effectiveness, test wer employed on large-scle standard and practical systems. Observability of buses in a network can improve reliability from several prospective in the case of any interruptions. Observability in a system should be such that if a PMU is out of operation, another PMU can perform its tasks. Otherwise, network observability will be reduced, meaning that the system reliability will be minimized. Network observability should be improved in order to maximize the system reliability. In this paper, *non-dominated* sorting genetic algorithm-II (NSGA-II) *is used for optimal placement of phasor units.*The rest of the paper is organized as follows. In section II, sitting problem of phasor units and power system observability are described. Section III explains the proposed algorithm in detail. In Section IV, simulation results and data analysis are examined. The paper is concluded in Section V.

2. Power System Observability Principles and Phasor Measurement Unit Placement Problem

2.1.Power system observability

A power network is observable when measured data is adequate and all state estimation variables of the network are estimable [6]. In other words, when voltage phasors of network buses are defined, the network is observable. Network observability depends on the number, location and type of measurements. In addition, network topology also influences network observability. Since it is possible to lose measurement data availability in any time or network topology changes, once these phenomena occur, network observability analysis should be implemented. If the network is observable, then state estimation is completed; otherwise, either non-observable parts should be eliminated from state estimation or those parts become observable by virtual measurements [7]. Two general approaches are available for observability analysis: numerical observability and topological observability [8].

2.1.1. Numerical observability

A network is observable when Jacobean Matrix or Measurement Gain Matrix order is equal to unknown states of the network. That is, these matrixes are of complete type. An efficient approach to examine completeness of the order of a matrix is to disintegrate it to upper triangle matrix and lower triangle matrix. Appearance of diagonal zero-elements in this procedure means non-observability of the network. Numerical observability methods for large-scale networks are along with complexities and can be time-consuming. In addition, due to faults occurring in rounding number, it is likely to define actual diagonal zero-elements in a difficult manner.

2.1.2. Topological Observability

With this approach, the network structure and the type of measurements available in each specific part is analyzed. Thus, by detecting an observable bus, one can determine the other observable buses around it. By repeating this procedure, all the network buses are examined. Topological observability methods have higher implementation speed compared to their numerical counterparts and are used highly in software packages. In conventional measurement systems, relating rules to topological observability are numerous due to measurements diversity. So, in PMU-based measurement systems, topological observability is performed more conveniently and fast. This is the reason why this approach is widely used in literature. Various publications have different rules to analyze network observability which are mainly on the basis of observable current and voltage phasors. In this part, three general rules are presented for network observability which are only based on voltage phasor. The network shown in Figure 1 is utilized to describe the rules.

Rule-1:by installing a PMU on a bus, that bus and other buses connected to it will be observable because voltage phasor of the bus to which a PMU is connected is measured directly. In addition, voltage phasors of the connected buses to that bus are calculated via measuring transmission lines' currents and those lines' defined parameters.

Rule-2: if a zero-injection bus and all connected buses to which are observable except one bus, that non-observable bus will be also observable by employing KCL on zero-injection bus.Zero-injection bus is a bus which is only the place of crossing transmission lines and it has no demand and/or supply power. In the network shown in Figure1, if zero-injection bus voltage's phasor is unknown while those of buses 1, 2 and 3 are known, bus-3 voltage phasor is calculated simply by employing KCL on bus-3.

Rule-3: if all buses around zero-injection bus are observable and zero-injection buses themselves are non-observable, all of them will be observable by employing KCL on zero-injection buses.

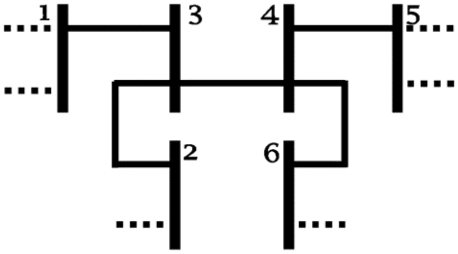

Fig.1. Topological observability

2.2. PMU Placement Formulation

Installed PMU on a bus is able to calculate that bus voltage as well as current phasor of all branches connected to that bus. Thus, by installing PMUs on strategic points of the network, one can obtain required observability data for the system. Two objectives of network observability for state estimation and/or reduction of PMUs are essential. In this paper, phasor unit placement problem is examined in a way that not only required units are minimized, but also sub-objectives such as the maximum frequency of observability and total observability of the network are obtained. Furthermore, placement regarding reliability should be done such that in the case of disturbance, system observability encounters the minimum disturbance.

