

Measurement Design and State Estimation for Distributed Multi-Utility Operation

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Abstract: With power market deregulation, companies cooperate to share one whole grid system but achieve their own economic goals. This paper focuses on how to improve the state estimation result of one company by exchanging raw or estimated data with other companies or ISO. First fundamentals to evaluate a measurement system are developed based on the concept of system redundancy index, leverage point and state estimation error variance. Then the investigations show the complexity of this interesting new topic. Accordingly a heuristic algorithm for the measurement design for distributed multi-utility operation is presented. The numerical results verify that data exchange does enhance the result of state estimation when some principles are applied.

Key words: Measurement placement, Distributed state estimation, Power market, Leverage point, Redundancy index.

I. INTRODUCTION

State estimation is essential for monitoring, control and optimization of a power system. Regardless of the different estimation algorithms, the locations and types of measurements are always decisive factors for successful state estimation.

There have been many measurement placement methodologies proposed in the literature [1,2]. However, though the development of power market is rather rapid, the influence of distributed multi-utility operation on the measurement design has not been discussed in these papers.

In the regulated environment, the whole power system is owned by a limited number of locally monopolistic organizations. These utilities have the responsibility and the ownership of the instrumentation in their local region to meet their needs to monitor and control. There is almost no need to exchange data with other organizations.

On the contrary, in a deregulated environment, no single company owns the whole system. They must cooperate to run the system and to achieve their own economic goals. Therefore, many new problems arise during the measurement design and state estimation, including:

1. How to design the measurement system for each subsystem.
2. How to improve the estimation result of one subsystem by exchanging data with other companies, and especially with ISO.

This paper focuses on these problems and is organized as follows: fundamentals to evaluate a measurement system are

developed first in Section II. Furthermore, in Section III the preliminary concept and some heuristic principles for data exchange are discussed. Accordingly, a heuristic algorithm for the measurement design of distributed state estimation is presented in Section IV. Implementation issues and numerical tests are discussed in Section V. In the last section, a conclusion is drawn.

II. EVALUATION OF MEASUREMENT SYSTEM

To develop basic concept and principles for data exchange, the problem on how to evaluate a measurement system scheme will be solved in advance. In this section three evaluation criteria are proposed based on traditional analysis of state estimation.

A. Traditional analysis of state estimation

Generally speaking, the problem of power system state estimation (SE) can be formulated as [1,3]:

$$z = h(x) + e \quad (1)$$

Where

z represents all measurements, including power injection, power flow and bus voltage magnitude measurements,

e is the measurement noise vector,

x is the state vector composed of the phase angles and magnitudes of the voltages at network buses,

$h(\bullet)$ stands for the nonlinear measurement functions. It is always assumed that the parameters and the topology of the systems are already determined in advance.

WLS algorithm has been used to solve the SE problem in many commercial software packages for electric power system, which is based on a nonlinear iteration method. At each iteration i , the following equations is solved:

$$(H^T R^{-1} H) \Delta x_i = H^T R^{-1} \Delta z_i \quad (2)$$

Where

R is the measurement covariance matrix

H is the Jacobian matrix,

$\Delta x_i = x_{i+1} - x_i$ is the correction of state variables vector,

$\Delta z_i = z - h(x_i)$ is the estimated error of the measurements.

The network is said to be observable when the state variables of an entire network can be calculated uniquely [1,4,5]; in other

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words, H is of full column rank and G^{-1} exists numerically. In most cases, the measurement system is always observable under normal operation condition.

$$\text{SE error is defined as: } \alpha = x^t - x^e \quad (3)$$

Where

x^t is the true value of system state variables,

x^e is the estimated value of system state variables.

