Measurement Design of Data Exchange for Distributed Multi-Utility Operation

Garng M. Huang, *Senior Member, IEEE*, and Jiansheng Lei, *Student Member, IEEE*

***Abstract*: With power market deregulation, member companies cooperate to share one whole grid system and try to achieve their own economic goals. This paper focuses on how to improve the state estimation result of member companies or ISO by exchanging raw or estimated data with neighboring member companies/ISO. The concept of Bus Redundancy Descriptor (BRD) is developed based on critical measurement set. BRD and leverage points are used as criteria to evaluate the quality of measurement systems. Accordingly, based on BRD a heuristic algorithm for measurement design under distributed multi-utility operation is presented to search for possible beneficial data exchange schemes. Numerical results verify that every member companies including ISO benefit from mutual data exchange when some principles of design are carefully applied.**

***Key words:* Power market, Measurement placement, Distributed state estimation, Redundancy level.**

I. Introduction

State estimation (SE) is essential for monitoring and control of a power system. Locations and types of measurements are always decisive factors for successful state estimation.

There have been many measurement placement methodologies proposed in the literature [1-4]. However, though the development of power market is rather rapid, impacts of distributed multi-utility operations on measurement design have not been discussed too much in literature.

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. There are multiple member companies who must cooperate to run the system and to achieve their own economic goals. Therefore, a new problem arises during the measurement design and state estimation for distributed multi-utility operation, which is how to improve the estimation result of one company by exchanging measurement data with neighboring member companies, and ISO.

This paper focuses on this issue and is organized as follows: the Bus Redundancy Descriptor (BRD) concept is developed in Section II. Fundamentals to evaluate a measurement system based on BRD and leverage points are studied in Section III. Furthermore, in Section IV the preliminary concept and some applicable characteristics of data exchange are discussed. Accordingly, a heuristic algorithm V based on BRD for the measurement design of distributed state estimation is presented in Section. Numerical tests are discussed in Section VI. In the last section, a conclusion is drawn.

II. Bus Redundancy Descriptor (BRD)

It is observed in [1,5,6,7] that in most cases the observability result of the active power portion is the same as that for full SE formulation. Algorithms based on the active power part can be applied to a full SE analysis easily. Therefore, this paper focuses only on the active power part.

A sample power system with its measurement system as shown in Fig.1 is used here to demonstrate the problem. It is part of the IEEE14-bus test system.

A. Concept of Measurement Redundancy Level [5]

A set of measurements is a critical measurement set if removals of all the measurements in the set will make an observable power system unobservable. And the size of the critical measurement set is defined as the amount of measurements in the set. Furthermore, such a set is called a critical *p*-set, where *p* is the size of the set.

A measurement is said to have a measurement redundancy level *p*, if the size of the smallest critical set in which this measurement appears is $(p+1)$.

B. A New Concept of Bus Redundancy Descriptor (BRD)

After the removals of a critical measurement set, the measurement system becomes unobservable and is split into several isolated measurement islands. Accordingly, the set of weak buses for this critical measurement set is defined as the boundary buses between these measurement islands.

Every bus has its own Bus Redundancy Descriptor (BRD). BRD of Bus *b* is defined as a set of critical measurement *p*-set whose weak bus set includes Bus *b*.

A bus is said to have a bus redundancy level *g*, if the smallest size of the critical sets in its BRD is $(g+1)$.

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The authors are with the Department of Electrical Engineering, Texas A&M University, College Station, TX 77843, USA
E-mail: huang@ee.tamu.edu, lei.jiansheng@ieee.org

C. Numerical Example

(9-10,10,12-13) is a critical measurement 3-set because removals of all these three measurements will make the system unobservable. Furthermore, the measurement system is split into two isolated measurement islands: {1,5,6,11,12} and {9,13,14}. The boundary buses are {6,9,10,12,13}, which is the corresponding weak bus set.

Note1: "*10*" stands for the active power injection measurement in Bus 10, while "*9-10*" stands for the active power flow injection measurements from Bus 9 to Bus 10.

