Cost Minimization in Power System Measurement Placement

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***Abstract*-- This paper presents an innovative method for the placement optimization of power system measurement. The goal of the method is to minimize the number of necessary measurements and required Remote Terminal Units (RTUs), subject to the system observability requirements. Three types of measurements are considered: bus voltage magnitude measurements, branch power flow measurements and bus injection power flow measurements. A fast algorithm for building up the spanning tree in the observability analysis is developed and applied for the measurement placing process. The algorithm consists of two steps. First, the branch power flow and bus voltage magnitude measurements are placed. The spanning tree of the network is selected by choosing the branches that are connected to the buses with large numbers of incident branches. Once the spanning tree is decided, branch power flow measurements are placed on its branches and installed into as few substations as possible. A voltage measurement is also placed in a substation that already has at least one branch measurement installed. Second, the bus injection power flow measurements are placed in selected substations to backup the branch measurements and add up to the robustness of the measurement placement scheme against the loss of observability. The proposed method can be used as a very helpful tool in planning power network measurement systems.**

***Index Terms*—measurement placement, observability, spanning tree, state estimation**

I. Introduction

A State Estimator (SE) is an essential application in the Energy Management Systems (EMS). The task of the SE is to estimate the system states, namely, the bus voltage magnitudes and phase angles, using the available measurements in the system. The measurement data are gathered and made available to the SE by Remote Terminal Units (RTUs).

In order for the SE to work, an important requirement is that the network must be observable. The network observability analysis determines if a state estimation solution for the entire system can be obtained using the available set of measurements. Network observability is a very important component in the EMS and it is usually analyzed before the execution of state estimation.

The network observability is determined by both the number of measurements and location of their deployment in the network. Usually, the more available measurements, the more likely that the system is observable and the system states can be estimated. The locations of the measurements also play an important role in deciding the network observability. A well designed measurement placement method can make the network observable using much fewer devices. The network observability may also change due to the changes in network topology or loss of measurements; therefore it is also desirable to have a measurement placement scheme that can endure certain types of network contingencies.

As usual, there is always a trade off between the cost and performance as the placement of measurements is considered. Reference [1] uses a general criterion to systematically eliminate some of the measurements in the system to obtain an optimal set of various measurements. Reference [2] compares the advantages and disadvantages of various methods of optimal measurement placement. References [3-4] present ways to minimize the investment cost while improving the accuracy of the state estimation. Our paper, similar to references [5-7], focuses on the issue of reducing the overall cost of placing measurements, subject to the observability requirements of the network. Reference [5] chooses the location of RTUs by comparing the total number of incident lines/transformers in substations and picking up substations with the largest number first. Reference [6] uses a similar method and puts RTUs on all substations in the network first, then removes the ones that are in substations with low number of incident lines/transformers until the observability constraints are not met. Reference [7] uses a two-stage method to reduce the number of RTUs by placing the measurements first and then adjusting some of the measurement types and locations.

In this paper, a new topological method is proposed. The philosophy of the new method is to install branch measurements in substations that have more branches, and then expand the observable area in the network step by step as the branch measurements link the observable buses to the unobservable ones. This makes it more cost effective with respect to the number of necessary physical measurement devices.

The proposed method has been applied to the IEEE 14-bus and 30-bus system. Test results show the advantage and demonstrate the effectiveness of the proposed approach and

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prove that it is fast and indeed a budget-saver.

The paper is organized as follows: section II is a brief introduction to the concept and methods of network observability analysis; section III explains in detail the algorithm of the proposed method. Section IV lists the test results and shows the advantage of the proposed method over other algorithms. Conclusions are presented in section V.

II. Network Observability Analysis

The power system state estimation problem can be described as:

$$\mathbf{z} = \mathbf{f}(\mathbf{x}), \tag{1}$$

where x is the state vector, containing the voltage magnitude and phase angles of buses; **z** is output vector, containing the measurements; **f** is the output matrix, which represents the relationship between the measurements and the state vector.

First-order Taylor approximation of (1) yields:

$$\mathbf{H} \cdot \Delta\mathbf{x} = \mathbf{z} - \mathbf{f}(\mathbf{x}^0) = \Delta\mathbf{z}\ , \tag{2}$$

where $\mathbf{H} = \dfrac{\partial \mathbf{f}(\mathbf{x})}{\partial \mathbf{x}}$, evaluated at some $\mathbf{x}^0$; $\Delta\mathbf{x} = \mathbf{x} - \mathbf{x}^0$.

