Methods of measurement placement design for power system state estimation

Robert Lukomski, Kazimierz Wilkosz

Abstract
Data redundancy is crucial for the success of state estimation (SE): for achievement of good and reliable estimates, for efficient processing bad data. The paper presents the review of the methods for measurement placement design assuring adequate data redundancy levels for state estimation. For each of the considered methods, the made assumptions, utilized approach, principles and features are analyzed. After the mentioned methods are characterized, results of their comparison are described.

Keywords: Power System, State Estimation, Observability

Introduction

One of the most important routines of real time modelling of power system is state estimation (SE). It processes the obtained set of measurements to estimate the state of a power system. Analog data and circuit breakers statuses are provided by SCADA to Energy Management Systems. Switching device statuses are used by topology processor to determine network connectivity. SE uses analog measurements, network topology data, network parameters, some pseudomeasurements to produce a best estimation of state variables: voltage magnitudes and phase angles. In the conventional SE, measurement set contains voltage magnitudes, active and reactive power flows, active and reactive power injections. The cases, in which current magnitudes belong to this set, are also considered. Utilisation of Phasor Measurement Units (PMU) expands the measurement set for SE with voltage and current phase angles.

The condition of SE solvability is the considered power system to be observable. The observability of a power system depends on the number of measurement data. Location of measuring devices in a power network is also essential. Increasing number of measurements data improves observability. However, increasing number of measurements data is costly, as well. There should be enough measurements available for SE to run when some of the measurements become unavailable due to RTU loss, meter failure, etc. Also measurement system should allow SE to detect bad data due to gross measurement errors etc. In this situation, such determination of the placement of measurements is required to satisfy the following requirements in designing a metering scheme: (i) the requirement of minimal measurement number, (ii) the cost requirement, (iii) the SE-accuracy requirement, (iv) the reliability requirement, (v) the bad data processing requirement.

The paper is aimed at presentig critical review of the methods for measurement placement design from view-point of state estimation. It is realized by: (i) classification of the existing methods for measurement placement design, (ii) characteristics of the distinguished methods, paying special attention to the made assumptions, utilized ideas, their features, (iii) comparative analysis of the methods.

1. Conditions for solvability of state estimation problem

The measurement model used in SE is as follows:

$$\mathbf{z} = \mathbf{h}(\mathbf{x}) + v\,, \tag{1}$$

where: **z** – measurement vector, **x** - state vector, **h**(**x**) – nonlinear measurement function, ***v*** – measurement noise vector.

The vector **x** is determined in the process of minimization of the additional function *J*(**x**), if certain conditions (the observability conditions) are satisfied. Very often, the minimized function has the form:

$$J(\mathbf{x}) = (\mathbf{z} - \mathbf{H}\,\mathbf{x})^T \mathbf{R}^{-1} (\mathbf{z} - \mathbf{H}\,\mathbf{x}), \tag{2}$$

where: $\mathbf{H} = \mathbf{H}(\mathbf{x}) = \partial h(\mathbf{x}) / \partial \mathbf{x}$ – the measurement Jacobian matrix of *h*(**x**), **R** – the measurement covariance matrix.

SE based on utilization of the minimization of the function (2) is called the Weighted Least Squares State Estimation (WLS SE). The solution of WLS SE depends on the matrix **H**(**x**). To have possibility of estimation of the state vector, we should have at least 2*n*–1 measurements, where *n* is number of buses. 2*n*–1 is the number of state variables. One can note, that the mentioned condition is satisfied in this special case when the number of active and reactive power pairs of measurements is *n*–1 and there is additional one voltage magnitude measurement.

The possibility of determination of **x** during the process of minimization of the function *J*(**x**) exists if the number of independent equations, which are utilized for calculation **x**, is equal to the number of elements of **x**, i.e. 2*n* – 1. The formulated condition is the condition of the so-called algebraic observability.

The power system is treated as algebraically observable if matrix **H** meets the condition:

$$\mathrm{rank}(\mathbf{H}) = 2n - 1 \tag{3}$$

The formula (3) is the condition of the solvability of the SE process and then it is the condition of a power network observability.