The covariance matrix of α is defined as [1]:

$$C = E(\alpha\alpha^T) = (H^T R^{-1} H)^{-1} \quad (4)$$

where E stands for expectation,

Residual sensitivity matrix W is defined by: $r = W \cdot e$ (5)

where

$r = z - h(x^e)$ is the measurement residual vector,

$$W = I - S = I - H(H^T R^{-1} H)^{-1} H^T R^{-1}. \quad (6)$$

B. Criterion 1: System Redundancy Index P

Essential Measurement Set is a set of measurements that make the system observable; and at the same time, removal of any measurement from this set will make the system unobservable. A measurement is said to be essential with respect to the essential measurement set if it is a member of the essential measurement set. However, there always exists more than one essential measurement set in one measurement system. In other words, there are different strategies of choosing an essential measurement set.

One measurement is a critical measurement if its removal will make the system unobservable. Obviously a critical measurement is always an essential measurement.

A set of measurements is a critical measurement set if removals of all the measurements in this set will make an observable power system unobservable.

A measurement is said to have a redundancy level/index $(p-1)$, if p is the size of the smallest critical set in which this measurement appears. Furthermore, such a set is called a critical p -set [6,7,8].

Redundancy index reflects the ability to detect and identify bad data in the measurements. A critical measurement has a redundancy index $p=0$, which means the error in this measurement can never be detected. A measurement with $p=1$ means the error can be detected but cannot be identified. The error in a measurement with $p=2$ can be detected and identified [7].

The system redundancy index P of one scheme for measurement placement is defined as:

$$P = \left(\sum_{i=1}^m p_i \right) / m \quad (7)$$

Where

m is the total number of measurements,

p_i is the redundancy index of measurement i .

SE using a measurement system with larger P will be more powerful to identify bad data and therefore the estimation results will be more reliable.

Based on matrix H , there are different ways to calculate the redundancy index of a measurement. In this paper, we use a numerical algorithm as described in [7,8]; however, topological approach can also be used [9].

C. Criterion 2: Leverage Point

Leverage points are situated far away from majority of the data in the factor space of regression defined by the measurement Jacobian. Leverage points are highly influential measurements that “attract” SE solution towards them. Thus, accurate leverage point measurements without incurring errors can improve the accuracy of SE. [1,10,11]

Since the corresponding diagonal element in W is close to zero for a single leverage point measurement, such a single leverage point can be detected by using matrix W . Accordingly, SE algorithm using W -Based normalized residual can detect the bad data in a single leverage point [10]. On the other hand, the corresponding diagonal element in W is zero for a critical measurement.

Unfortunately, when there are multiple leverage points, they can mask each other by increasing the corresponding diagonal element in W . As a result, the errors cannot be detected by hypothesis tests based on the weighted residuals [10]. Therefore leverage points can be very harmful to state estimation, and several methodologies have been developed to deal with leverage points.

The first approach is to remove all the leverage points, which make many good leverage points useless and waste the corresponding useful information. The second approach is to develop new state estimation algorithm that is insensitive to leverage points. However, the second approach is rather difficult to be feasible for online application. The third one is to modify the measurement equations by applying a linear transformation and then the transformed measurement set will no longer contain any leverage points. [10]

Note that the redundancy index of some interactive leverage points can be large.

D. Criterion 3: Variance of SE errors

The variances of the SE errors stand for the accuracy of SE. Statistically, they represent the “squared distances” of the estimates from their true values. The smaller the variances are, the better the SE solution is typically. [1]

When the system is numerically observable, the state estimation error variances, which are the diagonal elements of matrix C , can be computed and used as indices for the accuracy of the estimated state variables. [1]

III. IMPACT OF DATA EXCHANGE

Now we will study how to improve the state estimation of one subsystem by using information of other subsystems. It is quite possible that information exchange among individual companies and ISO will benefit all parties.

We expect that more benefits will be found if member companies start to exchange their measurement and estimation results. Member companies can establish contracts on how to exchange data. They may start to exchange data on the

boundary buses first. Then they can proceed to internal data. If there are sensitive data needed by their neighbors, they can set price tag on these data. Their neighboring companies can compare the benefit and cost for the data to decide whether they want the data exchange. Accordingly, when a company wants to improve their measurement system, they can have more choices: set up new instrumentation devices or buy/exchange data from their neighboring companies. In fact, member companies even can cooperate to decide the essential measurements of the whole system, and then add some redundant meters of their own. For the overall system, this approach is more efficient than that each member company set up their own essential measurements and redundant measurements set.

