A Robust State Estimation Framework Considering Measurement Correlations and Imperfect Synchronization

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Hybrid State Estimation Model

- Objective: obtain the best estimate of bus voltage magnitudes and angles from a redundant collection of SCADA and PMU measurements.
- Estimation Model: for an N-bus power system, the relationship between the m-dimensional measurement vector $\boldsymbol{z}$ and the n-dimensional state vector $\boldsymbol{x}$ is

$$\boldsymbol{z} = \boldsymbol{h}(\boldsymbol{x}) + \boldsymbol{e}$$

where $\boldsymbol{h}$ is the nonlinear vector-valued function; $\boldsymbol{e}$ is the error vector used to characterize the model uncertainties as well as measurement error.

Hybrid State Estimation Methods

- Strategy 1: PMU measurements are directly augmented with SCADA measurements for joint estimation;
- Strategy 2: measured PMU phasors are converted to power measurements, which are further used together with SCADA measurements for estimation;
- Strategy 3: SCADA and PMU measurements are separately processed and the data fusion process is initiated to obtain more consistent and accurate state estimates;
- Strategy 4: PMU measurements are buffered and their statistical information is extracted. The latter is used together with the latest SCADA measurements for state estimation.

Assumptions of Hybrid State Estimation

- Synchronization assumption: the SCADA and PMU measurements arrive simultaneously at the control center so that they can be used together for state estimation;
- Independence assumption: both SCADA and PMU measurements are assumed to have independent random errors with zero means and known variances σ;
- Noise assumption: Gaussian noise is assumed for both SCADA and PMU measurements.

[R1] J. B. Zhao, S. Wang, L. Mili, R. Huang, Z. Huang, "A robust state estimation framework considering measurement correlations and imperfect synchronization," IEEE Trans. Power Systems, vol. 33, no. 4, pp. 4604-4613, 2018.
[R2] J. B. Zhao, L. Mili, "A framework for robust hybrid state estimation with unknown measurement noise statistics," IEEE Trans. Industrial Informatics, vol. 14, no. 5, pp. 1866-1875, 2018.

Assumption Assessment

- Due to communication issues, different sampling speed, etc., SCADA and PMU measurements typically do not arrive the control center simultaneously (time-skewness);
- Since the metered real and reactive power pairs or flows are calculated by the same PT and CT, they are correlated;

$$P_i = V_i \, I_i \cos(\delta_i), \; Q_i = V_i \, I_i \sin(\delta_i),$$

$$P_i = \sum_{j \in \mathcal{N}_i} P_{ij}^f, \; Q_i = \sum_{j \in \mathcal{N}_i} Q_{ij}^f,$$

- Due to unknown communication channel noise, aging process of PT and CT, etc., the measurement noise is unknown and deviates from Gaussian assumption.