If active-reactive power measurement pairs are used in a power system, the matrix **H** can be decomposed. Assuming that state vector **x** contains voltage values in polar coordinates (voltage magnitudes and voltage phase angles) and using decomposition by decoupling active power-voltage phase angle (P-δ) quantities from reactive power-voltage magnitude (Q-V) quantities, one can obtain:

$$\mathbf{z}_P = \mathbf{H}_{P\delta}\mathbf{x}_\delta + \mathbf{e}_P\,,\ \mathbf{z}_{QV} = \mathbf{H}_{QV}\mathbf{x}_V + \mathbf{e}_{QV} \tag{4}$$

where: $\mathbf{z}_P$, $\mathbf{z}_{QV}$ – measurement vectors of active powers and reactive powers - voltage magnitudes respectively; $\mathbf{e}_P$, $\mathbf{e}_{QV}$ - vectors of measurement errors of active power and reactive power - voltage magnitude respectively; $\mathbf{H}_{P\delta}$, $\mathbf{H}_{QV}$ - measurement matrices related to $\mathbf{x}_\delta$; $\mathbf{x}_V$ respectively.

Using the P-δ model, the power network is algebraically observable if the following equation is fulfilled:

$$\mathrm{rank}(\mathbf{H}_{P\delta}) = n - 1 \tag{5}$$

For the Q-V model the algebraic observability condition is as follows:

$$\mathrm{rank}(\mathbf{H}_{QV}) = n \tag{6}$$

The power system is defined to be numerically observable if an estimation process can be performed with success for a state estimate $\hat{\mathbf{x}}$ from a flat start (all initial node-voltage magnitudes have nominal values and voltage angles are equal to zero): $\mathbf{x}_\delta = 0$, $\mathbf{x}_V = \mathbf{x}_{V0}$, where $\mathbf{x}_\delta$ - voltage phase angle vector ((n–1)×1); $\mathbf{x}_V$ - voltage magnitude vector (n×1), $\mathbf{x}_{V0}$ - vector of voltage magnitudes equal to nominal values.

During the state estimation process, a power system is treated as a set of nodes which are connected each other by branches. Thus, analyzing features of a power system it is possible to consider suitably-defined graphs instead of matrices. Such an approach, which assumes analyzing the so-called topological observability, is utilized, as well.

Topological observability concept uses graph representing a measurement placement. One of the results of considerations presented in [1] is, that a power network is topologically observable with respect to a measurement set consisting of one voltage magnitude measurement and paired P, Q measurements if, and only if, there exists a spanning tree of the power network of full rank, i.e. of the rank equal to n – 1.

Designing a measurement system, it is important to eliminate the possibility of occurrence of critical measurements. The critical measurement is a measurement whose removing from the measurement vector **z**, results in loss of power system observability.

2. Methods for determination of conventional measurements placement

2.1. Methods enabling only measurement-number reduction

Method of Abur and Gou: The method is for multiple measurement placement [2]. This method allows simultaneous placement of a minimal set of pseudomeasurements that make the system observable. It utilizes idea of the numerical observability. During performed analysis the rank deficiency of the gain matrix $\mathbf{G}=\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H}$ is considered. The used approach enables to extract the information about observable islands from the test matrix **W** being a result of transformation of the matrix $\mathbf{L}^{-1}$. The matrix **L** is obtained by decomposition of the gain matrix **G** into its Cholesky factors $\mathbf{L}\ \mathbf{D}\ \mathbf{L}^T$, where the diagonal factor **D** may have one or more zeros on its diagonal. The dimension of the test matrix **W** is equal to the rank deficiency of the gain matrix **G**. Using the matrix **W**, it is possible to determine the locations and types of the pseudo-measurements that will render the power system observable. The method assumes utilization of a small-dimension test matrix. This fact leads to the fast non-iterative computations. The method was tested on the IEEE 14- and 30-bus test systems.

Method of Madtharad and Premrudeepreechacham: The method utilizes the condition number of the measurement Jacobian matrix [3]. At the beginning, the mentioned matrix is formed for all possible locations of measurements. Seeking the best measurement placement, each possible location is temporarily eliminated one at a time and then the condition number of the corresponding measurement matrix is calculated. The location that has a minimum condition number is eliminated. The presented procedure is repeated until the number of row of the measurement matrix (i.e. the location of mesurements) is equal to the number of state variables. The disadvantage of the method is relatively large time of calculations. Determination of the condition number requires possession of singular values of the measurement Jacobian matrix. The use of singular value decomposition is significantly slower than solving the normal equations and requires more storage, but is less susceptible to round-off errors. Performance of the method was evaluated on the IEEE 14-bus test system.