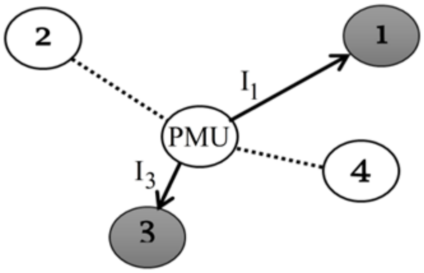

Fig. 2. A PMU’s observability

As shown in Figure 2, one PMU can measure installed bus voltage in phasor mode. It can also determine currents of connected lines to that bus.

Thus, having obtained network Impedance, one can get neighboring bus voltages. In this way, the number of PMUs installed is reduced. In addition, minimizing PMUs should be done in a way that each bus is observable at least one time. Therefore, the objective function can be modelled as follows:

$$\min \sum_{i=1}^{n} w_i \times x_i \tag{1}$$

$$y = Ax \geq b \tag{2}$$

where n denotes the number of system buses, w is the weighting matrix of the buses which can be modified based on the importance of each bus and it is considered as $n*n$ Unit matrix. x, A, and b are described as:

$$A_{n\times n}(i,j) = \begin{cases} 1 \rightarrow i = j \\ 0 \rightarrow othewise \end{cases}$$

$$x_{n\times 1}(i) = \begin{cases} 1 \rightarrow P M \bar{U} \cdot installed \cdot in \cdot bus \cdot i \\ 0 \rightarrow othewise \end{cases} \tag{3}$$

$$b_{n\times 1} = [111...11]^T \tag{4}$$

Inequity (2) is used for full observability of the system. ith row of matrix Ax is the number of bus i's observabilities which should be at least 1. In optimization of Eq. (1), several similar optimum states may be obtained. In other words, optimization of function (1) for a given network may provide a number of busbars where by considering PMUs in these busbars the system would be full observable and the number of obtained PMUs are also equal. So, after finding the number of PMUs by Eq. (1), placement is done by another function to maximize observability considering the constraint of inequality function (2). Thus, among two or more states, a state with full observability of the system is selected.

2.3. Power Systems' Reliability

In conventional power systems' planning studies, network reliability is considered as a constraint. This constraint in combined network studies is taken into account in two deterministic and probabilistic modes [9].

In the former mode, the reliability of power systems is calculated until the outage of at most one or two elements. This approach is used due to its low computations and ease of application in the studies. On the other hand, there exist higher uncertainties in restructured power networks that cannot be considered by deterministic approaches. Thus, because of their higher capabilities in modeling uncertainties in the network, probabilistic approaches are mostly used in reliability studies [9].Following reliability constraint is considered in probabilistic approach:

$$EENSTS\ ,G \leq EENSR \tag{5}$$

EENSTS, G: expected energy not supplied due to interruption of transmission lines and generator in planning studies in restructured environment. Reliability criterion is used as an objective function in order to reach optimal plans that are not only minimized in terms of cost, but also they are optimum for interrupted load cost [9].In this paper, risk cost, reliability, is one objective and installed PMU's reduced cost is another one. Reliability indices are obtained through Monte Carlo approach (the computations regarding Monte Carlo approach is not included to save the space [10]).

2.4. Reliability indices related to distribution system

System related reliability indices which show total behavior of the feeder are used in order to get a more tangible view of the network state [10]:

Expected Energy Not Supplied (not sold):

$$EENS = \sum EENS_i \tag{6}$$

System Average Interruption Frequency Index (SAIFI):

$$SAIFI = \frac{\sum N_i \lambda_i}{\sum N_i} \tag{7}$$

System Average Interruption Duration Index (SAIDI):

$$SAIDI = \frac{\sum N_i U_i}{\sum N_i} \tag{8}$$

Customer Average Interruption Duration Index (CAIDI)

$$CAIDI = \frac{\sum N_i U_i}{\sum N_i \lambda_i} \tag{9}$$

A) Loss of Load Probability (LOLP):

$$LOLP = \sum\nolimits_{Ci \neq 0} pi \tag{10}$$

Pi: probability of ith load with a value of Ci.

B) Expected energy not supplied (EENS):

EENS: Energy shortage in a given time period.