One key problem here is to find a way to measure the benefit of the data exchange. If we can provide a systematic way to guarantee the improvement, individual company will start to exchange their data and expecting improvement to their estimation result.

Before theoretical algorithm is developed, some basic concepts and heuristic principles for data exchange are explored first.

A. A network and its measurement system

To demonstrate, an IEEE 14-bus test system is used.

Whether it is in the regulated or deregulated environment, the power system including the measurement system is exactly the same in physics as shown in Fig.1 and Fig.2. The difference is only the ownership.

For deregulated one, the system may not belong to a single

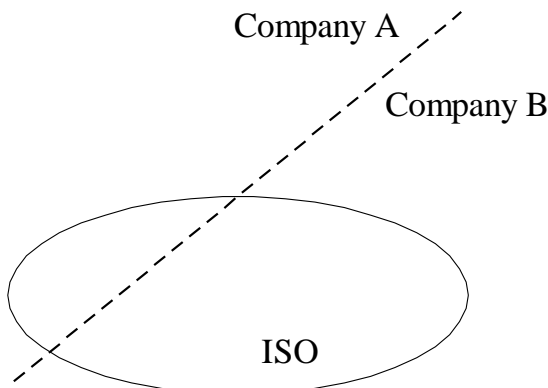


Fig.1 Deregulated Power System

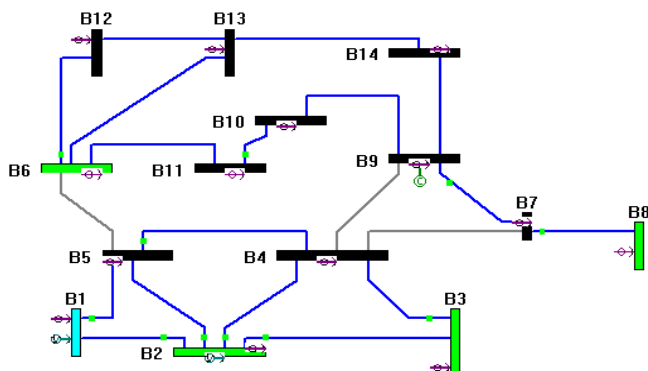


Fig.2 Measurement System of Whole System

company, but to company A and company B separately. In addition, an ISO manages the whole high voltage part of the system.

The network is decomposed mainly based on the natural industry boundaries defined by ownership.

Measurement system follows the exact same ownership boundary. The only difference is that ISO will receive all the measurements of the high voltage grid. Accordingly, the measurement system is divided into three subsystems as shown in Fig. 3, Fig. 4 and Fig.5.

For our analysis, the ISO runs state estimation for the high voltage grid of the whole system, and company A and B run state estimation on their own subsystems.

When all the usable measurements shown in the figures are good, state estimation can be executed successfully in ISO, Company A, and Company B separately.

B. Impact of raw data exchange

It is clear that the power injection measurements on the boundary buses cannot be usable if any power flow measurements on the tie lines are not available to local subsystems. Therefore many power injection measurements are useless and the redundancy index decreases accordingly.

For example, power injection measurement on Bus5 is unusable in Fig.3 because it is a boundary bus now and there is no power flow measurement on the tie line from Bus5 to Bus2.

Therefore, one important principle is that the measurements of tie lines should be available to all involved subsystems if possible. Then the boundary buses are extended.