2.2. Methods enabling measurement-number reduction and satisfying one of other requirements in designing a metering scheme

Method of Park et al.: The method is the addition-elimination method of measurement installation cost minimization subject to a power system accuracy [4]. For the optimal selection of measurement distribution, the state estimation accuracy is analyzed. The performance index of measurement system is established by calculating the expected state estimation accuracy with the probabilistic consideration of measurement failures. The special measurement sensitivity indices are introduced to determine the measurement to add to or to eliminate. The method uses some statistical quantities which are difficult to assess in practice The addition-elimination process is combinatorial and requires much computational effort for real large-scale power systems. The numerical tests were performed, using the IEEE 6- and 14-bus test systems.

Method of Celik and Liu: The method is based on the concept of an incremental measurement placement [5]. Minimization of the state estimation variance to achieve the best accuracy is used as a goal in optimization process. After identifying observable islands by using numerical observability testing of gain-matrix rank, the covariance matrix $\mathbf{C}=(\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H})^{-1}$ for the Weighted Least Absolute Value State Estimation (WLAV SE) is calculated. Critical and leverage point measurements are identified and the rank list of buses with low accuracy is created, using the diagonal of **C**. Candidate measurements for a selected bus are found and the **C** matrix is re-calculated with use of one of candidate measurements. A measurement with the smallest c_{ii} value, and which is not a leverage point, is appended to the original measurement set. The measurement set extension is continued until achieving assumed state estimation accuracy. The method is heuristic in nature and requires defining of thresholds values for candidate measurements. Performance of the method is presented for the IEEE 30-bus test system.

Method of Abur and Magnago: The method ensures an observability in the case of branch outages in a power system [6]. In the first step, one utilizes a linear programming based measurement placement method, whose objective is to find a minimum number of additional measurements to make the system observable and robust to branch outages. WLAV SE is considered for this purpose. In the second step, an optimal number and types of measurements are found to ensure observability in case of single branch outages. The topological observability concept is used to identify the candidate measurements. In the case of a branch outage, the measurement localisation is re-arranged to ensure spanning tree existence in the measurement graph. The installation cost is also considered. Performance of the method was tested on the IEEE 14-, 30- and 57-bus test system. Modification of the presented method with use of the numerical observability instead of the topological observability can be found in [7].

Method of Yehia et al.: The objective of the method is minimisation of RTU number under constraints which are observability, absence of critical measurements, robustness to loss of any measurement device [8]. First, all the buses are arranged in set Z_0 Removing the distinguished bus from the set Z_0 means that RTU is removed from this bus. Each time the described operation is made, satisfaction of the mentioned constraints is checked. If any of these constraints is violated, then the bus is placed in set Z_d and RTU is placed at this bus. At the end, in the set Z_d there are these buses in which there must be RTUs to have the considered constraints satisfied.

The algorithm guarantees absence of critical measurements and observability in case of loss information from single RTU. Performance of the method was tested using the IEEE 30-bus test systems and the 69-bus and 86-branch practical system.

Method of Huang et al.: The method allows minimising the number of RTU's under the constraint that the system is observable in such cases as: a single branch outage, single measurement or RTU loss [9]. In the method, the topological observability concept with analysing and modification of a measurement graph is used. The method is the two-stage method. In the first stage, based on the measurement graph, the measurements are placed in a power system as follows: injection measurement pairs on the buses located in the loops, flow measurement pairs on the radial branches, voltage magnitude measurements on buses. In the second stage, in order to reduce the number of RTUs, the injection measurement pairs on each of the buses, to which only two branches are connected (these branches are in the same loop) are replaced by flow measurement pairs on those two branches. As a result, the number of RTUs is reduced and the minimum number of measurements and the observability constraints are maintained. Numerical tests of the method were performed using the IEEE 30-bus test system. A modification of the method can be found in [10].

Method of Ongsakul and Kerdcheun: The method utilises genetic algorithms to design optimal measurement placement [11].The problem of optimal measurement placement is solved, taking into account a single measurement pair loss contingency. The objective function of measurement placement is to minimise the installation cost of those measurements placement, which is directly dependent on the number of measurements, subject to the observability constraints. An individual chromosome represents the types of measurements and their positions in a power network. Performance of the method was tested on the IEEE 10-, 14-, 30- 57- and 118-bus test systems. When genetic algorithms are used, reaching optimal solution is not guaranteed and for real-size power networks, many computational efforts are required to meet the solution.