Annual energy shortage can be obtained by:

$$EENS = \sum\nolimits_{Ci \neq 0} Ci \times \ pi \times 8760 \tag{11}$$

whereCi is the value of interrupted power and Pi is related probability. Since EENS is a very important index to study reliability, we used this index in this study.

3. Optimal placement of PMUs considering NSGA-II-based reliability

Nowadays, PMUs are used in power systems for several reasons such as linearization of state estimation equations and speed improvement of control and protection systems. In this paper, multi-objective placement problem of PMUs is done with the aims such as investment cost, risk cost along with observability constraint. Then, placement problem of PMUs is solved in an optimization problem frame by a multi-objective optimization algorithm of NSGA-II. At the end, the performance of the proposed approach is examined on 24-bus network.

3.1.NSGA-II

Main features of the NSGA-II [12]:

1) Defining crowding distance as an alternative feature for practices such as fitness sharing
2) The use selection operator of binary tournament
3) Storage and archive of non-dominated solutions obtained in previous steps (elitism)

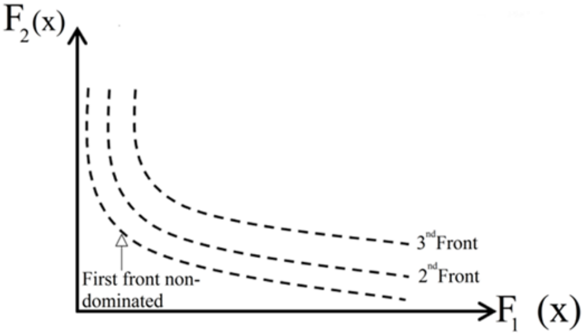

Fig.3. Solution sorting based on Pareto Front [12]

As seen in Figure 3, F2(x) and F1(x) are the spaces for objective functions or the value of objective functions (problem solutions). These solutions are sorted based on their non-domination. The first priorities are optimal solutions of First Pareto Front.

Crowding distance is higher for sporadic spaces than dense ones [12]. In addition, crowding distance is defined only among the members of a front. In Figure 4, solutions are first sorted based on their ranks. Then, based on crowding distance, their solutions are considered better. Our new population is formed [12], since new population size should be equal to that of initial population, a number of solutions should be rejected.

In this paper, first PMUs are placed in random fashion on different buses by NSGA-II. And, objective function includes cost of PMUs. Then, the number of PMUs is calculated considering reliability by NSGA-II. The cost of PMUs is taken into account with regard to their channel [13].The proposed method’s flowchart shown in Figure 3 is designed as follows. After initial placement in a random fashion (the least number of PMUs), observability condition is checked. If the network is not observable, placement is done again. Otherwise, a state is considered in which a disturbance (reliability) occurs in the network. We consider states in which the network continues to be observable when a disturbance takes place. In this state, observability condition is rechecked and the best obtained solutions are stored until reaching given iterations

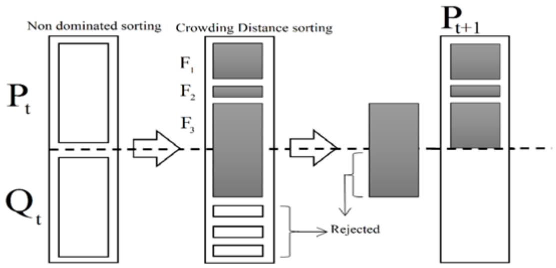

Fig.4.NSGA-II procedure [12]

