Data Exchange Design and A Textured State Estimation Algorithm For Distributed Multi-Utility Operations In Electric Power Market

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Topics Today

• Topic 1: An expert system is proposed to search for most beneficial and efficient data exchange schemes while avoid harmful data exchange at the same time. In addition, the impact of data exchange on new measurement design and the issues on price of exchanged data are also discussed.

• Topic 2: Based on the data exchange design, a concurrent non-recursive textured algorithm for distributed multi-utility state estimation is formulated to avoid the disadvantages of both One State Estimator (OSE) and existing distributed state estimation (DSE) algorithms. The newly proposed algorithm is especially useful for large-scale power systems with multiple independent existing distributed estimators, such as Mega Regional Transmission Organizations (Mega-RTOs).
Background (1)

- State estimation (SE) 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.
Background (2)

- In the regulated environment, the whole power system is owned by a limited number of locally monopolistic organizations. There is almost no need to exchange data with other organizations. Note: ‘Data’ mainly refers to both raw instrumentation data and estimation results.

- In a deregulated environment, there are multiple member companies who must cooperate to run the system and to achieve their own economic goals. Power companies are releasing their transmission grids to form ISOs/RTOs while their own local state estimators are already in use.
A recent trend for these ISOs/RTOs is to further cooperate and to run the power market on even a bigger grid as a Mega-RTO for a better market efficiency. The grid of an ISO/RTO could be large. The size of Mega-RTO is even bigger, as concluded recently by Federal Energy Regulatory Commission (FREC) [2] that only four Mega-RTOs should cover the entire nation beside Texas.
Topic 1 Data Exchange

• How to exchange instrumentation or estimated data with neighboring entities?
  ➢ New issues under power market environment
  ➢ Selected data exchange improves the quality of estimators in individual entities, on both estimation reliability and accuracy.
  ➢ Traditional measurement placement methodology need to be modified to fully utilize the benefit of data exchange.
  ➢ Not necessarily all data exchanges are beneficial.
  ➢ Critical to the newly proposed textured distributed state estimation algorithm in Topic 2.
Bus Credibility Index \( BCI(b,S) \)

- Estimation Reliability: bad data detection and identification capability and probability to maintain observability under measurement loss
- BCI is a probability measure that quantifies the estimation reliability on bus \( b \) with respect to a specified system \( S \).
- A more accurate criterion compared with local or global bus redundancy level
- data exchanges modify the original system \( S \) to \( S' \), and the incremental difference of BCI from \((b,S)\) to \((b,S')\) stands for the benefit of such a data exchange on bus \( b \).
Knowledge Base

- **Raw facts**
  - The configuration, parameters and ownership of current power system network and measurement system;
  - The failure probability and accuracy of measurements;
  - The cost of instrumentation and estimated data exchange;

- $BCI(b, S)$

- **Variance of State Estimation Errors**
  - Accuracy on bus $b$ with respect to a specific system $S$
A Reasoning Machine (1)

- The distributed state estimation algorithm is discussed in Topic 2. Here the design of data exchange scheme is the focus.
- An IEEE-14 Bus system is used to illustrate how the reasoning machine works.
- Note that the algorithm and rules are applicable to any system.

Two RTOs merge into one Mega-RTO
A Reasoning Machine (2)

- **Step 1:** Determine maximum possible benefit on SE reliability performance

  \[ BCI \left( b_A, \text{Whole} \right) - BCI \left( b_A, A \right) \]

  \[ BCI \left( b_B, \text{Whole} \right) - BCI \left( b_B, B \right) \]

- **Remark:** Only boundary buses are concerned because in most cases BCI of internal buses also improves with a much smaller rate when BCI of boundary buses improve.