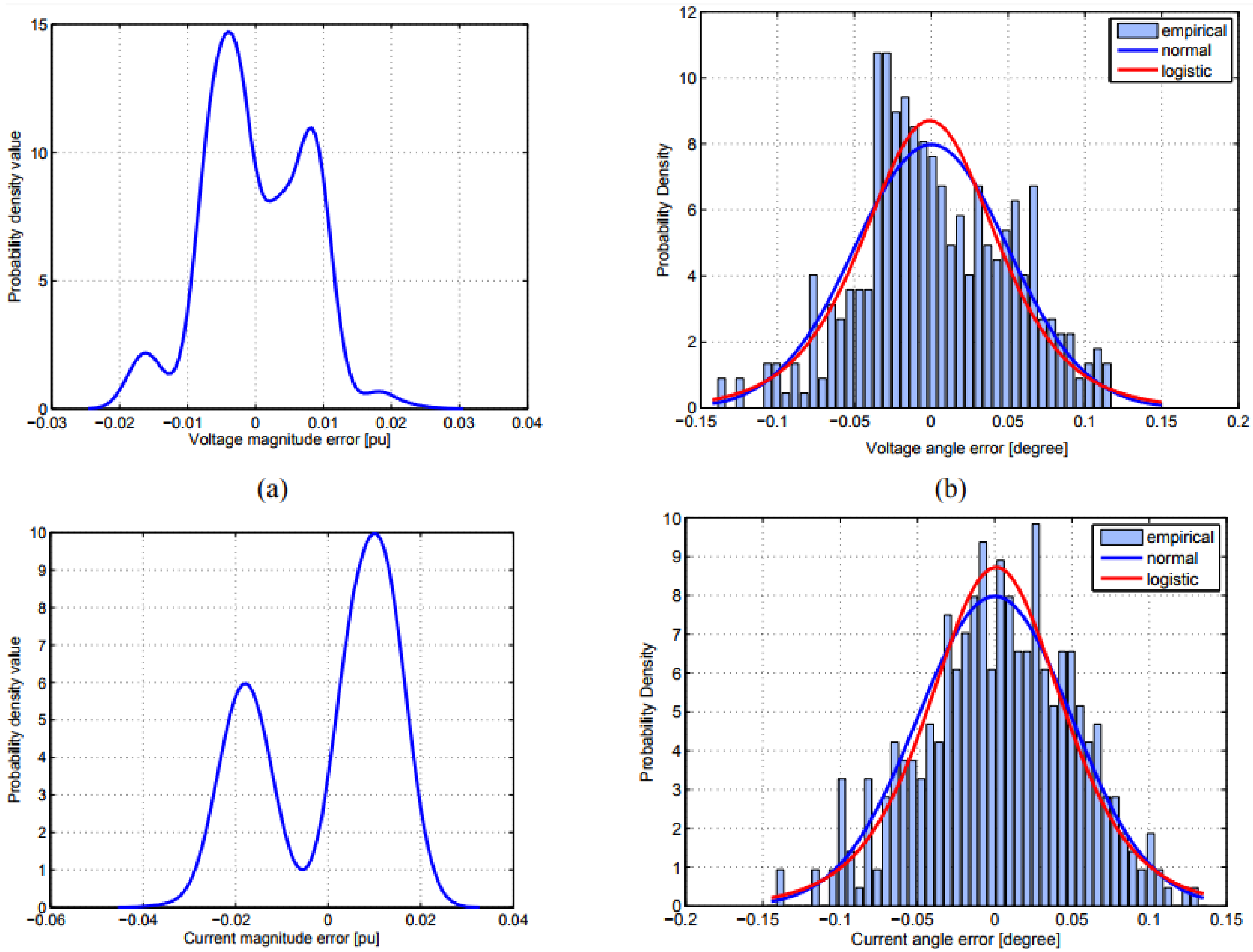
Non-Gaussian PMU Measurement Noise

Voltage magnitude

Voltage angle

Current magnitude

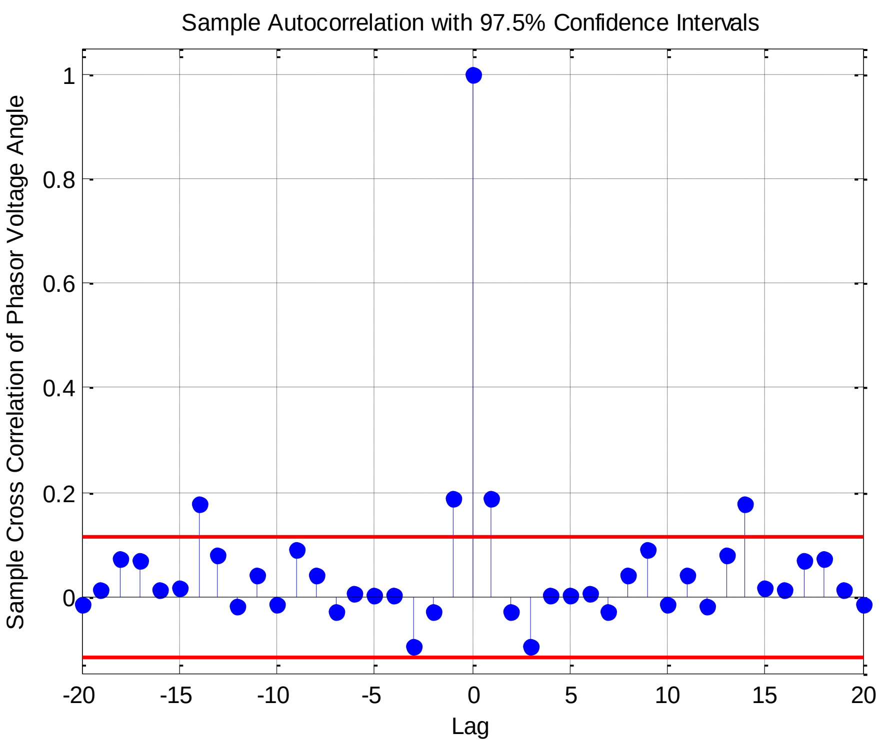
Current angle



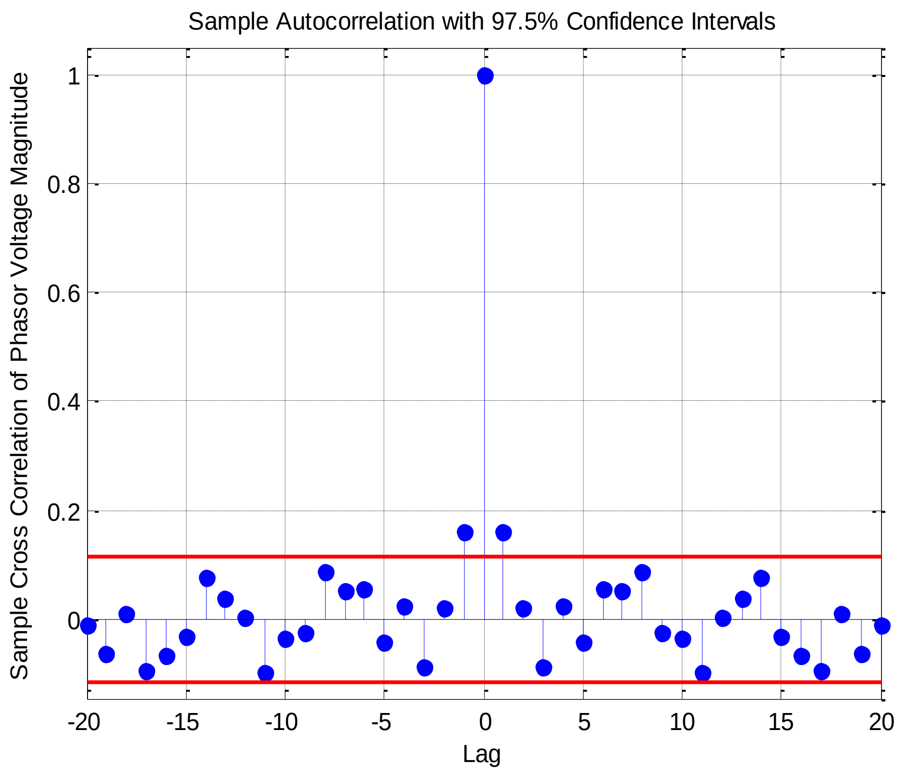
(a) (b)

[R3] S. Wang, J. B. Zhao, Z. Huang, R. Diao "Assessing Gaussian Assumption of PMU Measurement Error Using Field Data," IEEE Trans. Power Delivery, 2017.