Note2: {6,9,10,12,13|*(9-10,10,12-13)*} denotes the weak bus set of critical set *(9-10,10,12-13)* is Bus6, 9, 10, 12 and 13.

BRD of Bus6 consists of at least *(9-10,10,12-13)* and some other possible critical sets. The size of *(9-10,10,12-13)* is 3. If the size of other possible critical sets in the BRD of Bus6 is greater than 3, then the redundancy level of Bus6 is 2.

Note3: {6|2: (9-10,10,12-13), …} denotes the redundancy level of Bus6 is 2, and BRD of Bus6 consists of a critical 3-set (9-10,10,12-13) and other sets.

D. Determination of BRD

The algorithm to determine BRD of a bus is:

Step 1: Based on analysis of symbolic Jacobian matrix [8], the methodology in [5] is used here to find out all critical 1-set, 2-set, 3-set and 4-set of the measurement system and the corresponding weak bus set. The result for the sample system in Fig.1 is given as Table 1:

TABLE 1. CRITICAL SET AND WEAK BUS SET OF SAMPLE SYSTEM IN FIG.1

p	Constitution of Critical *p*-set and the weak bus set
1	{5,6|*(5-6)*}
2	{6,11,12,13|*(6-11,6-12)*}; {6,11,12,13|*(6-11,12-13)*}; {6,12,13|*(6-12,12-13)*}; {1,5|*(1-5,5-1)*}
3	{6,9,10,12,13|(9-10,10,12-13)}; … …
4	… …

Step 2: BRD is determined based on its definition. BRD for the sample system in Fig.1 is:

{1|1: (1-5,5-1), …};
{5|0: (5-6), (1-5,5-1), …};
{6|0: (5-6), (6-11,6-12), (6-11,12-13), (6-12,12-13), (9-10,10,12-13) , …};
{9|2: (9-10,10,12-13), …};
{10|2: (9-10,10,12-13), …};
{11|1: (6-11,6-12), (6-11,12-13), …};
{12|1: (6-11,6-12) (6-11,12-13) (6-12,12-13), (9-10,10,12-13), …};
{13|1: (6-11,6-12) (6-11,12-13) (6-12,12-13), (9-10,10,12-13), …}.

E. Some Remarks

Remark 1: A critical measurement set not necessarily constitutes a connected measurement area. For example, in the critical set *(9-10,10,12-13)*, *12-13* is isolated from *9-10*.

Remark 2: The weak bus set of a critical set is not limited to the buses linked directly to the measurements of the critical set. For example, a weak Bus6 does not link directly to any measurement of critical set *(9-10,10,12-13}*.

Remark 3: Similar to measurement redundancy level, bus redundancy level indicates the ability of a bus to be immune of the pollution from the bad data on the SE result.

If redundancy level *g* of Bus *b* equal to *0*, then bad data in the corresponding critical set can never be detected and will harm the accuracy of SE result on Bus *b*. If *g=1,* single bad data in the critical set of BRD can be detected but cannot be identified, which will make Bus *b* not reliable. If *g=2*, a single bad data can be both detected and identified, but two bad data in the critical set of BRD cannot be detected. Even if *g=3*, two simultaneous bad data in the set is still hard to be identified.

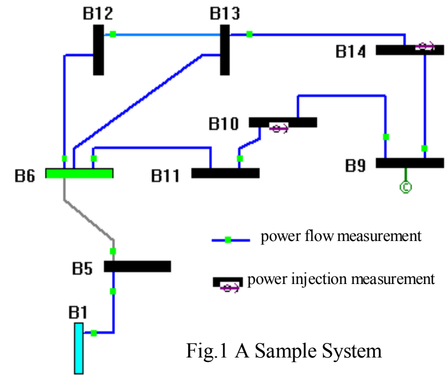

Fig.1 A Sample System

Remark 4: Redundancy level of one bus can be obtained easily from the definition of BRD.