- **Step 2:** Ignore the boundary bus whose maximum possible benefit is small
A Reasoning Machine (3)

**Step 3.1: Rules to search for beneficial Instrumentation data exchange:**

- For boundary bus $b_A$ in A, instrumentation data exchange should extend to boundary bus $b_B$ in B under the condition:

$$BCI (b_B, Whole) > BCI (b_A, A)$$

For example, it is reasonable for $b_2$ and $b_4$ in B to extend to include $b_1$ and $b_5$ in A. But it does not follow the rule that $b_9$ in B extends to include $b_{10}$ or $b_{14}$ in A.

- Avoid forming a radial structure; instead, a loop is preferred. For example, $b_9$ in B extend only to $b_{10}$ in A will form a new radial branch $b_9$-$b_{10}$, which violates this principle.
Step 3.2: Rule to search for beneficial estimation data exchange:

If $BCI(b,A) > BCI(b,B)$

where bus $b$ is in the common part of A and B

Then estimation result exchange from A to B on this bus will improve $BCI(b,B)$ to the magnitude of $BCI(b,A)$. 
A Reasoning Machine (5)

- **Step 4.1** System A or B are modified accordingly based on the data exchange newly found.
  - BCI, estimation accuracy and the economic cost are evaluated on the ‘new’ system S’ to verify the benefit.
  - If BCI(b,S’) are already close to BCI(b,Whole), then there is no need to search for new data exchange for bus b.

- **Step 4.2** Searching process is iterated on all boundary buses.
Economic Factor (1)

- Hardware/software cost on data exchange implementation should be minimized given the condition that performance is satisfied.

  ➢ Even if scheme D1 is slightly better than scheme D2 in performance, but it is still possible for industry to select D1 when D1 is much more economical than D2.

  ➢ The benefit of different data exchange schemes may differ greatly. The benefit may saturate after some data exchange, which implies no major benefit can be obtained for further data exchange.
Economic Factor (2)

- Price tag reflects not only installation cost but also market value.
  - It is possible for system A to attach a rather high price tag to a measurement that is especially useful to system B.

- The proposed expert system is critical for the companies to determine the market price based on the benefit of data exchange.
Economic Factor (3)

- New measurements can be sold to other companies
- Data exchange will have some impact on measurement placement decision.
- Proposed expert system is useful for the new measurement placement decision
Case 1: Harmful Data Exchange (1)

- Not following our principles
- SE reliability decreases
- SE accuracy decreases
- Wasted investment

<table>
<thead>
<tr>
<th></th>
<th>Original B</th>
<th>Modified B</th>
<th>Whole System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average BCI on the buses of B</td>
<td>0.9647</td>
<td>0.9643</td>
<td>0.9662</td>
</tr>
</tbody>
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<tr>
<td>Average Estimation Error on the buses of B</td>
<td>7.7314e-007</td>
<td>8.1738e-007</td>
<td>2.6326e-007</td>
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</table>
Case 1: Harmful Data Exchange (2)

**Normalized Residues For Local Estimator B**

<table>
<thead>
<tr>
<th>Iteration No.</th>
<th>B before data exchange</th>
<th>B after harmful data exchange</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>9</td>
<td>164.72</td>
</tr>
<tr>
<td>2nd</td>
<td>9-7</td>
<td>108.05</td>
</tr>
<tr>
<td>3rd</td>
<td>No bad data detected</td>
<td>4</td>
</tr>
<tr>
<td>4th</td>
<td>N/A</td>
<td>No bad data detected</td>
</tr>
</tbody>
</table>

**Assumption:**
- 9 and 9-7 are bad data, where the sign of measurements are reversed.
- No bad data on the exchanged data.

**Facts:**
- Before data exchange these two bad data are identified correctly.
- After harmful data exchange these bad data cannot be detected at all.
- Estimation result on local estimator area is harmed.
Case2: Efficiency of Beneficial Data Exchange

- BCI is as good as the whole system
- Estimation Accuracy is almost as good as the whole system
- Following our rules lead to high efficient data exchange

Local estimators after beneficial data exchange

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<td>2.6326e-007</td>
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Case 3: Impact on New Measurement Placement (1)

- Suppose the probability of accidents in the SCADA on station of b1 is extremely high
- System becomes unobservable and traditionally at least one new measurement has to be installed.
- With data exchange, such a new measurement is not necessarily needed.