Temporal and Spatial Correlation of PMU Measurements



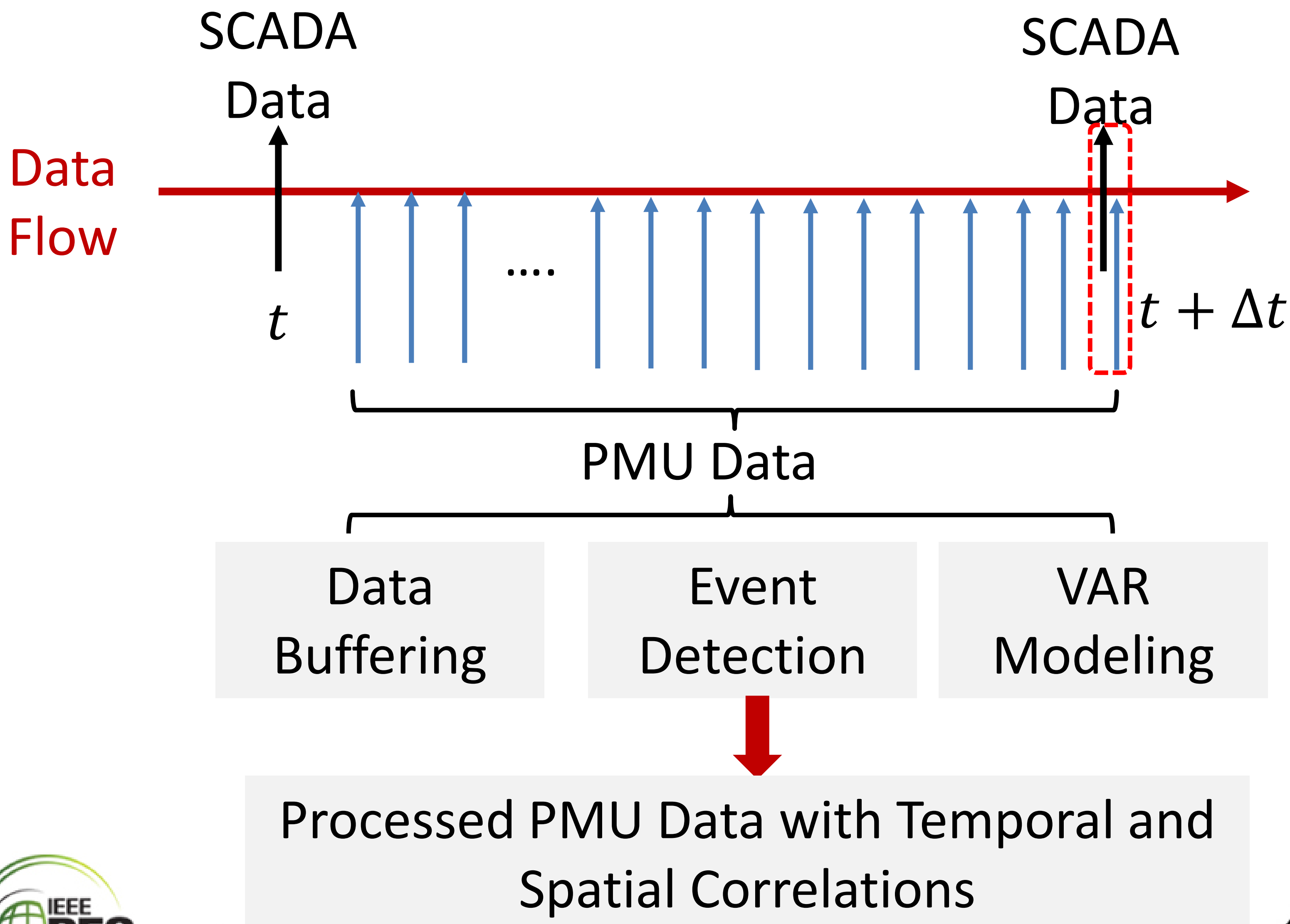
Voltage angle



Voltage magnitude

Validated using the field PMU data from WECC system

Proposed Multi-scale Data Processing Scheme



Proposed Estimation Framework

- **Modeling SCADA measurement correlation**: leveraging the unscented transformation to propagate the PT/CT error through the following nonlinear function

$$\boldsymbol{z}^s = \boldsymbol{f}(\boldsymbol{u}), \quad \begin{cases} P_i = V_i\, I_i \cos(\delta_i),\; Q_i = V_i\, I_i \sin(\delta_i), \\ P_i = \sum_{j\in\mathcal{N}_i} P_{ij}^f,\; Q_i = \sum_{j\in\mathcal{N}_i} Q_{ij}^f, \end{cases}$$