Furthermore, BRD reveals the detailed relationship among measurements. It not only pinpoints the weak buses with low redundancy level, but also tells us how the bad data will harm the weak bus. For example, based on {5|0:(5-6), (1-5,5-1), …}, the result on Bus5 will be harmed from simultaneous errors on *1-5* and *5-1* because they cannot be detected, even though their measurement redundancy level is 1. On the other hand, simultaneous errors on *1-5* and *6-11* are not related and can be detected separately. Such information cannot be obtained through measurement redundancy level alone.

Remark 5: When the bus redundancy level is greater than 3, it is high enough and the small reliability difference between them can be ignored. Thus, only buses with redundancy level less than 4 are potential weak parts of the system, which we should focus. Accordingly, we only consider critical measurement sets with size p=1,2,3 or 4 in Step 1.

Remark 6: Note that average of measurement redundancy level is too crude an indicator for analysis of a measurement system. For example, suppose that a system has two different measurement designs A and B. All measurements in A have redundancy level 3, while in B half measurements have redundancy 0 and half have redundancy 6. It is clear that A is much better than B, even though they have the same average redundancy level. Accordingly, BRD on a bus is a much more accurate and powerful indicator than a local or a global measurement redundancy level index.

III. EVALUATION OF MEASUREMENT SYSTEMS

Some criteria to evaluate the measurement system are developed based on the concept of BRD and leverage points. According to these criteria, it can be concluded whether data exchange benefits the original measurement system or not.

A. Criterion 1: Measurement Reliability of a Bus

In terms of SE reliability, Bus *b1* is said to be stronger than Bus *b2* (*b2* is said to be weaker than *b1*) when:

1) Redundancy level of *b1* is higher than *b2*;

2) The amount of critical (*p+1*)-set in BRD of *b1* is smaller than that of *b2* when the redundancy level of *b1* and *b2* have exactly the same *p*.

A measurement system whose buses are stronger is better.

B. Criterion 2: Location of buses with low redundancy level

The importance of a bus depends on its location. As an example, when a system is extended by data exchange, the extended new bus is generally much less important than the buses in the original system. Therefore, if other factors are the same, it is better that buses with low redundancy level are located on the less important buses.

C. Criterion 3: Amount of leverage points

Leverage points are highly influential measurements that “attract” SE solution towards them. The redundancy index of some interactive leverage points can be large. It is observed in [1,9,10] that leverage points appears in flow/injection measurements at ends of relatively short lines, or in injection measurements at buses which connect a large number of buses.

Accurate leverage-point measurements can improve the accuracy of SE. On the other hand, when there are multiple interrelated leverage points, the errors on these leverage points cannot be detected by the weighted residuals hypothesis testing. Therefore leverage points can be very harmful to state estimation. That is why we avoid new leverage points in a measurement system. A few methodologies have been developed to handle leverage points [9].

Therefore, it is better if the amount of leverage point in a measurement system is smaller.

IV. Impact Of Data Exchanges

A. Background

This section studies how to improve the state estimation of one subsystem by using information of other subsystems. It is quite possible that information exchange between individual member companies and ISO will benefit all parties.

If benefit does exist, these companies can establish contracts on data exchange. If there are sensitive data needed by their neighbors, they can set price tags on these data. Their neighboring companies can compare the benefit and cost for the data to decide if 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 themselves 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 to improve the measurement quality of their own part. For the overall system, this approach is perhaps more efficient than systems designed independently. On the other hand, data exchange needs communication channels. Therefore a trade-off between the cost for data exchange and measurement system quality must be considered carefully.

We need to develop a systematic way to find possible beneficial data exchanges and to evaluate their benefit. Before developing a theoretical algorithm Section V, we explore some basic concepts and characteristics for data exchange first.

B. Power Network And Its Measurement System

The IEEE 14-bus test system is used to demonstrate our developed concepts.