Because each company usually will measure power flow on

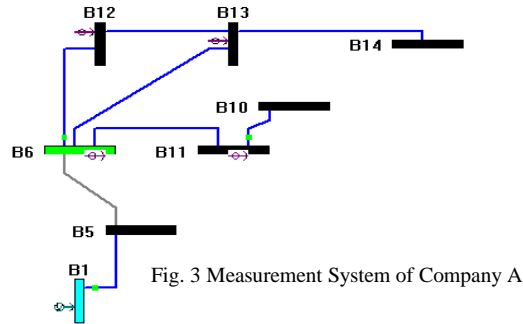


Fig. 3 Measurement System of Company A

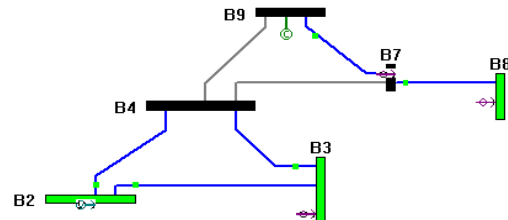


Fig.4 Measurement System of Company B

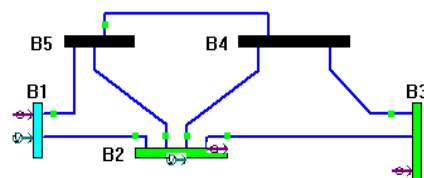


Fig.5 Measurement System of ISO

the boundary very carefully due to exchange contracts, the data on the boundary buses and tie lines will have good accuracy and high reliability.

Fig.6 shows some possible schemes of measurement system for Company A after the utilization of the above heuristic principle.

The implementation of such a principle will increase the system redundancy index of the subsystem in most cases because of the following reasons:

First, whenever another boundary bus of our neighboring company is included (two more state variables for state estimation is added then), at least two more measurements (real and reactive power flow measurements on the boundary tie lines) are included at the same time.

Second, the former boundary buses such as Bus5 is not a boundary bus any more, which will make the power injection measurement usable again and then another two measurements are included here.

Finally, if the newly introduced bus connects to more than one boundary buses, even more measurements can be included without adding new buses, which is shown as Fig.6-2.

However, raw data can be leverage point with low accuracy, which can be very harmful to state estimation as mentioned before. Therefore, raw data exchange is not always beneficial to the original measurement system.

C. Impact of estimated data exchange

Compared to raw data exchange, the estimated data exchange is much more powerful. The raw data is limited to the original value of one measurement device, but the estimated data being exchanged can be the result of state estimation performed by other subsystems in real time. Theoretically speaking, even the angle difference of two buses can be treated as a pseudo measurement from the estimated data exchange.

Note that the estimated data is much more reliable than raw data. For example, when the exchanging raw data is bad, the danger of accuracy deterioration of original state estimation does exist, especially when some other bad data in local systems already exist. However, such a danger is greatly reduced by exchanging estimated data, since these bad raw data can be detected and removed by the exchanging companies before they are exchanged to the local company. Accordingly, the redundancy index of the estimated exchanging data is set the same value as its exchanging subsystem, which can be higher than the local system redundancy index.

In addition, the leverage point is avoided when raw data is exchanged. However, when estimated data is exchanged and the estimation accuracy of other subsystems such as ISO is much higher than the local subsystem, leverage point data is encouraged because accurate leverage point can greatly improve the accuracy and reliability of the local SE. In other words, we try to make leverage points reliable and accurate to avoid incurring error.

IV. A HEURISTIC ALGORITHM FOR MEASUREMENT DESIGN

There are many measurement placement methods developed in literature [1,2]. Though incremental and elimination methods