2.3. Methods enabling satisfaction more than two requirements in designing a metering scheme

Method of Sarma et al.: The method consists of the following phases: (i) placement of measurements in a power network until redundancy defined as number of measurements to number of state variables ratio is equal or greater than 1, (ii) testing the power system for observability; (iii) placement of additional measurements to remove critical measurements, (iv) placement of additional measurements to maintain the observability under losing of part of measurement set [12]. Costs of measurement equipment are also taken into consideration. The performance of the method depends on initial distribution of measurements. The obtained results may not be optimal. However, the method guarantees good covering of a power system by measurement and maintaining observability in case of single measurement device failure. The method was tested on the IEEE 14-, 30-, 57-bus test systems and the 65-bus and 77-branch practical systems.

Method of Baran et al.: The method consists of three following stages: (i) determination of basic measurement localisation that will satisfy the accuracy and minimum cost requirements, using a combinatorial search method, (ii) identification of the minimum additional measurements that are needed to satisfy the reliability requirements (robustness to losing the RTU's), (iii) identification of the minimum set of additional meters that are needed to improve the local redundancy of the metering scheme and hence satisfy the bad data processing requirements [13]. The method was implemented by using the IEEE 14-bus test system.

Method of Wu et al.: The method is an optimal measurement placement method, consisting of the following steps: (i) placement of the branch power flow and bus voltage magnitude measurements, (ii) placement of the bus injection power flow measurements in selected substations to backup the branch measurements and to increase the robustness of the measurement placement scheme against the loss of observability [14].

To preserve the network observable under the loss of any single measurement, each critical branch power flow measurement, is converted to a non-critical measurement by placing a bus injection measurement at either end of the branch on which the mentioned branch power flow measurement is placed. To maintain the network observability against the loss of any single RTU, in every substation, that has measurements, a backup RTU is installed. The method is fast and a budget-saver. It was tested on the IEEE 14- and 30-bus test system.

3. Methods for localization of PMU

Method of Phua and Dillon: The method is based on reduction in entropy to site new meters for SE [15]. Assuming Guassian distribution of measurement errors and utilization of WLS SE, the Shannon entropy function value is calculated. Simulations performed with use of the IEEE 300-bus test system reveal strong correlation between entropy reduction and both local bus angle variance reduction and original bus angle variance [16]. Effect of the PMU placement is very “local”, and will significantly improve overall estimation accuracy only when the accuracy of the ‘local’ state is poor.

Method of Baldwin et al.: The method is based on the original approach to determining an optimal measurement placement [17]. A graph theoretic procedure provides an initial PMU placement set, that makes the system observable. This initial set constitutes the upper limit for the bisecting search. This bisecting search determines the number of PMUs considered at each step. Then, for a given number of PMUs, the simulated annealing-based method attempts to identify the PMU placement set which minimises the unobservable region of the power system. In successive steps, the PMU placement set with a minimum number of PMU for which a power system is observable, and the PMU placement set with a maximum number of PMU for which a power system is still unobservable are determined. If for the mentioned PMU placement sets, the difference between the number of installed PMUs are equal to 1, then the first PMU placement set is the solution of the considered problem. The method was tested on systems ranging in size from 14 to 265 buses.

Method of Dongjie et al.: In [18], utilisation of the depth first search technique or the graph theory based procedure is considered as a first step towards subsequent optimising techniques, i.e. simulated annealing, tabu search or genetic algorithms, which optimise PMU distribution in a power network. Especially, for larger problems, tabu search and simulated annealing produce better solutions than a genetic algorithm. In addition, the genetic algorithm runs take more time than it is in the case of the remaining techniques. The IEEE 14- and 39-bus test systems were used to evaluate the performance of mentioned techniques.

Method of Abur and Xu: The method solves the optimisation problem of measurement placement by application of an integer programming [19]. In the method, different cases of the PMU placement with or without conventional measurements (branch flows and bus injections) are taken into account. The method was tested with use of the IEEE 14-, 57- and 118-bus test systems.