Whether deregulated or not, the power system and the measurement system remain the same in physics as shown in Fig.2. The difference is the ownership. The system no longer belongs to a single company, but to companies A and B. In addition, an ISO manages the high voltage portion of the system. The network is decomposed by the natural industry boundaries defined by ownership. Measurement system follows ownership boundary. ISO will receive all the measurement data of the high voltage grid. Accordingly, the measurement system is divided into three subsystems as shown in Fig. 3, 4 and 5. The ISO runs state estimation of the high voltage grid, and company A and B run state estimation on their own subsystems. When all the measurements shown in the figures are good, state estimation can be executed successfully in ISO, Company A, and Company B separately.

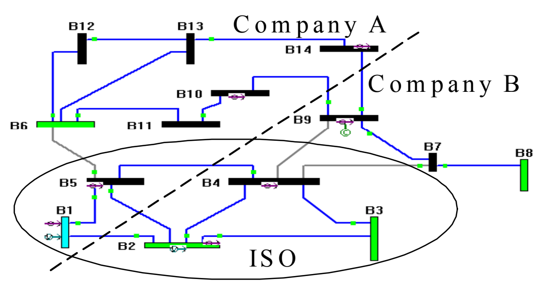

Fig.2 Deregulated System with Measurement System

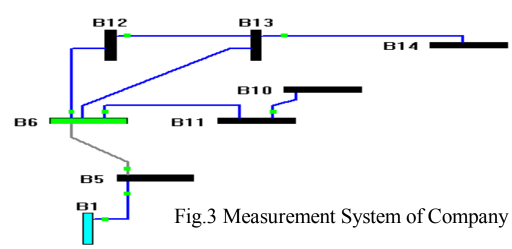

Fig.3 Measurement System of Company A

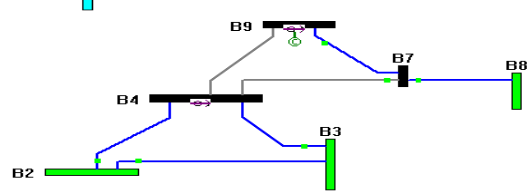

Fig.4 Measurement System of Company B

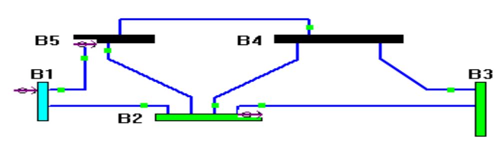

Fig.5 Measurement System of ISO

C. Impact Of Raw Data Exchange

Note that the power injection measurements on the boundary buses are useless if power flow measurements on some tie lines are not available to local sub-systems, which will further reduce the redundancy indices accordingly.

For example, power injection measurement on Bus5 is useless in Fig.3 because it is a boundary bus and there is no power flow measurement on the tie line from Bus5 toBus4.

Therefore, it is perhaps good to make the measurements on tie lines available to all involved subsystems.

On the other hand, arbitrary exchanged raw data can be leverage point with low accuracy, which is harmful to SE.

D. Impact of Estimated Data Exchange

Compared to raw data exchange, the estimated data exchange is more powerful. The raw data is limited to the original value of one measurement device, but the estimated data being exchanged are the result of SE 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.

The estimated data is also more reliable than raw data. For example, when the exchanged raw data is bad, the danger of reducing the accuracy of original state estimation increases, especially when there is some other bad data in local systems. However, such a danger is greatly reduced by exchanging estimated data, since the bad raw data can be detected and corrected before the data are exchanged. Accordingly, it is desirable for the redundancy level of the estimated data to be higher than that in the local subsystem.

In general, we should avoid exchanging the raw leverage point data. However, when estimated data is exchanged and the estimation accuracy of other subsystems is much higher than the local subsystem, leverage point data is encouraged. Accurate leverage point can greatly improve the accuracy and reliability of the local SE.

V. Measurement Design Algorithm For Data Exchange

Though incremental and elimination measurement placement methods 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 will be made.

Furthermore, most algorithms are based on some heuristic rules because it is hard to give the quantitative relations between add/removal of one measurement device and the reliability of the whole measurement system. It is possible for SE error variance to obtain such a sensitivity relationship. However, reliability is much more important than accuracy in industry applications. It is much better to obtain the SE results with reasonable accuracy without bad data than with extremely high accuracy but possible undetected bad data.