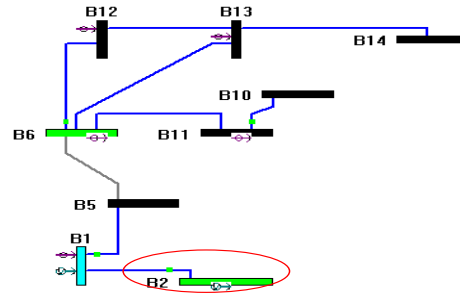


Fig.6-1 Measurement Scheme 1 for Company A

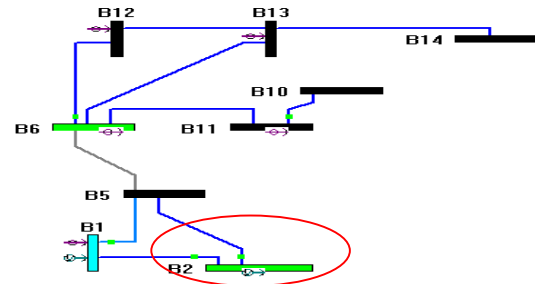


Fig.6-2 Measurement Scheme 2 for Company A

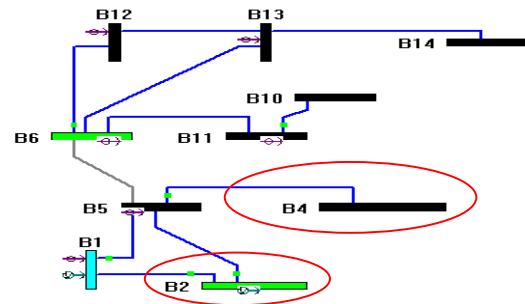


Fig.6-3 Measurement Scheme 3 for Company A

are both widely utilized, incremental method is more practical for industry applications, especially when the current measurement configuration already exists and thus no major modification can be applied any more.

Furthermore, most algorithms are based on some heuristic rules because it is hard to give the quantitative relations between add/removal of one measurement and the performance of the whole measurement system. It is possible for only criterion 3 to obtain such a sensitivity relationship. However, criterion 1 and 2 are much more important than criterion 3 in industry applications, because it is much better to obtain the SE results with sufficient accuracy and without bad data than those with higher accuracy but at the same time with possible undetected bad data.

Based on the above analysis, a heuristic algorithm is proposed as:

- Step 1. Read online information, including the network data and measurement placement/values.
- Step 2. Obtain current system redundancy index and some necessary matrix H/W/G as described in section II.
- Step 3. Based on criterion 1, determine a ranked list of low redundancy measurement and the corresponding buses.
- Step 4. Find some candidate measurements to support this bus.

Step 5. Based on the three criteria, evaluate the different measurement placement schemes, and choose the best one.

Step 6. Go back to step 2 if further improvement is still possible and economical feasible.

Obviously Step 4 is the decisive step and there are some important factors to consider in step 4:

1. Generally speaking, due to the localization characteristic of SE, data exchange on the boundary is not very effective to improve the redundancy index of the buses far away from the boundary;
2. Raw data exchange occurs usually on the boundary tie lines, which extends the original system;
3. Since estimated data exchange is effective only if the other subsystem is more reliable than local system, the SE result of ISO is potentially a good source for estimated data exchange because the SE of ISO is hopefully more accurate than other subsystems due to its monitoring role;
4. Adding leverage point is very harmful when raw data is exchanged. However, as explained in Section III, when estimated data is exchanged, it is a good choice to add leverage point.

V. NUMERICAL RESULTS

IEEE 14-bus system mentioned in Section III is used here to verify our conclusions.

Case1: Raw data exchange for company A

In the original system for Company A shown in Fig.3, the measurement system is exactly critical, and the redundancy index of all buses is zero. Using the algorithm proposed on Section IV, the boundary bus1 is ranked first to be supported. Therefore, scheme 1 is obtained as shown in Fig.6-1. And then, Bus5 is selected and alternative scheme 2 and 3 are obtained as shown in Fig.6-2 and Fig.6-3. Similar process can be continued until the measurement placement scheme is satisfactory.

The comparison between these different schemes for company A is given in table 1.