Equation (2) relates all existing measurements to the state variables, using the first-order Taylor approximation. An estimate for $\Delta\mathbf{x}$ can be obtained as long as the rank of **H** is equal to the dimension of $\Delta\mathbf{x}$ or **x**. Therefore, the necessary and sufficient condition for a power system to be observable is:

$$\text{rank}\ \mathbf{H} = n\ , \tag{3}$$

where n is the dimension of the state vector **x**.

It should be noted that the system observability is independent of the branch parameters as well as the operating state of the system. So, all system branches can be assumed to have an impedance of $j1.0$ per unit (p.u.) and all bus voltages can be set equal to 1.0 p.u. for the purpose of observability analysis. It can be shown that in such a power system network, **H** can be calculated by:

$$\mathbf{H} = \mathbf{M} \cdot \mathbf{A}^T\ , \tag{4}$$

where **M** is the measurement-branch incidence matrix,

$$\mathbf{M}_{ij} = \begin{cases} 1 & \text{If measurement } i \text{ is incident to bus } j \text{ at the "from end".} \\ -1 & \text{If measurement } i \text{ is incident to bus } j \text{ at the "to end".} \\ 0 & \text{If measurement } i \text{ is not incident to bus } j. \end{cases}$$

A is the branch-bus incidence matrix,

$$\mathbf{A}_{ij} = \begin{cases} 1 & \text{If branch } i \text{ is incident to bus } j \text{ at the "from end".} \\ -1 & \text{If branch } i \text{ is incident to bus } j \text{ at the "to end".} \\ 0 & \text{If branch } i \text{ is not incident to bus } j. \end{cases}$$

The method that uses (3) and (4) to decide whether a network is observable is called the *numerical method*.

It is shown that the observability analysis can also be carried out by using a *topological method* [6]. If a spanning tree, i.e., a tree that reaches every bus in the system, can be formed such that each branch of this tree contains a power flow measurement, then the phase angles at all buses can be determined, i.e. the system will be fully observable. The available measurements should be assigned to the branches according to the following rules:

1) If the branch flow is measured, the branch is assigned to its flow measurement.
2) If an injection is measured at a terminal node of a branch, the branch can be assigned to that injection.
3) Once a branch is assigned to a measurement, it can not be assigned to any other measurement.

The essential steps of the algorithm can be summarized as follows:

1) First assign all the flow measurements to their respective branches.
2) Then, try to assign the injection measurements in order to reduce the existing forest by merging existing trees. Note that there is no way to predict the correct sequence for processing injections. Implementation of the method requires proper back-up and re-assignment of injections when necessary.

III. Cost Minimization in Measurement Placement

The cost of measurement placement for the purpose of state estimation usually comes from the following:

1) Measurement transducers. These devices are needed to obtain measurement data from the measurement apparatus such as current transformers (CTs), voltage transformers (VTs), and CB status measurements relays. Each measurement point needs to be assigned a transducer, so that the parameter being measured can be converted to a standard 4-20mA DC signal.
2) RTUs. An RTU needs to be installed in a substation, if one or more measurements from this substation need to be transmitted to the EMS. An RTU is capable of gathering the DC signals converted by the transducers from both analog measurements (such as power flows and voltage magnitudes) and digital measurements (such as CB contacts). Each measurement needs to be assigned a separate input channel.

It can be seen that the cost of state estimation measurements is decided by the number of measurements and RTUs. To minimize the cost associated with measurement placement, the least number of measurements should be used. Also, these measurements should appear in as few substations as possible, so that the number of RTUs can also be reduced. Currently, transducers can be built at fairly low cost [5]. The price of transducers is much lower than the price of an RTU. Therefore, reducing the number of necessary RTUs is especially important in the cost minimization.

There are three options regarding the placement of RTUs in a power system [5]:

1) Placing RTUs at all substations to gather the information of the network topology status (the position of switches and breakers) and all the analog measurements like active/reactive power flow, bus voltage magnitude, etc.
2) Placing RTUs at all substations and gather the network topology status. Analog measurements are gathered only at selected substations.
3) Placing RTUs at selected substation to obtain the network topology status and analog measurements. The

remaining topological information from other substations is updated manually.

Option 1) is the most desirable one but it also costs the most. Option 2) can save some cost from 1) by reducing the number of analog measurements. Option 3) is the most economical way at the expense of not being able to update the network topology in real time.