Based on the above analysis, a heuristic measurement design algorithm for data exchange is proposed:

Step 1. Read online information, including the network topology data and measurement placement information.

Step 2. According to definition of BRD in Section II, calculate the information of BRD on every bus in the whole system and in individual subsystems.

Step 3. Find possible beneficial data exchange based on:

Principle 1: If overlapped buses, such as buses in the common part of subsystem A and B, are stronger in A by Criteria 1, data exchanges of estimated results from A to B on these buses have potential benefit to B. Note that the redundancy level on these estimated data equals to that in its original exchanging subsystem, which is higher than that in the local subsystem.

Remark1: Overlapped buses generally appear between ISO and a member company.

Remark2: During the application of *Principle 1*, even the estimated angle difference between the overlapped buses can be exchanged as a pseudo measurement from A to B. However, modification in the original SE algorithm of B has to be made in order to utilize such a new type of measurements.

Therefore, a more practical scheme is to treat the power flow on the lines connecting the overlapped buses as the pseudo measurement to be exchanged from A to B. Note that the value on these measurements is not from raw data but from the result of SE in A. In other words, these power flow measurements should be treated as very special pseudo measurements in B, because their reliability are as high as in A, which is higher than that in B. Such an alternative scheme has similar effect to the angle difference exchange scheme, while it does not influence the original SE algorithm in B.

Principle 2: It is observed that if some boundary buses between subsystems are much stronger in the whole system than in individual subsystems, it benefits all involved member companies to have mutual raw data exchange near these boundary buses.

Step 4. Based on the three criteria developed in Section III, choose only the beneficial data exchange scheme from the multiple candidates proposed in Step 3.

VI. Numerical Results

IEEE 14-bus system mentioned before is used here to verify our conclusions. Our examples verify that:

1. Both member companies and ISO can benefit from mutual data exchange.
2. Arbitrary data exchange can harm the original measurement system sometimes.
3. The proposed principles are effective to find candidate of potential beneficial data exchanges.
4. The three criteria developed in Section III are valid to evaluate the quality of measurement system.

First, the information of BRD for the original systems as shown in Fig.2, 3, 4 and 5 is given in Table 2.

Case1: Member companies benefit from mutual data exchange

Bus1, Bus2, and Bus 5 are boundary buses between Company A and B. According to Table 2, those buses are much stronger in the whole system than in Company A and B.

Based on *Principle 2*, the mutual raw data exchange scheme on these three buses, which is shown in Fig.6 and Fig. 7, is selected as a candidate.

Based on Table3, in both Company A and B, Bus1, 2 and 5 become stronger after data exchange. According to the criteria, such a mutual data exchange is beneficial to both A and B.

TABLE 2. BRD INFORMATION BEFORE DATA EXCHANGE

System	BRD Information of Weak Buses
Whole System in Fig.2	{4|3:(9,9-7,4,7-4)} {6|2:(6-11,11-10,10)} {7|0:(7-8),(9,9-7,4,7-4)} {8|0:(7-8)} {9|3:(9,9-7,4,7-4),(11-10,10,9,9-10),(13-14,9-14,14,9)} {10|2:(6-11,11-10,10),(11-10,10,9,9-10)} {11|2:(6-11,11-10,10),(11-10,10,9,9-10)} {13|3: (13-14,9-14,14,9)} {14|3: (13-14,9-14,14,9)}
Company A in Fig.3	{1|1:(1-5,5-1)} {5|0: (5-6), (1-5,5-1)} {6|0:(5-6), (6-11), (6-12), (12-13)} {10|0:(11-10)} {11|0:(6-11),(11-10)} {12|0:(6-12),(12-13)} {13|0:(6-12),(12-13),(13-14)} {14|0: (13-14)}
Company B in Fig.4	{2|2:(2-3,4,2-4) ,(2-3,4,3-4),(4,2-4,3-4)} {3|2:(2-3,4,2-4),(2-3,4,3-4),(4,2-4,3-4)} {4|2:(4,9,7-4),(4,9,9-7),(9,7-4,9-7),(2-3,4,2-4),(2-3,4,3-4),(4,2-4,3-4)} {7|0:(7-8),(4,9,7-4),(4,9,9-7),(9,7-4,9-7)} {8|0:(7-8)} {9|2:(4,9,7-4),(4,9,9-7),(9,7-4,9-7)}
ISO in Fig. 5	{2|2:(2-3,2,3-4)} {3|2:(2-3,2,3-4)} {4|2:(2-3,2,3-4)}