Method Rakpenthai et al.: The method assumes that the entire power network is decomposed in non-overlapping observable sub-networks [20]. Different sub-networks can be connected each other by tie-lines. Independently for every sub-network the PMU placement is considered, using one of the known method. In the paper [20], especially the method from [3] is recommended because of its simplicity and relatively small size of the parts of the entire power network, for which the problem of measurement placement is solved. The authors propose the measurement placement obtained from the characterised procedure to be rearranged to minimise the number of placement sites by the heuristic algorithm, described in [20]. Since the size of the measurement-placement problem solved for one sub-network is relatively small, the used decomposition improves the computational time required to obtain types and positions of the available measurements compared to the method from [3] where the whole network is considered. Performance of the method was tested on the IEEE 14-, 30-, 118-bus test systems.

Method of Hurtgen et al.: The method places measurement devices on the network by considering the importance of the nodes in a power network [21]. It utilizes the PageRank algorithm for importance internet page analysis to determine PMU distribution. Using a recursive computational method, the PageRank algorithm associates a numerical value with each node which describes the relative importance of this node. The method was tested on the IEEE 14-, 57- and 118-bus test systems.

Conclusion

The optimal meter placement problem can be formulated by an optimization approach to minimize a chosen performance index subject to certain system constraints. Earliest measurement localization methods use sufficient measurement redundancy to maintain observability as a goal. However, installation costs, accuracy and reliability of SE with respect to designed measurement system should be treated also as important factors.

Features of the considered methods for measurement placement for SE are presented in Tab. 1.

Reduction of measurement devices number as a goal is used for all the presented methods. It usually results in reduction of installation costs. However, in practice, the measurement data are gathered and send to the SE by channels of RTUs and to cut the costs the measurement should be so distributed to reduce the number of these units.

Few designing methods incorporate constraints resulting from reliability. Efficient bad data processing in SE requires usually sufficient measurement redundancy to detect and eliminate gross measurement errors. Many methods are focused on maintenance of observability subject to reduction of measurement number. “Quality” of measurement set should also be investigated by exploring accuracy of SE and dealing with bad data with respect to the measurement number, type and localization generated by placement method.

Limitation of conventional optimization techniques results in utilization of heuristic methods based on topological or numerical observability concept and meta-heuristics: genetic algorithms, tabu search, simulated annealing or its combinations which are utilized to search optimal solution.

References

[1] KRUMPHOLZ G.R., CLEMENTS K.A., DAVIS P.W.: Power system observability: a practical algorithm using network topology. IEEE Trans. on PAS, Vol. 99, No. 4, 1980, pp. 1534–1542.

[2] ABUR A., GOU B.: An improved measurement placement algorithm for network observability. IEEE Trans. on PS, Vol. 16, No. 4, 2001, pp. 819-824.

[3] MADTHARAD C., PREMRUDEEPREECHACHAM S.: Measurement placement method for power system state estimation. Part I. IEEE Power Engineering Society General Meeting, Vol. 3, 2003, pp. 1629-1632.

[4] PARK M., MOON Y. H., CHOO J. B., KWON T. W.: Design of reliable measurement system for state estimation. IEEE Trans. on PS, vol. 3, no. 3, 1988, pp. 830-836.

[5] CELIK M.K., LIU W-H. E.: An Incremental measurement placement algorithm for state estimation. IEEE Trans. on PS, Vol. 10, No. 3, 1995, pp. 1698-1703.

[6] ABUR A., MAGNAGO H.: A unified approach to robust meter placement against loss of measurements and branch outages, IEEE Trans. on PS, Vol. 15, No. 3, 2000, pp. 945-949.

[7] ABUR A., MAGNAGO H.: Optimal meter placement for maintaining observability during single branch outage. IEEE Trans. on PS, Vol. 14, No. 4, 1999, pp. 1273-1278.

[8] YEHIA M., JABR R., EL-BITAR I., WAKED R.: A PC based state estimator interfaced with a remote terminal unit

placement algorithm. IEEE Trans. on PS, Vol. 16, No. 2, 2001, pp. 210-215.

[9] HUANG G. M., LEI J., ABUR A.: A heuristic approach for power system measurement placement design. IEEE ISCAS, Vol. 3, 2003, pp. 407-410.

[10] HUANG G. M., LEI J.: A topological measurements and RTU's design against contingency. IEEE ISCAS, Vol. 5, 2004, pp. 920-923.