It is also assumed that there are enough channels in each RTU. As discussed in [7], modern analog-to-digital (A/D) converter in RTUs can deal with more than 100 analog measurement inputs per second. Considering that the number of analog measurements required by the state estimation in a single substation is usually far lower than 100, it is safe to assume that the limitation of RTU channels is not a problem. The cost of each channel is still not trivial due to the interfacing cost, hence it is also a desirable goal to have fewer channels.

The proposed method for placing measurements consists of two steps, which will be discussed in detail below.

A. The observability constraint and the placement of branch power flow and bus voltage magnitude measurements

The first and most important constraint of a measurement placement scheme is that the measurements must make the network observable under normal running conditions. In this paper, the branch power flow and bus voltage magnitude measurements are placed to meet this requirement.

As described in section II, whether a network is observable depends on whether a spanning tree can be formed using the existing measurements. Since branch power flow measurements are assigned to their corresponding branches, the network observability is therefore determined by checking whether the branches whose power flows are measured can form a spanning tree of the whole network. It is known that for an n-bus network, the spanning tree consists of n-1 branches. Therefore, at least n-1 branch power flow measurements are needed to make the network observable.

There are many ways to form a spanning tree. The task of branch measurement placement is to decide how to form the spanning tree so that measurements are concentrated in fewer substations rather than scattered all over the network. Since a single RTU is capable of obtaining all measurements from a single substation, a "concentrated" measurement placement scheme would be preferable, as fewer RTUs are needed. A thorough enumeration of all possible solutions is practically impossible. Some kind of heuristic method must be used.

In order to describe the algorithm of the new method, two terms are defined first. The *degree* of a bus is the total number of branches connected to this bus. A bus B1 is called to be *adjacent* to a bus B2, if there is a branch between B1 and B2.

The flowchart of the algorithm is shown in Fig. 1. An example of the algorithm for placing the branch power flow measurements in the IEEE 14-bus system is demonstrated in Table I.

It can be seen that at the end, the IEEE-14 bus system is made observable by 1 voltage magnitude measurement, 13 branch power flow measurements and 2 RTUs. It should be

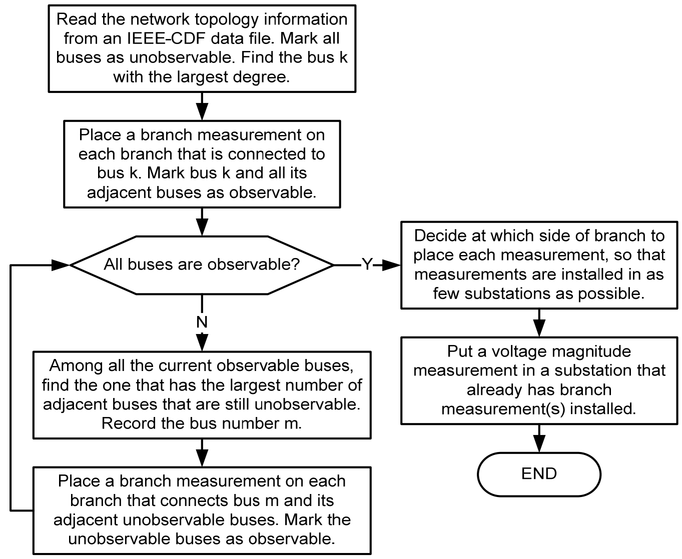


Fig. 1. Flowchart of the branch power flow and voltage magnitude measurement placement.

noted that these numbers correspond to the least possible number of measurements and RTUs in order to make the IEEE 14-bus system observable. Therefore, the proposed algorithm has found the most economical measurement placement scheme that preserves observability under normal running conditions.

B. The reliability constraints and the placement of bus injection power flow measurements

Besides the observability constraint under normal running conditions, it is often desirable to maintain the network observable under certain contingencies. The following contingencies are usually taken into consideration:

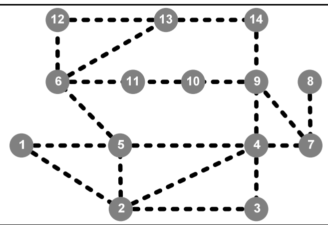
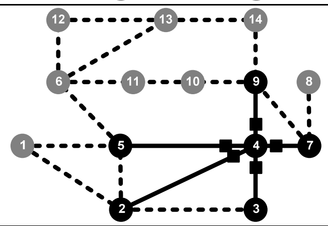
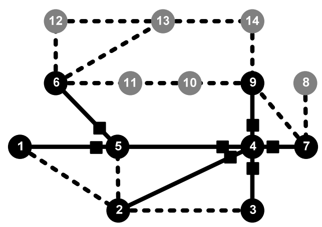
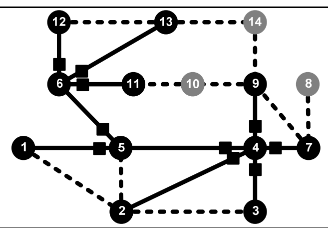
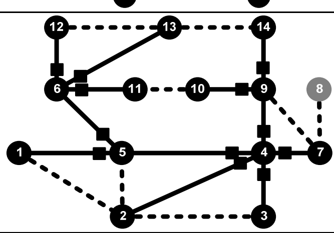
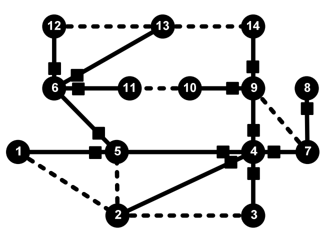
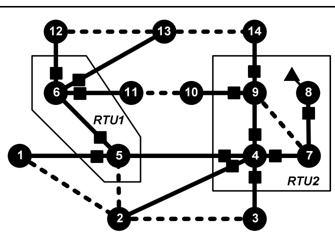
1) The loss of any single measurement.
2) The loss of any single RTU.
3) The loss of any single branch in the network.

This part talks about how to add bus injection power flow measurements to deal with such contingencies.

To preserve the network observable under the loss of any single measurement, it is required that the network has no critical measurement. There are known ways to identify critical measurements in the power system network [6], [9]. Once a critical branch power flow measurement is found, it can be converted to a non-critical measurement by placing a bus injection power flow measurement at either end of the branch. With the help of the extra bus injection measurement, the loss of the branch measurement will no longer affect the network observability. This procedure should be repeated for every single critical branch power flow measurement in the network.

To maintain the network observability against the loss of any single RTU, a simple method is used: installing a backup RTU in every substation that has measurements. This approach simply doubles the number of RTUs in the basic measurement placement design described in part A. All measurements in the substation feed both RTUs simultaneously. In the case of the primary RTU loss, the

TABLE I
BRANCH MEASUREMENT PLACEMENT IN THE IEEE 14-BUS SYSTEM

	Step 1: No measurement is placed in the network. All branches are represented in dashed lines, which means that none of them has an assigned measurement. All the buses are gray, which means that they are unobservable.
	Step 2: Bus 4 is found to be the bus of the largest degree (five). Place one branch power flow measurement on each of these five branches, and mark the branch using a solid line. Mark bus 4 and its five adjacent buses as observable (black).
	Step 3: Among all the current observable buses, find the one that has the largest number of adjacent buses that are still unobservable. Bus 5 is one of such buses. Place a branch power flow measurement on branches 5-1 and 5-6 respectively, so that bus 1 and 6 become observable. Note that no branch measurement should be placed on 5-2, since bus 2 is already observable.
	Step 4: Using the same criteria as in step 3, bus 6 is found to be the next eligible bus to be processed. Place branch power flow measurements on 6-11, 6-12 and 6-13. Buses 11, 12 and 13 become observable.
	Step 5: Using the same criteria as in step 3, bus 9 is found to be the next eligible bus to be processed. Place branch power flow measurements on 9-10 and 9-14. Buses 10 and 14 become observable.
	Step 6: Using the same criteria as in step 3, bus 7 is found to be the next eligible bus to be processed. Place branch measurements on 8-7 (bus 7 is inside a three-winding transformer and therefore the measurement should be placed at the bus-8 side). Now the spanning tree has been formed for the network and all buses are observable.
	Step 7: It is found out that all branch measurements are installed in two substations – substation (5,6) and substation (4,7,8,9). A voltage measurement is chosen to be placed on Bus 8 in substation (4,7,8,9). Only two RTUs are needed to gather all the measurements.

backup RTU will continue transmitting measurement data to the control center.

To deal with the situation of the loss of any single branch, the branches are temporarily disconnected from the network one at a time and a network observability analysis is then carried out. If the network is found to be unobservable, unobservable branches should be identified using the method described in [10]. In such a situation, the network will be rendered observable again if a bus injection power flow measurement is placed on either end of any one of the unobservable branches. This procedure should be repeated until every single branch has been tested.