TABLE 3. BRD INFORMATION OF A & B AFTER DATA EXCHANGE IN CASE1

System	BRD Information of Weak Buses
Company A in Fig.6	{1|3:(2,2-1,1,5-2)} {2|3:(2,2-1,1,5-2)} {5|0: (5-6), (2,2-1,1,5-2)} {6|0:(5-6), (6-11), (6-12), (12-13)} {10|0:(11-10)} {11|0:(6-11),(11-10)} {12|0:(6-12),(12-13)} {13|0:(6-12),(12-13),(13-14)} {14|0: (13-14)}
Company B in Fig.7	{1|3:(1,2,2-1,5-2) } {2|3: (1,2,2-1,5-2),(2-3,4,3-4,2),(2-3,4,3-4,2-4),(2-3,3-4,2,2-4),(4,3-4,2,2-4)} {3|3:(2-3,4,3-4,2) ,(2-3,4,3-4,2-4), (2-3,3-4,2,2-4) ,(4,3-4,2,2-4)} {4|2:(4,9,7-4),(4,9,9-7),(9,7-4,9-7), (2-3,4,3-4,2) ,(2-3,4,3-4,2-4), (2-3,3-4,2,2-4) ,(4,3-4,2,2-4)} {5|3:(1,2,2-1,5-2) } {7|0:(7-8),(4,9,7-4),(4,9,9-7),(9,7-4,9-7)} {8|0:(7-8)} {9|2:(4,9,7-4),(4,9,9-7),(9,7-4,9-7)}

The following facts verify the above conclusion:

Benefit to Company A: Suppose that both measurement *1-5* and *5-1* are bad data (all decreased by 0.1 p.u.). Since the measurements with largest normalized residues will be selected as the bad data according to the WLS algorithm of SE, from Table 4, it is concluded that there is no bad data when no data is exchanged. By contrast, *1-5* and *5-1* are both successfully identified after data exchange.

TABLE 4. NORMALIZED RESIDUES IN WLS ALGORITHM

Order	Original Company A in Fig.3		A after data exchange	
	Meas.	Residue	Meas.	Residue
1	The residues are all very small.		*5-1*	73
2	No bad data is found.		*1-5*	71

Benefit to Company B: Suppose that both measurement *2-3* and *2-4* are bad data (all increase by 0.1 p.u.). According to Table 5, it is concluded that before data exchange *4*, *7-4* and *3-4* is detected as bad data, which is totally wrong. By contrast, *2-3* and *2-4* are detected successfully after data exchange.

TABLE 5. NORMALIZED RESIDUES IN WLS ALGORITHM FOR B

Order	Original Company B in Fig.4		B after data exchange	
	Meas.	Residue	Meas.	Residue
1	4	47	*2*	88
2	7-4	44	*2-4*	64
3	3-4	30	*2-3*	58