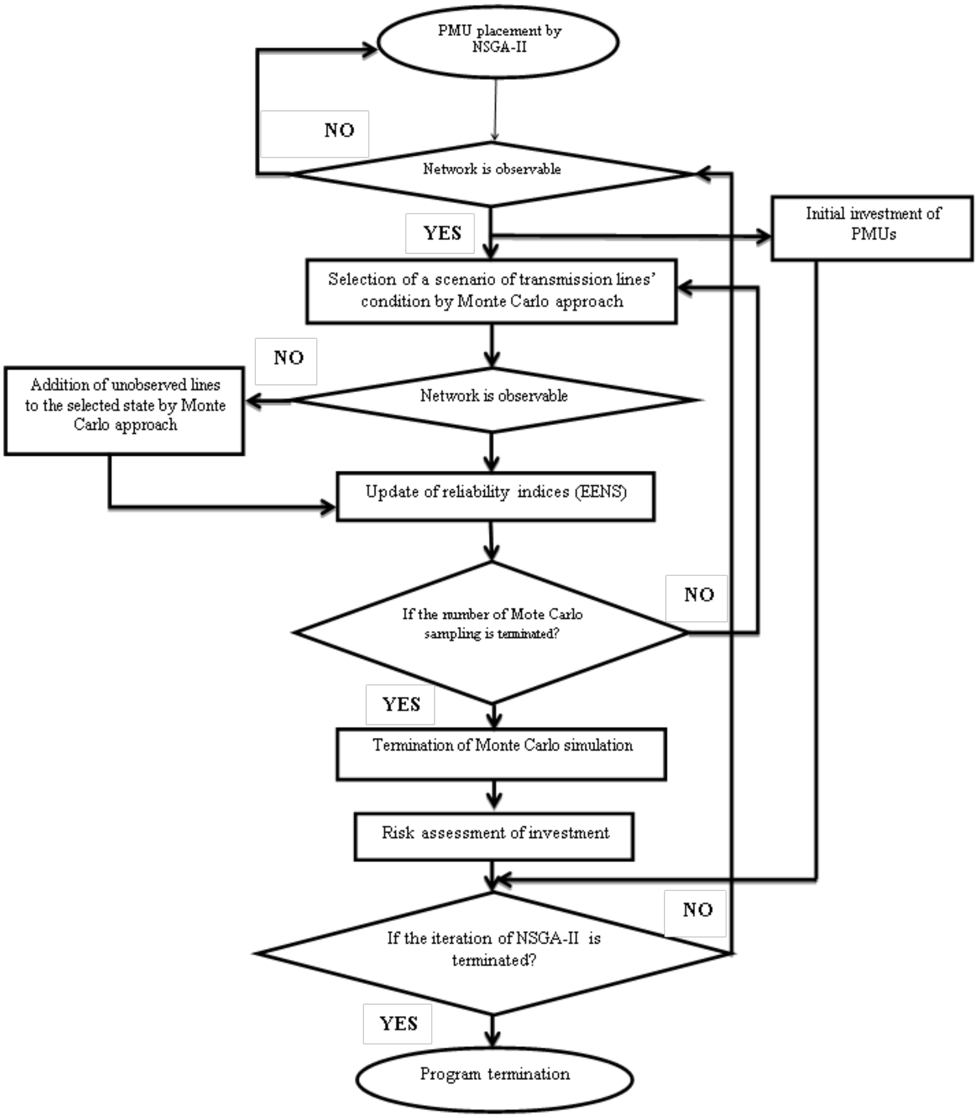

Fig.5. NSGA-II Flowchart

4. Simulation Results and Data Analysis

Figure 6 depicts the standard IEEE 24-bus test system. The data related to this system is given in detail in [11].

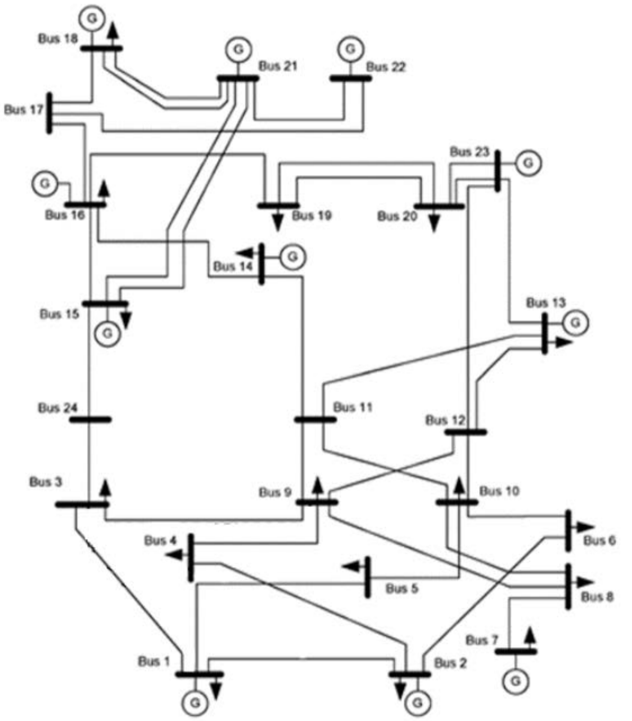

Fig.6. Illustration of standard IEEE 24-bus test system [11]