Specifically, generate $2n_s$ sigma points with weights $\varpi_i = 1/2n_s$and calculate the correlation matrix:

$$\widehat{\boldsymbol{z}}_k^s = \sum_{i=1}^{2n_s} \varpi_i \boldsymbol{l}_i, \quad \boxed{\widehat{\boldsymbol{R}}_k^s = \sum_{i=1}^{2n_s} \varpi_i (\boldsymbol{l}_i - \widehat{\boldsymbol{z}}_k^s)(\boldsymbol{l}_i - \widehat{\boldsymbol{z}}_k^s)^T,}$$

$$\boldsymbol{\chi}_i = \boldsymbol{u} \pm \left(\sqrt{2n_s \boldsymbol{\Omega}}\right)_i, \quad \boldsymbol{l}_i = \boldsymbol{f}(\boldsymbol{\chi}_i).$$

Non-diagonal matrix

Proposed Estimation Framework

- Modeling temporal and spatial correlations of PMU measurements: the PMU measurements between two SCADA scans are buffered and a vector-auto regressive (VAR) model is adopted to capture correlations.

$$\boldsymbol{p}_k = \boldsymbol{\Phi}_k \boldsymbol{p}_{k-1} + \boldsymbol{\varepsilon}_k$$

where $\boldsymbol{p}_k$ denotes the buffered PMU measurement vector; $\boldsymbol{\Phi}_k$ denotes the non-diagonal transition matrix; $\boldsymbol{\varepsilon}_k$ is assumed to be Gaussian. Let M denote the length of the buffered measurements, $\boldsymbol{Y} = [\boldsymbol{p}_{k-2}, \dots, \boldsymbol{p}_{k-M-3}]^T$ $\boldsymbol{\tau} = [\boldsymbol{\varepsilon}_{k-1}, \dots, \boldsymbol{\varepsilon}_{k-M-3}]^T$ $\boldsymbol{X} = [\boldsymbol{p}_{k-1}, \dots, \boldsymbol{p}_{k-M-2}]^T$, we get

$$\boldsymbol{X} = \boldsymbol{Y}\boldsymbol{\Phi}_k + \boldsymbol{\tau}$$

Proposed Estimation Framework

- **Event detection and weighting buffered measurements**: detect event and downweight the affected measurements through projection statistics

$$PS_i = \max_{\|\boldsymbol{\ell}\|=1} \frac{\left| \boldsymbol{l}_i^T \boldsymbol{\ell} - med_j \left(\boldsymbol{l}_j^T \boldsymbol{\ell} \right) \right|}{1.4826\, med_\varrho \left| \boldsymbol{l}_\varrho^T \boldsymbol{\ell} - med_j \left(\boldsymbol{l}_i^T \boldsymbol{\ell} \right) \right|},$$

Then, the transition matrix and the VAR model error covariance matrix can be estimated by

$$\widehat{\boldsymbol{\Phi}}_k = (\boldsymbol{Y}^T \boldsymbol{W}_v \boldsymbol{Y})^{-1} \boldsymbol{Y}^T \boldsymbol{W}_v \boldsymbol{X},$$

$$\widehat{\boldsymbol{S}}_k = (\boldsymbol{Y}^T \boldsymbol{W}_v \boldsymbol{Y})^{-1},$$

Subsequently, the PMU measurements can be forecasted through

$$\widehat{\boldsymbol{p}}_{k|k-1} = \widehat{\boldsymbol{\Phi}}_k \boldsymbol{p}_{k-1},\ \widehat{\boldsymbol{\Sigma}}_{k|k-1} = \widehat{\boldsymbol{\Phi}}_k \widehat{\boldsymbol{\Sigma}}_{k-1|k-1} \widehat{\boldsymbol{\Phi}}_k^T + \widehat{\boldsymbol{S}}_k,$$

Proposed Robust Estimator

- **Robust estimation:** upon the arrival of the SCADA and the PMU measurements at time step *k*, we can obtain the following generalized regression model

$$\boldsymbol{y}_k = \boldsymbol{g}(\boldsymbol{x}_k) + \boldsymbol{\eta}_k$$

Then, robust GM-estimator criterion is adopted

$$J(\boldsymbol{x}) = \sum_{i=1}^{m+m_p} \omega_i^2 \rho(r_{S_i}),$$

$$\rho\left(r_{S_i}\right) = \begin{cases} r_{S_i}^2/2 & \text{for } \left|r_{S_i}\right| \leq \lambda \\ \lambda\left|r_{S_i}\right| - \lambda^2/2 & \text{for } \left|r_{S_i}\right| > \lambda \end{cases},$$

where r_{Si} is the standard residual.

[R1] J. B. Zhao, S. Wang, L. Mili, R. Huang, Z. Huang, "A robust state estimation framework considering measurement correlations and imperfect synchronization," IEEE Trans. Power Systems, vol. 33, no. 4, pp. 4604-4613, 2018.

Evaluation of Different Methods

- A1: only the SCADA measurements without correlations;
- A2: only the SCADA measurements but with correlations;
- A3: the latest PMU measurements and the correlated SCADA measurements;
- A4: the forecasted PMU measurements with temporal and spatial correlations and the correlated SCADA measurements;
- A5: the forecasted and the latest arriving PMU measurements together with the correlated SCADA measurements-**proposed non-robust method**;
- A6: **robust version of A5-proposed method**; when PMU measurements are delayed, only the other two types of measurements are processed.