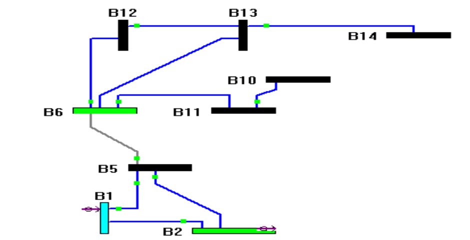

Fig.6 Extended System of Company A after data exchange from B

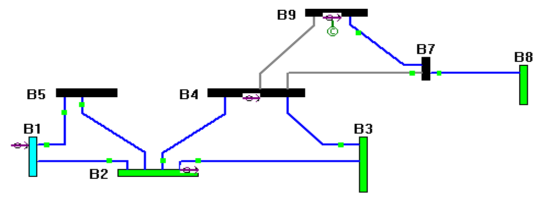

Fig.7 Extended system of Company B after data exchange from A

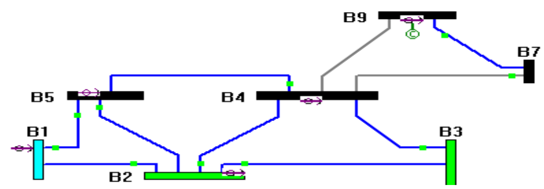

Fig.8 Extended system of ISO after data exchange from B

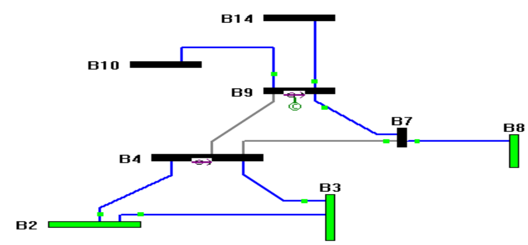

Fig.9 Extend system of Company B after data exchange from A

Case2: ISO and company benefit from mutual data exchange

Bus 3 and 4 are boundary buses of ISO to B, which are much weaker in ISO than in the whole system.

According to *Principle 2*, the data exchange on these boundary buses from B to ISO as shown in Fig. 8 is selected as a candidate for data exchange.

After such a data exchange, BRD information on weak buses in ISO turns to be:

{4|2:(4,9,7-4),(4,9,9-7),(9,7-4,9-7),(4,7-4,9-7)};{7|2:(4,9,7-4),(4,9,9-7),(9,7-4,9-7),(4,7-4,9-7)};{9|2:(4,9,7-4),(4,9,9-7),(9,7-4,9-7),(4,7-4,9-7)}

It is found that the weak buses change from Bus 2 and 3 to Bus7 and 9. Since Bus7 and 9 are the extended buses with much less importance, the quality of measurement system for ISO improves according to Criteria 2.

The following fact verifies the above conclusion:

Benefit to ISO: Suppose that both measurement *2-3* and *2* are bad raw data (all increase by 0.1 p.u.). Based on Table 6, *3-4* is selected wrongly as the bad data before data exchange. By contrast, *2-3* is identified successfully after data exchange.

TABLE 6. NORMALIZED RESIDUES IN WLS ALGORITHM FOR ISO

Order	Original ISO in Fig.5		ISO in Fig.8 after data exchange	
	Meas.	Residue	Meas.	Residue
1	3-4	68	*2-3*	54

In addition, overlapping buses, Bus2, 3 and 4, are stronger in ISO than in Company B.

According to *Principle 1*, data exchange from ISO to B on these buses is a candidate. To avoid too much impact on the original SE algorithm of B, an alternative scheme is to exchange the power flow measurement on the lines connecting these buses, such as power flow measurement *2-3* and *2-4*. Since there are already raw measurements *2-3* and *2-4*, Company B can ignore these raw data and use the more reliable exchanged estimated data accordingly.

The following fact verifies the benefits of the estimated data exchange:

Benefit to Company B: Suppose that both measurement *2-4* and *2-3* are bad raw data (all increased by 0.1 p.u.). *4* and *7-4* are identified as bad data for B according to Table 7, which is totally incorrect. By contrast, *2-3* and *2-4* are identified successfully as bad data in ISO at the same time.

Therefore, SE in ISO corrects the value on *2-3* and *2-4* before ISO exchanges them to B. Then B uses the corrected estimated data and ignore the raw data on *2-3* and *2-4*. Accordingly, the influence of the bad data is eliminated in B.