TABLE 1. COMPARISON BETWEEN DIFFERENT SCHEMES FOR COMPANY A

Scheme	System Redundancy Index	Measurements Number	Possible Leverage point
Fig.3	0/15=0	15	No
Fig.6-1	(0+6)/(15+4)=0.32	15+4=19	Yes
Fig.6-2	(6+10)/(19+2)=0.77	19+2=21	No
Fig.6-3	(16+10)/(21+4)=1.04	21+4=25	Yes

It is clear that with different weights for those three criteria, different schemes will be selected.

On the other hand, such an improvement in state estimation is at the cost of more measurement channels. Therefore a trade-off between the economic and state estimation performance must be considered carefully.

Case2: Estimated data exchange for company A

The system redundancy index of ISO as shown in Fig.5 is much higher than Company A and B. For example, the redundancy index of power flow measurement from Bus2 to Bus1 is 6. So estimated data exchange is encouraged here.

In Fig.6-1 if the exchanged power flow measurement from Bus2 to Bus1 is not raw data but the estimated data from ISO, then the redundancy index of this measurement is not 2 but 6 based on our argument that the redundancy index of estimated data is set to the same value as its original subsystem.

The comparison between raw and estimated data exchange is given in Table 2, which shows the redundancy index after estimated data exchange is much higher than that after the corresponding raw data exchange.

TABLE 2. COMPARISON BETWEEN RAW & ESTIMATED DATA EXCHANGE

Data Type	Original Redundancy Index	New Redundancy Index
Raw	0/15=0	(4+2)/(15+4)=0.32
Estimated	0/15=0	(4+12)/(15+4)=0.84

TABLE 3. RESIDUES FOR COMPANY A WITH RAW DATA EXCHANGE

Measurement	Order	Normalized Residue
The normalized residues are all very small. No bad data is found.		

TABLE 4. RESIDUES FOR ISO IN FIG.5

Measurement	Order	Normalized Residue
Power flow from B2 to B1	1	465
Power flow from B1 to B5	2	404
Power Injection on B2	3	285

Suppose that power flow measurement from Bus2 to Bus 1 and from Bus1 to Bus5 are both bad data (all decreased by 0.1 p.u.), which happens to keep the power balanced on Bus1.

Note that the measurements with the largest normalized residues will be selected as the bad data according to the WLS algorithm of SE. It is verified as follows that the estimated data exchange is much more powerful than both raw data exchange and the original Company A without data exchange.

Company A without any data exchange:

Since all measurements are critical in the original Company A, the bad data (power flow measurement from Bus1 to Bus 5) cannot be detected at all in Company A as shown in Fig.3.

Company A with raw data exchange:

Based on Table 3, no bad data is found in the raw data exchanged scheme as shown in Fig.6-1, which verifies that raw data exchange scheme for Company A still can not detect any bad data at all.

Company A with estimated data exchange:

However, even under such a serious situation, according to Table 4, power flow measurements from Bus2 to Bus1 and from Bus1 to Bus5 are identified as bad data correctly in ISO as shown in Fig.5. Accordingly, SE result of ISO is not influenced by these two correlated bad data.

Therefore, the value of power flow measurement from Bus2 to Bus1, which is being exchanged from ISO to Company A, will not be the bad raw value but the good estimated value from SE result of ISO. In other words, after estimated data exchange, there are only one bad data (power flow measurement from Bus1 to Bus5) in Company A, which can be detected easily in Fig.6-1 because all other measurements including power flow measurement from Bus2 to Bus1 are all good data.

VI. CONCLUSIONS

This paper focuses on how to improve the state estimation of one company by exchanging raw or estimated data with other

companies or ISO.

A theoretical method to evaluate a measurement system is developed based on three criteria: the system redundancy index, leverage point and state estimation error variance.

Accordingly a heuristic algorithm for the measurement design for distributed multi-utility operation is presented. The numerical tests on IEEE-14 Bus sample system verify that raw data exchange does enhance the result of state estimation when some principles are applied. Furthermore, estimated data exchange is much more powerful and reliable than raw data exchange, especially during serious situation which involves multiple correlated bad measurements.

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VIII. BIOGRAPHIES

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