Simulation Results

- Test systems: IEEE 30-bus and 118-bus systems;
- Measurement configuration:
  - IEEE 30-bus system: 18 pairs of power injections, 28 pairs of power flows and bus 1 voltage magnitude;
  - IEEE 118-bus system: 14 pairs of power injections, 186 pairs of power flows and bus 1 voltage magnitude;
- A varying percentage of system buses are randomly chosen for PMU installation, such as 20%-30%;
- Measurement noise: Gaussian with standard deviation 10^{-2} for PTs and CTs.

Ideal Condition: SCADA and the PMU measurements are synchronized, implying that they arrive simultaneously; no bad data occurs.

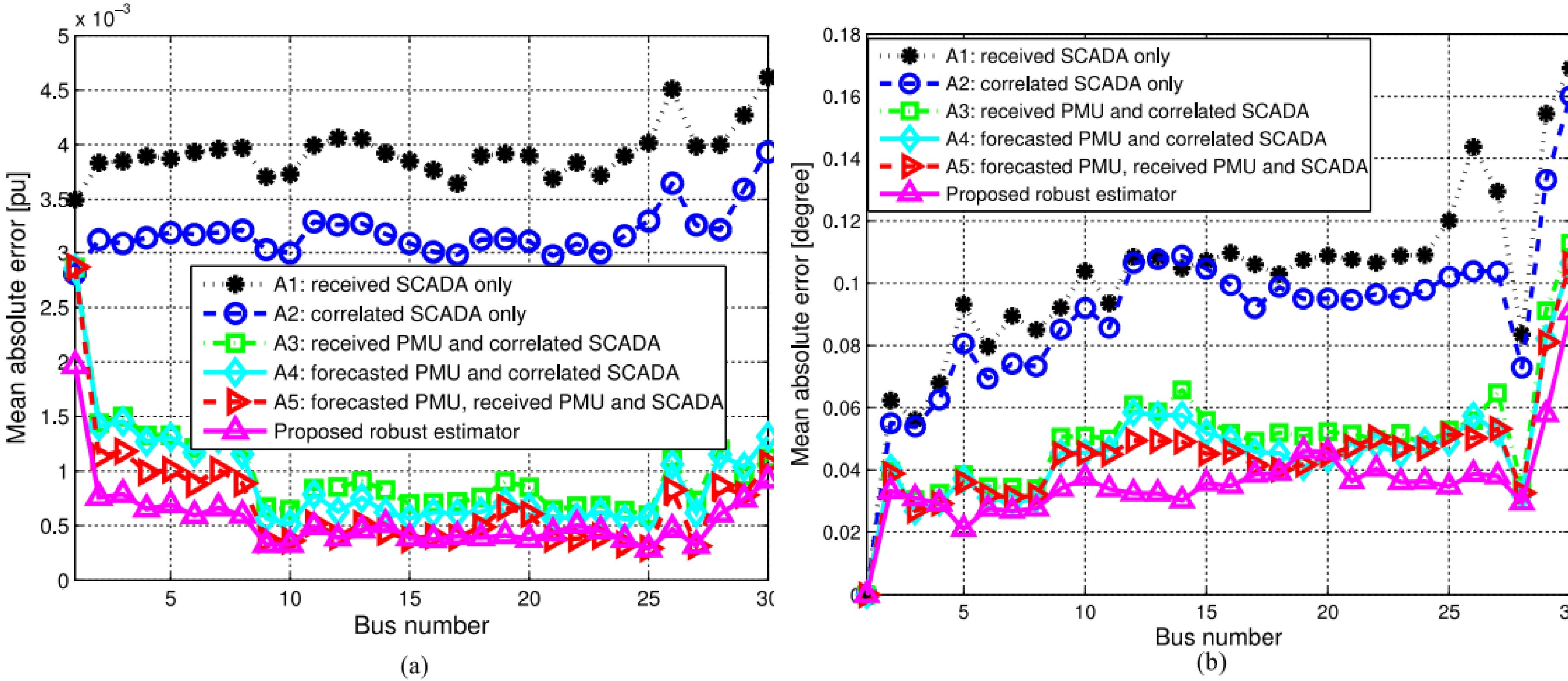


Fig. 1. MAE of the alternatives A1 through A6 for the IEEE 30-bus system, where 20% randomly chosen buses are deployed with the PMUs; (a) voltage magnitude; (b) voltage angle.

Impacts of the number of PMU measurements

Different percentages of buses are provided with PMUs for the IEEE 30-bus system

i) Case 1: 10%;

ii) Case 2: 20%;

iii) Case 3: full system observability with the minimum number of PMUs, that is, Buses 2, 3, 6, 9, 10, 12, 15, 19, 25 and 27 are provided with PMUs.