4.1. Placement location and frequency of PMUs' observabilities for standard IEEE 24-bus test system with/without reliability

As seen in Table I, the installation place of PMUs in two modes with/without reliability is examined. From the results it is seen that it is necessary to install more PMUs in order to have observable network during disturbance occurrence and reduce risk cost. This scenario is useful when the revenue of risk cost reduction difference is more than the difference of the PMU installation cost in terms of the number of PMUs. According to the results and assuming $\mu=0.8$for two objective functions, the installation cost is \$83750 and risk cost is 79.1382 billion dollars

Table I. Installation place of PMUs for IEEE standard 24-bus test system [11]

Network state	Installation place of PMUs
Without reliability	1,2,7,9,10,13,14,17,18,20,22,24
With reliability	1,3,5,6,8,9,10,11,14,17,20,21,22,23, 24

Table 2. Frequency of observabilities for IEEE standard 24-bus test system [11]

Network state	Frequency of observabilities for each bus
Without reliability	2,1,2,1,1,2,1,2,1,1,2,1,2,1,1,1,3,1,1,1,1,1,1,1
With reliability	3,2,4,2,2,2,1,3,2,2,2,1,2,2,2,2,2,1,2,2,2,1,1,1

In Figure 7, the distribution of solutions based on Pareto Fronts is illustrated. Table V provides frequency of observabilities of each bus based on the placement performed. As seen, in the case of considering reliability, the frequency of buses' observabilities increases.

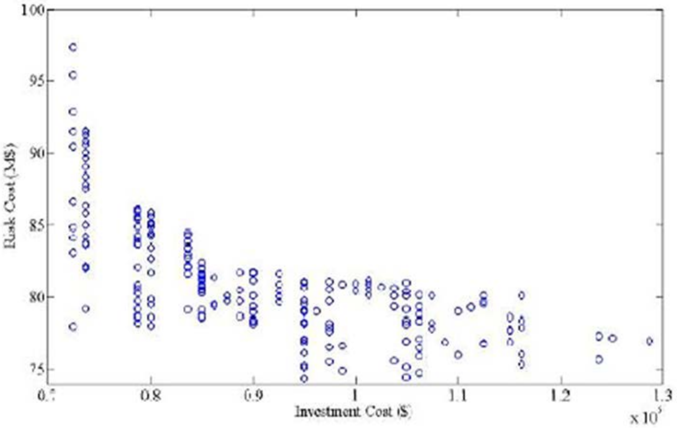

Fig.7. Pareto front distribution for objective functions [11]

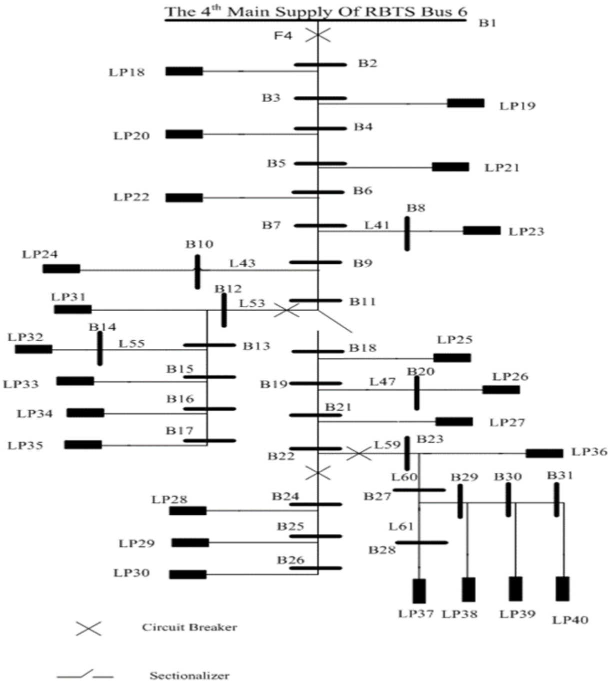

Fig.8. single-line diagram of the studied feeder in a simplified illustration

4.2 Placement location and frequency of PMUs' observabilities for IEEE 31-bus test system with/without reliability

As seen in Table III, the installation place of PMUs in two modes with/without reliability is examined. From the results it is seen that it is necessary to install more PMUs in order to have observable network during disturbance occurrence and reduce risk cost. This scenario is useful when the revenue of risk cost reduction difference is more than the difference of the PMU installation cost in terms of the number of PMUs.