TABLE 7. NORMALIZED RESIDUES IN WLS ALGORITHM FOR B & ISO

Order	Original Company B in Fig.4		Original ISO in Fig.5	
	Meas.	Residue	Meas.	Residue
1	*4*	47	*2-3*	95
2	*7-4*	44	*2-4*	83

Case3: Arbitrary data exchange harm original system

Bus 9, 10 and 14 are boundary buses of Company A and B. According to Table 2, these buses are not stronger in the whole system than in Company B.

Therefore, data exchange on these buses from A to B, which is shown in Fig.9, should not be selected as a candidate by our two principles. We can evaluate if we miss any potential benefit by ignoring the exchange.

Detailed BRD information for company B in Fig.9 is:

{2|2:(2-3,4,2-4) ,(2-3,4,3-4),(4,2-4,3-4)}
{3|2:(2-3,4,2-4),(2-3,4,3-4),(4,2-4,3-4)}
{4|2:(4,9,7-4),(4,9,9-7),(9,7-4,9-7),(2-3,4,2-4),(2-3,4,3-4),(4,2-4,3-4)}
{7|0:(7-8),(4,9,7-4),(4,9,9-7),(9,7-4,9-7)} {8|0:(7-8)}
{9|1: (9,9-10), (9,9-14),,(9-10,9-14),(4,9,7-4),(4,9,9-7),(9,7-4,9-7)}
{10|1: (9,9-10) ,(9-10,9-14)} {14|1: (9,9-14),(9-10,9-14)}

It is found that no bus is getting stronger. In other words, no obvious benefit is obtained.

In addition, such a data exchange introduces possible raw leverage point and also increases the number of calculated buses, which make SE more complicated and time-consuming. Also, data exchange needs investment on communication channel devices, which costs Company B more money.

Therefore, such a data exchange scheme will not benefit Company B. This further verifies our principles.

VII. CONCLUSIONS

This paper focuses on how to improve the quality of measurement system of member companies or ISO by exchanging raw or estimated data with member companies or ISO. With the concept of BRD and leverage points, some criteria to evaluate the quality of measurement system are developed. Accordingly, a heuristic measurement design algorithm under distributed multi-utility operation is presented to search for possible beneficial data exchange schemes. The numerical tests on IEEE-14 Bus sample system verify that every member companies including ISO can benefit from mutual raw or estimated data exchange when some principles of design are carefully applied. On the other hand, arbitrary data exchange scheme may harm the estimators.

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IX. BIOGRAPHIES

Dr. Garng M. Huang received his B.S. and M.S. in E.E. from National Chiao Tung University, Hsinchu, Taiwan, R.O.C. in 1975, 1977 respectively. He received his doctorate degree in Systems Science and Mathematics from Washington University, St. Louis in 1980. He had been teaching there since then until 1984. He joined Texas A&M University, Department of Electrical Engineering in 1984. He is currently a professor and the director of graduate studies there. He has been working on many funded research projects, such as Emergency Control of Large Interconnected Power System, HVDC Systems, Restoration of Large Scale Power Systems, On-line Detection of System Instabilities and On-line Stabilization of Large Power Systems, Fast Parallel/Distributed Textured Algorithms, Fast Parallel Textured Algorithms for Large Power Systems, Hierarchical Aggregation and Decomposition Algorithm for Data Network Routing Problem, etc. His current interest is the large-scale systems theory, large scale parallel/distributed computing and control and their applications.

Dr. Huang is a senior Member of IEEE, and a Registered Professional Engineer of Texas. He has served as the Technical Committee Chairman of Energy System Control Committee and an associated editor in the IEEE Automatic Control Society; he has also been serving in a number of committees and subcommittees of IEEE PAS Society. Dr. Huang has published more than a hundred papers and reports in the areas of nonlinear distributed control systems, parallel/distributed computing and their applications to power systems, data networks and flexible structures.

Jiansheng Lei received his B.S. and M.S. both in Electrical Engineering from Tsinghua University, Beijing, China, respectively in 1998 and 2000. Presently he is a PH.D. student under the guidance of Dr. Huang in Texas A&M University. His current research interests include power system analysis and its application in power market.