TABLE I
MAE FOR THE VOLTAGE ANGLES OF THE IEEE 30-BUS SYSTEM WITH DIFFERENT PMU PLACEMENTS

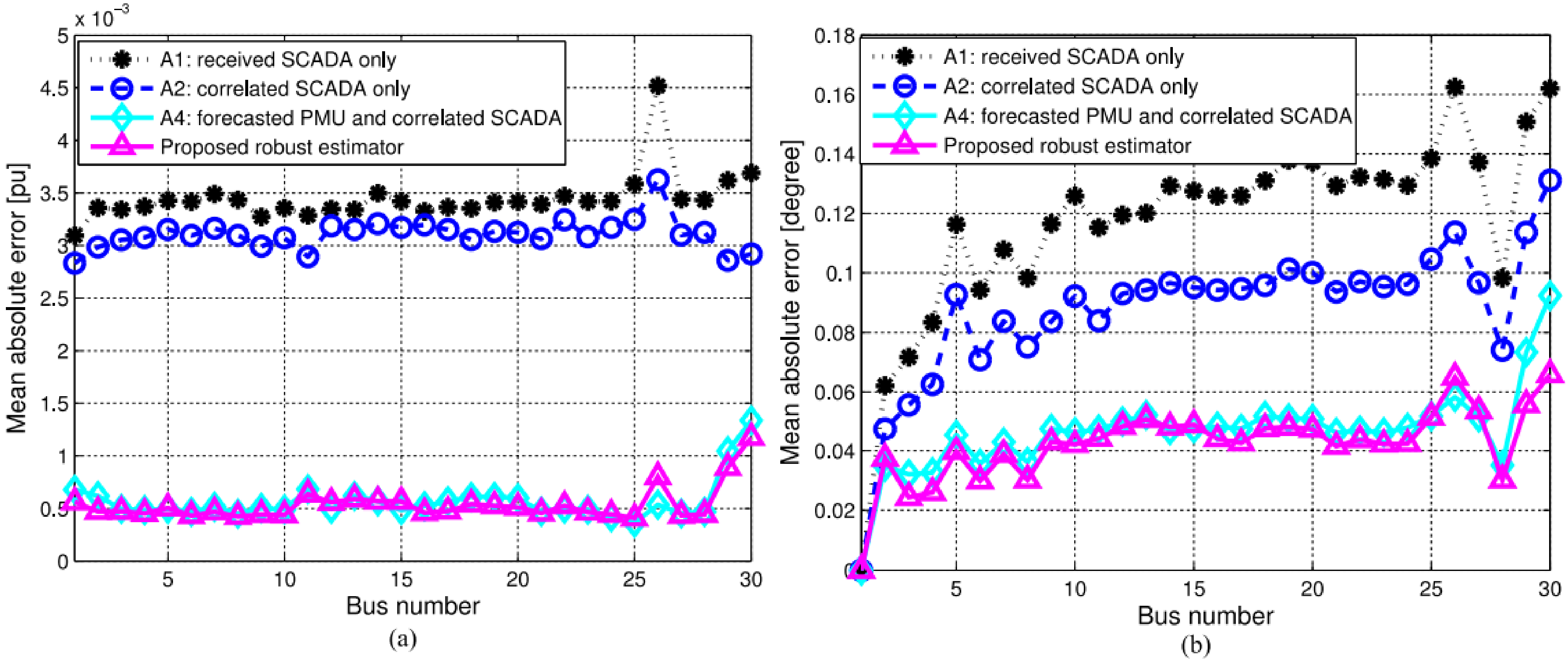
Cases	A3	A4	A5	Proposed method
Case 1	0.092	0.0875	0.0806	0.068
Case 2	0.0825	0.0749	0.071	0.051
Case 3	0.052	0.042	0.032	0.014

Impact of Imperfect Measurement Time Synchronization

Scenario 1: at the time instant where the state estimator is executed, only SCADA measurements arrive while PMU measurements are delayed. Then, the approaches A1 and A2 are not affected and A3 reduces to A2; A5 reduces to A4; the proposed approach will be the robust version of A4.