IV. TEST CASES

Tests have been executed on both the IEEE-14 bus system and the IEEE-30 bus system. The diagrams of both networks are shown in Figures 2 and 3, and further details can be found in [9-10]. For each network, two sets of results were obtained. First, a basic measurement placement scheme was generated to make the whole network observable. Then, more measurements were added to maintain the network

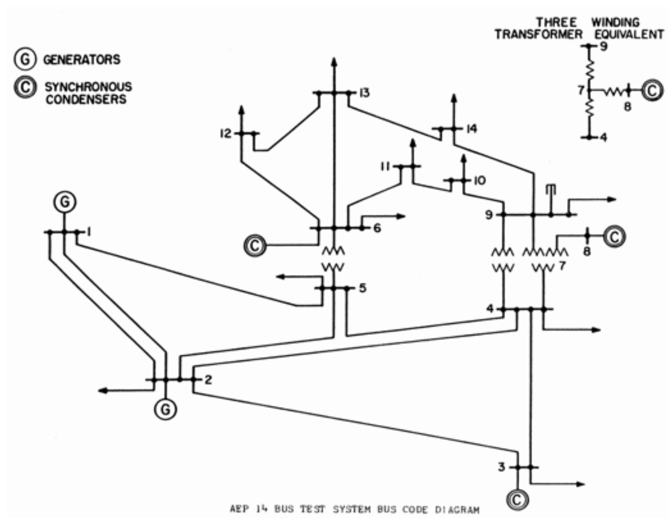


Fig. 2. IEEE-14 bus system diagram.

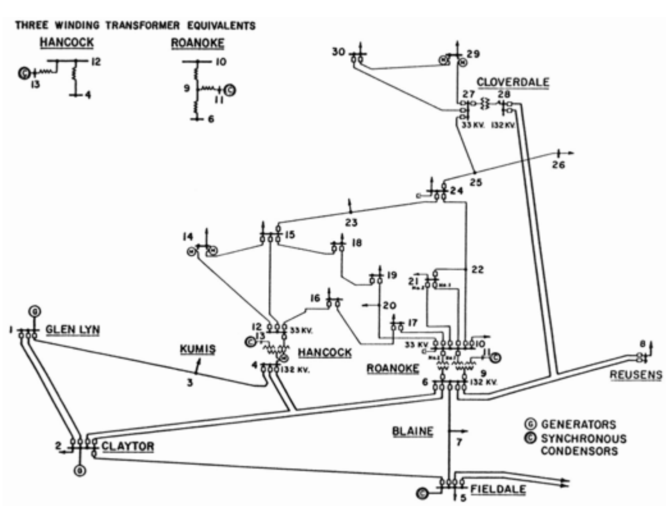


Fig. 3. IEEE-30 bus system diagram.

observability under any contingency of the following three categories: the loss of any single measurement, any single RTU or any single branch.

The first set of measurement placement results that meets the observability constraint is listed in Table II.

The results were compared to the results from the test cases mentioned in [5] under the same observability constraint, as shown in Table III. It can be seen that since the proposed method uses a heuristic method to group measurements into fewer substations, the numbers of RTUs and measurements are both greatly reduced, resulting in a more economical design.

The second set of results that meet the reliability constraints is listed in Table IV.

The second set of results was also compared with the results from the references, as shown in Table V. Reference [5-7] did not consider the contingencies of the loss of any single branch. For the purpose of comparison, the proposed method was carried out for two different situations: 1) when the loss of any single branch is not considered (at the same level of contingency requirements as in [5-7]); 2) when the loss of any single branch is considered (at a stricter level of contingency requirements).

It can be seen that the proposed method shows advantage in reducing the number of RTUs that are used. The method in [7] optimizes the number of measurements and therefore has advantage over the proposed method in this aspect. However, considering that the price of an RTU is much higher than a transducer for a measurement, the proposed method's overall cost is still expected to be less. All the other cited methods did not consider the physical feasibility when placing measurements. For example, bus 9 in the IEEE-30 system is an internal bus of a three-winding transformer and therefore it is not practical to place measurement on bus 9. All the other methods chose to place at least two measurements on bus 9, while the proposed method did not place any. The consideration of such an additional constraint might result in more measurements and/or RTUs to be installed for other methods.