[11] ONGSAKUL W., KERDCHEUN T.: Optimal measurement placement with single measurement loss contingency for power system state estimation using refined genetic algorithm. Conference on Energy for Sustainable Development: Prospects and Issues for Asia, Phuket, Thailand, March 1-3, 2006, pp.1-3.

[12] SARMA N., RAJU V., RAO K.: Design of telemetering configuration for energy management systems. IEEE Trans. on PS, Vol. 9, No. 1, 1994, pp. 381-387.

[13] BARAN M. E., ZHU J., ZHU H., GARREN K. E.: A meter placement method for state estimation. IEEE Trans. on PS, Vol. 10, No. 3, 1995, pp. 1704-1710.

[14] WU, Y., KEZUNOVIC, M., KOSTIC, T.: Cost Minimization in Power System Measurement Placement. International Conference on Power System Technology (PowerCon 2006), Chongqing, China pp.1 - 6.

[15] PHUA K., DILLON T.: Optimal choice of measurements for state estimation. The 1977 Power Industry Computer Applications Conference, 1977, pp. 431-441.

[16] NOVOSEL D. ED.: Eastern interconnection phasor project. Part II. Targeted application: State estimation. KEMA report, 2006.

[17] BALDWIN T. L., MILI L., BOISEN M. B., ADAPA R.: Power system observability with minimal phasor measurement placement. IEEE Trans. on PS, Vol. 8, No. 2, 1993, pp. 707-715.

[18] DONGJIE X., RENMU H., PENG W., TAO X.: Comparison of several PMU placement algorithms for state estimation. The 8th IEE Int. Conference on Developments in Power System Protection, Vol. 1, 2004, pp. 32-35.

[19] ABUR A., XU B.: Observability analysis and measurement placement for systems with PMU's. IEEE PES Power Systems Conference and Exposition, Vol.2, 2004, pp. 943 - 946 .

[20] RAKPENTHAI C., PREMRUDEEPREECHACHARN S., UATRONGJIT S., WATSON N. R.: Measurement placement for power system state estimation using decomposition technique. Electric Power Systems Research, Vol. 75, No. 1, 2005, pp. 41-49.

[21] HURTGEN M., PRAKS P., ZAJAC P., MAUN J.-C.: Measurement placement algorithm for power system state estimation using PageRank - Case Studies. Proc. of Risk, Quality and Reliability, Ostrava, Czech Republic, 2007, pp. 75-81.

Dr Robert Lukomski

Wroclaw University of Technology
Electrical Engineering Faculty
Electrical Power Engineering Institute (I-8)
Wybrzeze Wyspianskiego 27
50-370 Wroclaw, Poland
Fax: +48 71 3202656
E-mail: robert.lukomski@pwr.wroc.pl

Prof. Kazimierz Wilkosz, Ph.D., D. Sc.

Wroclaw University of Technology
Electrical Engineering Faculty
Electrical Power Engineering Institute (I-8)
Wybrzeze Wyspianskiego 27
50-370 Wroclaw, Poland
Fax: +48 71 3202656
E-mail: kazimierz.wilkosz@pwr.wroc.pl

Method	Objectives					Solving method
	N	R	A	C	BD	
Conventional measurements						
Abur and Gou	+					Numerical observability based method
Madtharad et al.	+					Heuristic sequential eliminations
Park et al.	+		+			Heuristic, addition-elimination
Celik et al.	+		+			Addition-elimination, heuristic analysis of statistical quantities
Abur and Magnago	+	+				Topological/numerical observability based method
Yehia et al.	+	+				Heuristic, addition-elimination
Huang et. al.	+	+				Graph theoretic based heuristic method
Ongsakul et al.	+			+		Genetic algorithm
Sarma et al.	+	+		+		Heuristic, addition-elimination
Wu et al.	+	+		+		Graph theoretic based heuristic method
Baran et al.	+	+	+	+	+	Group optimization methods
PMU						
Phua and Dillon	+		+			Entropy function
Baldwin et al.	+					Dual search, genetic algorithms
Dongjie et. al.	+					Genetic algorithms, simulated annealing, tabu search
Abur and Xu	+					Linear, integer programming
Rakpenthai et al.	+					Heuristic sequential eliminations
Hurtgen et al.	+					PageRank algorithm

Tab. 1. Features of the measurement placement methods. Objectives: N- measurement number reduction, R – reliability, A – SE accuracy, C – investment costs, BD – bad data processing.