When we follow the data exchange scheme suggested in Case 2, state estimation in A can be run normally because the estimation result on b1 and b5 is exchanged from B to A (B is still observable even under such an accident).
Case 4: Impact on New Measurement Placement (2)

- Suppose A wants to improve the estimation accuracy on b5.
- From a traditional measurement placement viewpoint, there are basically two alternatives: improve the accuracy on measurement 5-1 or 5-6.
- With data exchange, it is better for A to invest on measurement 5-1 instead of on measurement 5-6.
  - If the accuracy of 5-1 improves, the accuracy of B also improves with data exchange in Case 2.
  - It makes sense for B to share part of the cost with A.
Conclusions on Topic 1 (1)

- Selected data exchange improves the estimator quality of individual entities on both estimation reliability and accuracy.

- Benefit of different data exchange can be quite different:
  - Properly selected data exchanges will enable the local distributed estimator perform as well as the one estimator for the whole system in both SE reliability and accuracy.
  - Poorly designed data exchanges, which does not follow our design principles, may be harmful to local estimators.

- Data exchange has an impact on new measurement design
Conclusions on Topic 1 (2)

- Proposed expert system is useful in:
  - Design of the data exchange scheme
  - New measurement placement decision
  - Determination of the market price for date exchange
  - Newly proposed distributed SE algorithm
**Topic 2: State estimation on Mega-RTO**

- **How to avoid the disadvantages of One State Estimator (OSE) in Mega-RTO?**
  - Huge investment and maintenance cost
  - Poor performance because of the size of system
  - Waste of existing local state estimators

- **How to avoid the disadvantages of existing distributed state estimation (DSE) algorithm?**
  - Low bad data detection ability
  - Low estimation accuracy on boundary buses
  - Bottleneck issues on central controlling node

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*Whole System Diagram*

- RTO A
- RTO B
- RTO C
- RTO D
- *Mega-RTO*
Concurrent Textured DSE Algorithm

- Step 1. Select a set of real time instrumentation data to be exchanged between neighboring entities.
- Step 2. Select a set of estimated data to be exchanged between neighboring entities.
- Step 3. Taking the exchanged instrumentation data into account, multiple local estimators distributed in different entities are executed simultaneously and asynchronously until they converge individually to the desired tolerance.
- Step 4. In view of the exchanged estimated data, modify the estimation result of local estimators accordingly and re-run bad data analysis.
- Step 5. Based on the modified results of local estimators, finally determine the state of whole system according to the different accuracy and reliability of estimators.
Advantages Of New Algorithm

- Higher bad data detection ability
- Higher estimation accuracy on boundary buses
- Avoid central controlling node
- Faster speed after removal of recursive process from original textured algorithm
- More flexible and economic where current existing estimators can be fully utilized
- The performance of individual existing estimators improves as well. Accordingly, they are more willing to share the information for their own benefits even without the estimation on whole system.
Textured Decomposition For Step 1 and Step 2

- Two main rules in Topic 1 are proposed to search for the estimated data/instrumentation exchange.
- Poorly designed data exchanges, which did not follow our design principles, may be harmful to local estimators.
- Properly selected data exchanges will enable the local distributed estimator performance almost as good as one estimator on the whole system in both estimation reliability and estimation accuracy.
- Refer to Topic 1 for details
Sparse Technique In Step 4

- Sparse Technique

\[(A + MaN^T)^{-1} = A^{-1}A^{-1}M(a^{-1} + N^T A^{-1}M)^{-1}N^T A^{-1}\]