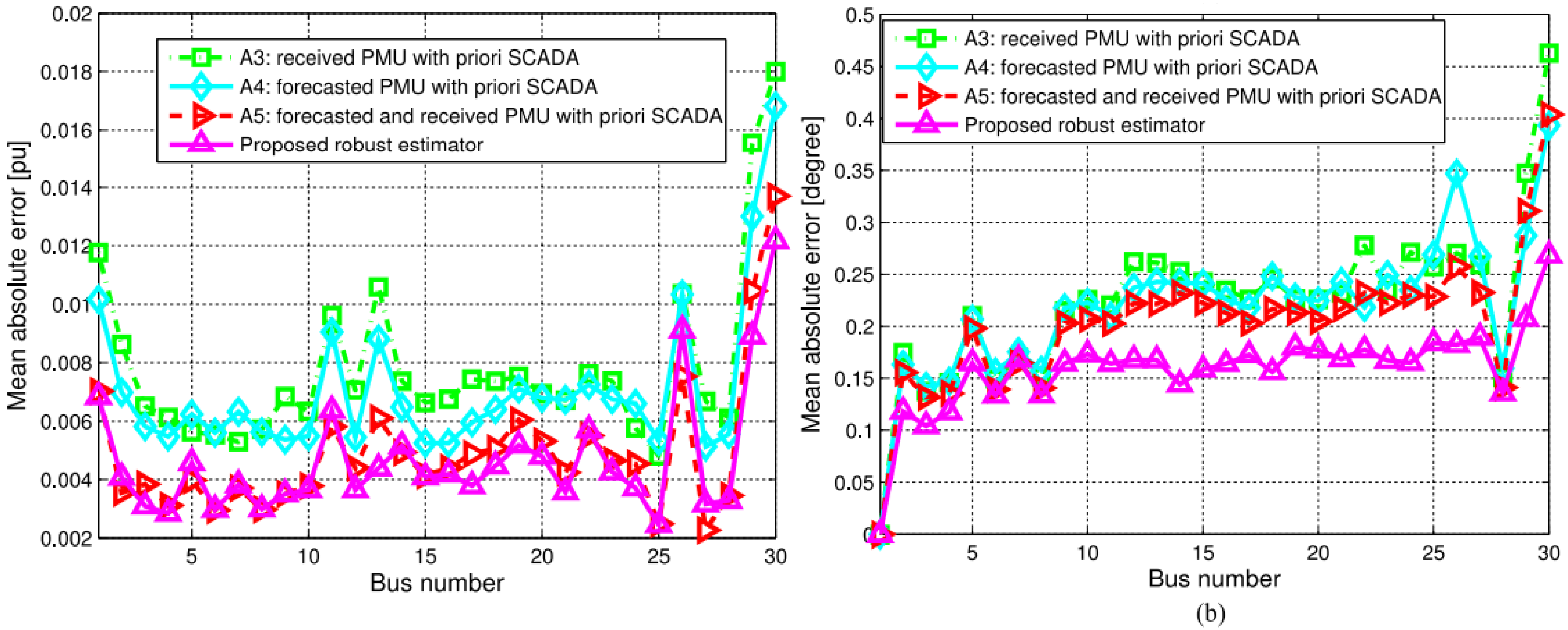
Scenario 2: only the received and the forecasted PMU measurements are available while the SCADA measurements are delayed. Consequently, the system is partially observable. To resolve this problem, prior estimates obtained at the latest state estimation run is used. It is found that for this scenario, the results provided by the alternatives A1 and A2 are very poor, making them not suitable for state estimation.

Results for Scenario 1: Delayed PMU Measurements



Scenario 1: MAE of each alternative on the IEEE 30-bus system in presence of imperfect measurement time synchronization, where 20% randomly chosen buses are provided with PMUs; (a) voltage magnitude; (b) voltage angle.

Results for Scenario 2: Delayed SCADA Measurements



Scenario 2: MAE of each alternative on the IEEE 30-bus system in presence of imperfect measurement time synchronization, where 20% randomly chosen buses are provided with PMUs; (a) voltage magnitude; (b) voltage angle.

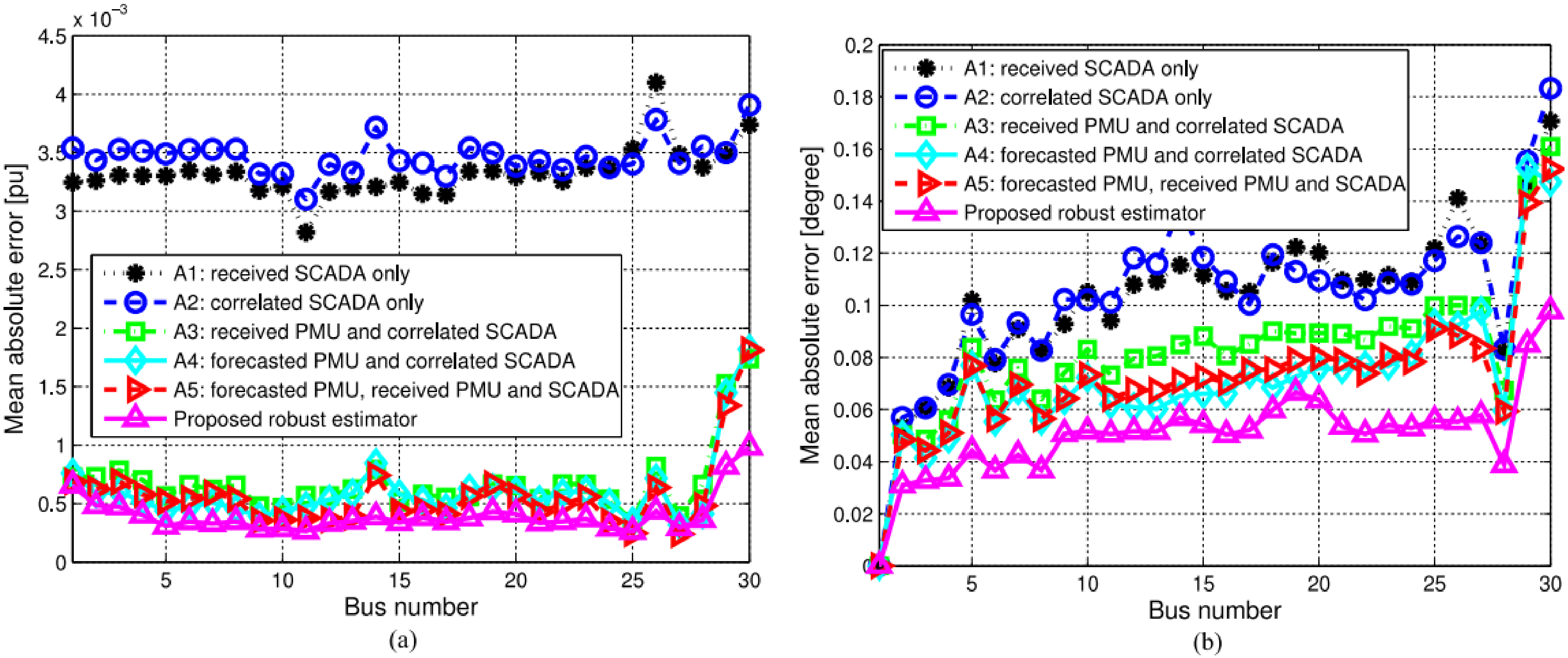
Impact of Bad Data

Case 1: four bad data occur, including two bad SCADA measurements P_8 and Q_8, as well as two bad PMU measurements, θ_{12} and current flow θ_{12-13}. They are assumed to be contaminated with 30% errors.