Table 3. Installation place of PMUs for IEEE 31-bus test system

Network state	**Installation place of PMUs**
Without reliability	1,5,9,15,16,18,19,20,22,25,26,27,29,31
With reliability	1,3,5,6,8,11,13,14,17,18,20,24,26,27,31

Table 4. Frequency of observabilities for IEEE 31-bus test system

Network state	**Frequency of observabilities for each bus**
Without reliability	1,1,2,2,1,2,3,1,1,1,1,2,2,1,1,3,1,3,3,2,2,1,2,3,2,2,1,2,2,3,2
With reliability	2,4,1,4,4,4,1,2,2,3,1,3,1,3,2,4,3,4,4,2,3,1,1,3,3,2,4,3,3,4,4

4.2.1. Distribution of Pareto Front for the objectives with/without reliability

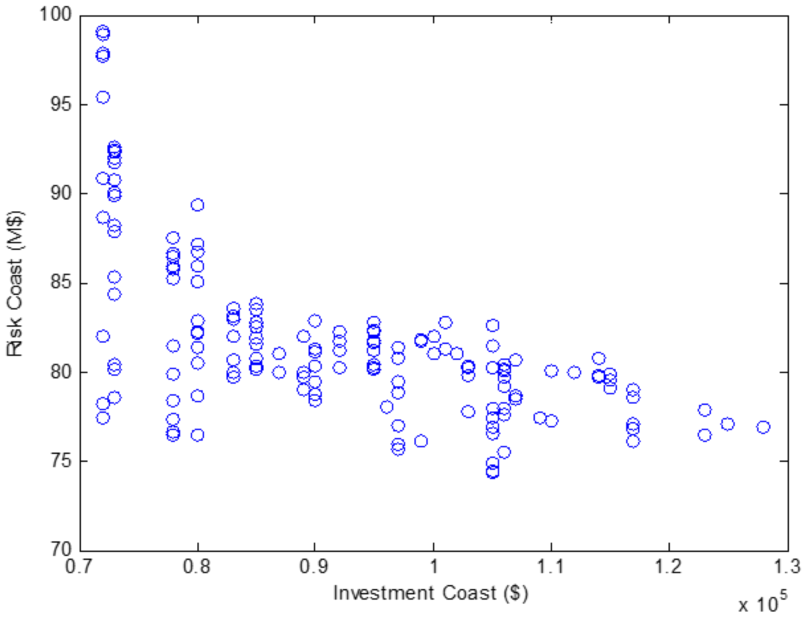

Fig.9. Distribution of Pareto front for objectives with/without reliability

4.2.2. Comparison of 24-bus and 31-bus with/without reliability

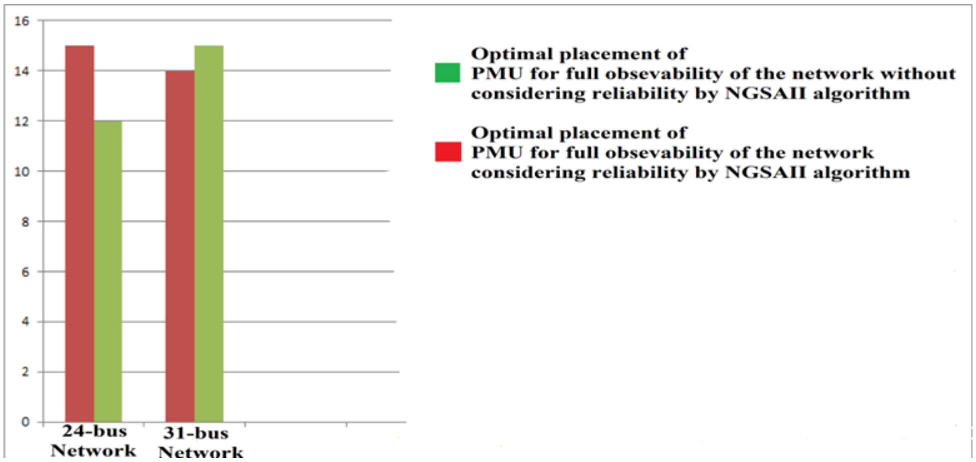

Fig.10. Optimum placement of PMUs with/without reliability with NSGA-II

4.3.Effectiveness of Pareto

Pareto is a concept in economics with applications in engineering and social sciences. This term is named after Wilfred Pareto who employed this concept on the effectiveness of economics and revenue distribution. It is assumed that an initial allocation of goods is performed among a group of unique individuals. A change in different allocation with at least one improved individual condition without worsening the others is called Pareto improvement. An allocation is defined as a Pareto effectiveness or Pareto optimum that no further improvements of Pareto are seen. In Pareto diagram, the denser part is where the optimum solutions are located.