TABLE II
MEASUREMENT PLACEMENT TO MEET THE OBSERVABILITY CONSTRAINT

Type	Location	
	IEEE-14	IEEE-30
Voltage magnitude measurement	8	2
Branch power flow measurement	4-2, 4-3, 4-5, 4-7, 4-9, 5-1, 5-6, 6-11, 6-12, 6-13, 9-10, 9-14, 8-7	6-2, 6-4, 6-7, 6-8, 6-9, 6-10, 6-28, 10-20, 10-17, 10-21, 10-22, 2-1, 2-5, 4-3, 4-12, 13-12, 12-14, 12-15, 12-16, 15-18, 15-23, 11-9, 27-28, 27-25, 27-29, 27-30, 25-24, 25-26, 19-20
RTU	Substation(4,7,8,9), Substation(5,6)	Substation(6,9,10,11), Substation(2), Substation(4,12,13), Substation(15), Substation(27,28), Substation(25), Substation(19)

TABLE III
COMPARISON OF TEST RESULTS UNDER THE OBSERVABILITY CONSTRAINT

Type		Number of measurements		Number of RTUs
		Voltage	Power flow	
IEEE-14	Reference [5]	1	28	5
	Proposed method	1	13	2
IEEE-30	Reference [5]	1	60	13
	Proposed method	1	29	7

TABLE IV
MEASUREMENT PLACEMENT TO MEET THE RELIABILITY CONSTRAINTS

Type	Location	
	IEEE-14	IEEE-30
Voltage magnitude measurement	8	2
Branch power flow measurement	4-2, 4-3, 4-5, 4-7, 4-9, 5-1, 5-6, 6-11, 6-12, 6-13, 9-10, 9-14, 8-7	6-2, 6-4, 6-7, 6-8, 6-9, 6-10, 6-28, 10-20, 10-17, 10-21, 10-22, 2-1, 2-5, 4-3, 4-12, 13-12, 12-14, 12-15, 12-16, 15-18, 15-23, 11-9, 27-28, 27-25, 27-29, 27-30, 25-24, 25-26, 19-20
Bus injection power flow measurement	2, 5, 6, 8, 9, 13	1, 4, 5, 10, 11, 13, 15, 17, 19, 21, 23, 25, 28, 30
RTU	Substation(4,7,8,9)*, Substation(5,6)*, Substation(2), Substation(13)	Substation(2)*, Substation(6,9,10,11)*, Substation(4,12,13)*, Substation(15)*, Substation(27,28)*, Substation(5), Substation(1), Substation(17), Substation(21), Substation(23), Substation(30), Substation(25)*, Substation(19)*

*: two RTUs need to be placed in this substation.

TABLE V
COMPARISON OF TEST RESULTS UNDER THE RELIABILITY CONSTRAINTS

Type		Number of measurements		Number of RTUs
		Voltage	Power flow	
IEEE-14	Ref. [5]	1	35	8
	Proposed method (same constraints)	1	18	4
	Proposed method (more constraints)	1	19	6
IEEE-30	Ref. [5]	1	68	17
	Ref. [6]	1	74	18
	Ref. [7]	1	30	17[1]
	Proposed method (same constraints)	1	40	14
	Proposed method (more constraints)	1	43	20

V. CONCLUSIONS

This paper proposed a new algorithm for cost minimization in the measurement placement design for the purpose of state estimation. The new algorithm is developed based on topological observability analysis method, and therefore is faster than the numerical methods. Two levels of measurement placement designs are obtained: the basic level design guarantees the whole network to be observable using only the voltage magnitude measurement and the branch power flow measurements. The advanced level design keeps the network observable under the following contingencies:

1) The loss of any single measurement.

[1] Reference [7] uses a two-stage optimization method for the measurement placement. At the end of stage I, 21 RTUs are needed. The stage II further reduces the number of RTUs to 17. However, no strict algorithm has been provided for stage II.

2) The loss of any single RTU.
3) The loss of any single branch in the network.

The test results on the IEEE 14-bus and 30-bus systems show that the proposed measurement placement designs are more efficient and the cost involved is less than the previous methods. The proposed method can be very helpful in planning power network measurement systems.

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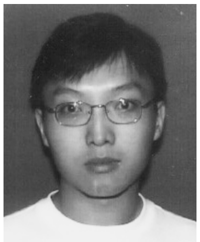
VII. Biographies



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Tatjana (Tanja) Kostic (M’95) received her BSEE (’89) and MSEE (‘94) from the University of Belgrade, Yugoslavia, and the Dr. of Sc. Techn. degree (‘97) from the Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland. After her post-doc year with Mitsubishi Electric, Amagasaki, Japan, she joined ABB Corporate Research in Switzerland, where she is currently working as a principal scientist in Utility Solutions group. Her research interests include IT applications for power system operation and for utility asset management, standardized utility domain models, object-oriented analysis and design, and artificial intelligence. She is a member of the IEEE PES and Computer societies, a working member of the Cigré WG C2.01, and an IEC expert in TC57 WG14.