Case 2: four bad data occur, including two PMU measurements and two SCADA measurements; the latter are P_{19-20} and Q_{19-20}, which are leverage points whose magnitudes are assumed to be contaminated with 30% errors. Note that this is the case of interacting and conforming bad data. The bad PMU measurements are the same as in Case 4.

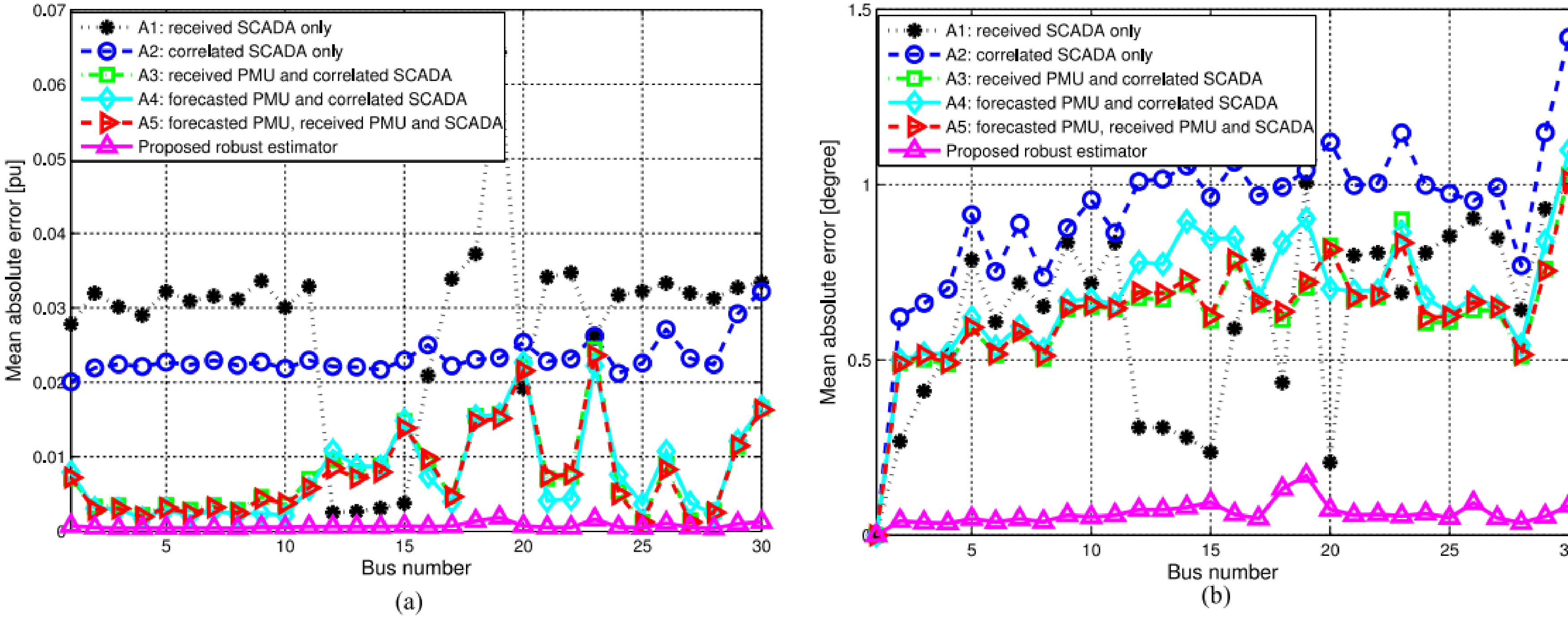
Bad data processing: the largest normalized residual statistical test is used to detect bad data; the latter is removed and state estimation is repeated until no bad data is identified.

Results: Non-Interacting and Conforming Bad Data



Case 1: MAE of each approach on the IEEE 30-bus system in presence of bad data, where 20% buses are deployed with PMUs; (a) voltage magnitude; (b) voltage angle.

Results: Interacting and Conforming Bad Data



Case 2: MAE of each of the six alternatives on the IEEE 30-bus system in presence of bad data, where 20% randomly chosen buses are provided with PMUs; (a) voltage magnitude; (b) voltage angle.

Conclusions

- The correlations of both the SCADA and the PMU measurements are taken into account to improve the state estimation accuracy;
- The impacts of imperfect time synchronization of the SCADA and the PMU measurements on the state estimation accuracy are investigated and mitigation methods are initiated;
- An extension of the robust GM-estimator is proposed by integrating the measurement correlations using a derived generalized regression model;
- The proposed method is robust to various types of bad data.

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