Conclusions

Due to ever-increasing increase of PMUs installed in power systems, application of these tools with higher reliability and reduced installation cost should be prepared for network monitoring. In this paper, the effect of network reliability increase (cost risk reduction) is performed by optimal placement of PMUs considering low installed cost of PMUs. Simulation results revealed that more PMUs are required when a disturbance occurs in order to increase reliability to maintain network observability. And, as previously mentioned, an optimum condition is when the revenue of the difference between the risk cost reduction is higher than that of installed PMUs.

Reference

[1] Ahmadi, A., AlinejadBarmi, Y, Moradi, M. ‘Optimal placement of PMUs using BPSO algorithm’ PSC 2009.

[2] Chin K.P. W Liu, Yu C.S., and Jiang J.A., “Transmission network fault location observability with minimal PMU placement,” IEEE Transaction on Power Delivery, vol. 21, no. 3, pp. 1128-1136, Jul. 2006.

[3] Liu C. W, and Thorp J., “Application of synchronized phasor measurements to real-time transient stability prediction,” Proc. Inst. Elect. Eng. General Transmission Distribution, vol. 142, pp. 355-360, Jul. 1995.

[4] Nguyen T. T., and Nguyen V. L., “Application of wide-area network of phasor measurements for secondary voltage control in power systems with FACTS controllers,” IEEE Power Engineering Society General Meeting, 2005.

[5] Phadke A. G. , “Synchronized phasor measurements in power systems,” IEEE Computer Applications in Power, pp. 10-15, 1993.

[6] Xu, B. Abur, A. “Observability Analysis and measurement placement for system ith PMUs”, Power Systems Conference and Exposition, 2004. IEEE PES, vol. 2, pp. 943- 946.

[7] Chakrabarti, S. Venayagamoorthy, G.K. Kyriakides, E., “PMU Placement for Power System Observability using Binary Particle Swarm Optimization”, Universities Power Engineering Conference, Dec 2008. AUPEC apos;08. Australasian, pp.1-5.

[8] Phadke A.G. and Thorp J. S., Synchronized Phasor Measurements and theirApplications. New York: Springer, 2008.

[9] Choi J, Mount T. D , Thomas R. J. , and Billinton R. , “Probabilistic reliability criterion for planning transmission system expansions,” Generation, Transmission and Distribution, IEEE Proceedings., vol. 153, no. 6, pp. 719 – 727, Nov.2006.

[10] Yang, Gao. Zhijian, Hu. Xixiong, He. Dong, Liu.,“Optimal Placement of PMUs in Power Systems Based onImproved PSO Algorithm”, Industrial Electronics and Applications, 3rd IEEE Conference on 3-5 June 2008, ICIEA, pp.2464-2469.

[11] Khaleghi A., Haj Ebrahimi A., Ghazi ZadehAhsaei M., “PMU placement considering NSGAII-based reliability”. 28th International Power System Conference, November 2-5 2013.

[12] Deb K, “Multi-objective optimization using evolutionary algorithms,” 1st ed., Wiley, 2009.

[13] Gholiha M. M., JalilZadeh S., Abbasi R., “Application of GA-PSO algorithm in optimum placement of PMUs considering busbars’ importance and the number of PMU 2 channels” 7th Technical Protection and Control of Power Systems December 2012.

[14] L.Huang, Y. Sun, J.Xu and etc, "Optimal PUM placement considering controlled islanding of power system," IEEE Trans. Power Syst., vol. 29, no.2 ,pp. 742-754, March 2014.

[15] Akhlaghi, Shahrokh "Optimal PMU placement considering contingency-constraints for power system observability and measurement redundancy", Power and Energy Conference at Illinois (PECI), 2016 IEEE, On page(s): 1 – 7

[16] S.Azizi, A.S.Dobakhshari, S.A.N. Sarmadi and A.M.Ranjbar, "Optimal PMU placement by an equivalent linear formulation for exhaustive research," IEEE Trans. Smart Grid, vol.3, no. 1, pp. 174-182, Mar.2012.