- Application

\[
\begin{bmatrix}
    z \\
    z_{new}
\end{bmatrix}
= \begin{bmatrix}
    h(x) \\
    h_{new}(x)
\end{bmatrix} + \begin{bmatrix}
    e \\
    e_{new}
\end{bmatrix}
\Rightarrow
\]

\[\Delta x_i = \left( G + H_{new}^T R_{new}^{-1} H_{new} \right)^{-1} \left( H^T R_{new}^{-1} \Delta z + H_{new}^T R_{new}^{-1} \Delta z_{new} \right)\]

where the dimension of \( R_{new} \) is much lower than that of \( G \)

\[(H^T R_{new}^{-1} \Delta z) \text{ and } G^{-1} \text{ are known already}\]

- Step 4 is no longer time-consuming
Determination of State Over The Whole Grid in Step5

- Determine the angle difference of reference buses between any two local estimators:
  \[
  \Delta \theta_{AB} = \sum_{i \in I} (\theta_{i,A} - \theta_{i,B})(c_{i,A}^{-1} + c_{i,B}^{-1}) / \sum_{i \in I} (c_{i,A}^{-1} + c_{i,B}^{-1})
  \]

- Select a reference bus of one estimator as global reference bus.

- Determine the angle difference between this global reference bus and reference bus of any local estimator:
  \[
  \Delta \theta_{AC} = \Delta \theta_{AB} + \Delta \theta_{BC}
  \]

- Estimated angle of local estimator C is subtracted with \( \Delta \theta_{AC} \).

- For overlapping bus i belonging to multiple local estimators:
  \[
  x_i = \sum_{j=1}^{m} (x_{i,K_j} c_{i,K_j}^{-1}) / \sum_{i=1}^{m} c_{i,K_j}^{-1}
  \]
Estimation Accuracy and Boundary Discrepancy

- Derivation 0.01 p.u. on meas. 5-2
- Estimation accuracy increases compared with existing DSE while boundary discrepancy decreases from 0.004 in existing DSE to 0.002 in textured DSE

Table 1. Estimation Result Derivation

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>OSE</th>
<th>Existing DSE</th>
<th>Textured DSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_2$ derivation</td>
<td>0.003</td>
<td>0.007</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Fig. 1 Local estimators after raw data exchange
Bad Data Detection Ability

Table 2. Normalized Residues For Local Estimator A and B

<table>
<thead>
<tr>
<th>Order</th>
<th>A in Fig.1</th>
<th>B in Fig.1</th>
<th>A in Fig.1 after estimated data exchange</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>68.95</td>
<td>5-1</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>59.4</td>
<td>1-5</td>
</tr>
</tbody>
</table>

- **Step1.** A in Fig.1 is executed and 1 and 5 are identified incorrectly as bad data.
- **Step2.** Simultaneously, B in Fig.1 is executed and 1-5 and 5-1 are both identified as bad data successfully one by one.
- **Step3.** The corrected values on 1-5 and 5-1 are exchanged from B to A, And these values are treated in A as pseudo measurements with particular high accuracy and reliability.
- **Step4.** Taking the new pseudo measurements into account, A modifies its own estimation result and re-run bad data analysis. This time 1-5 and 5-1 are both identified successfully as bad data.
Conclusion on Topic 2

- The determination of state over Mega-RTO becomes very challenging due to its size. Instead of starting a totally new estimator over the whole grid, a distributed concurrent textured algorithm is proposed, where the currently existing state estimators distributed in different companies/ISOs/RTOs are fully utilized.

- The new algorithm is based on some extra communication for some instrumentation and estimated data exchange, and such an algorithm is non-recursive, asynchronous and avoids central controlling node. Therefore, it is fast, flexible and practical.

- Performance of each estimator improves greatly via data exchange when some principles are applied carefully. And the state of whole system can be determined directly based on the result of current distributed estimators almost without any loss of accuracy and reliability compared with integrated SE.
References


Thanks!

Any comments are highly appreciated.

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