An Alternative Tool for Power System State Estimator

Introduction to Accurate Non-Divergent State Estimator (SE+)

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About Myself

Education:

Ph.D., Texas A&M University, 2000. Ph.D. advisor: Dr. Ali Abur, Northeastern University.

Work Experience:

2000 ~ 2002, power system engineer, ABB Automation Control, Santa Clara

2002 ~ 2003, senior analyst, ISO New England

2003 ~ 2008, assistant professor, UT Arlington (UTA)

2010 ~ 2013, associate professor, North Dakota State University (NDSU). Resigned the professor position to focus on developing a novel state estimator after our company obtained the first NSF grant in July 2013.

NSF Grants to develop a novel state estimator:

July – December 2013, Award ID #1315374

July – December 2015, Award ID #1519498

Mar. 2017 – Sept. 2019, Award ID #1660022

Mar. 2018 – Sept. 2019, Award ID #1660022 (extended to 2021)

Publications: 87

Published: 1 patent, 4 patent pending, 2 books, 3 book chapters, 27 journal papers, 55 conference papers.

Outline

1. Introduction to our Company SEG
2. Main Problems of Today's State Estimators (50+ years)
3. Introduction to State Estimator Plus (SE+) and IEEE 14 bus system example
4. An example of bad data rejection and recovery
5. Massive Testing results of SE+ on 13659 system and a real case.
6. Conclusions

Introduction to Smart Electric Grid, LLC

1. Registered at Texas in 2009 with an angel investment.

2. First National Science Foundation grant received in 2013.

3. We received 4 NSF grants so far since 2013, up to UD$ 1.2M.

4. State Estimator Plus was developed in 2020, solved vulnerability problems of SE open for 50+ years.

5. We have finished the testing on 25 real cases provided by 4 large companies in North America.

The Role of State Estimator in Power System Operations

Two things to be done by the driver:

1. Observe road condition using his eyes
2. Control the wheal

Two things to be done by the operator:

1. Observe system state by State Estimator
2. Control the generators / load

The Role of State Estimator in Power System Operations

The entire control and management software package is called Energy Management System (EMS)

Observe road state: driver's eyes

Run the car safely: driver

Observe system state: State Estimator

Run the system safely: Operator

State estimator:

1. Introduced by Prof. Schweppe from MIT in 1969
2. The first main function in EMS
3. Provides the data input to other functions in EMS
4. Runs every 2 minutes.

State estimator → Control the power system → EMS

(SE diverges) (Power system goes wild) (Entire EMS Crashes)

State estimator handles tens of thousands of measurements. Current state estimators in the market cannot guarantee a solution.

The Vulnerability of Today's WLS Based State Estimators

- ➢ 100% convergence is not guaranteed
- ➢ Not Optimal in Power System Applications
- ➢ Not Available when they are Most Needed
- ➢ Not able to Recover the True Values of bad measurements
- ➢ Almost Impossible to detect all three types of bad data at once
- ➢ Leverage point disables the bad data detection

In summary, the existing State Estimators are

Not Robust or Not Smart

Objective Function of WLS Based State Estimators

$min \quad f = \sum_{i=1}^{N} w_i(z_i - h_i(x))^2 = w_1(z_1 - h_1(x))^2 + w_2(z_2 - h_2(x))^2 + \ldots +$
$w_k(z_k - h_k(x))^2 + \ldots$

The objective function is to minimize the sum of squared residuals.

When a bad measurement is present, WLS SE still tries to minimize its residual.

Common Understandings in Industry of WLS based SE

1. To minimize the sum of squared residuals is the ultimate goal!

2. Usually adjust the measurement weights for this object!

3. Once a voltage solution is obtained, then everything is fine!

So, what is the purpose of state estimation?

To obtain the accurate system operating state.

So, is state estimation an art or a science?

It is an art when human manipulate it; it is a science when human do not manipulate it.

Minimizing Square Residuals by WLS based SE

$$min \quad f = \sum_{i=1}^{N} w_i(z_i - h_i(x))^2 = w_1(z_1 - h_1(x))^2 + w_2(z_2 - h_2(x))^2 + \ldots + w_k(z_k - h_k(x))^2 + \ldots$$

Situations:

1. No bad data, noise only. WLS SE obtains the optimal solution.

2. General bad data. WLS SE tries to minimize their residuals.

3. Bad data on leverage points. WLS SE forces their residuals to be zero.

Performance of WLS State Estimator

When measurements have noise only:

1. The resolution is optimal and WLS is prefect when only noise is precent.
2. The residuals are small.

When bad data exist:

1. Bad measurements are hidden by minimizing the residuals. Up to today, there does not exist an effective bad data detection algorithm.
2. The voltage solution is biased because bad measurements have small residuals.
3. The true values of bad measurements are impossible to be recovered.

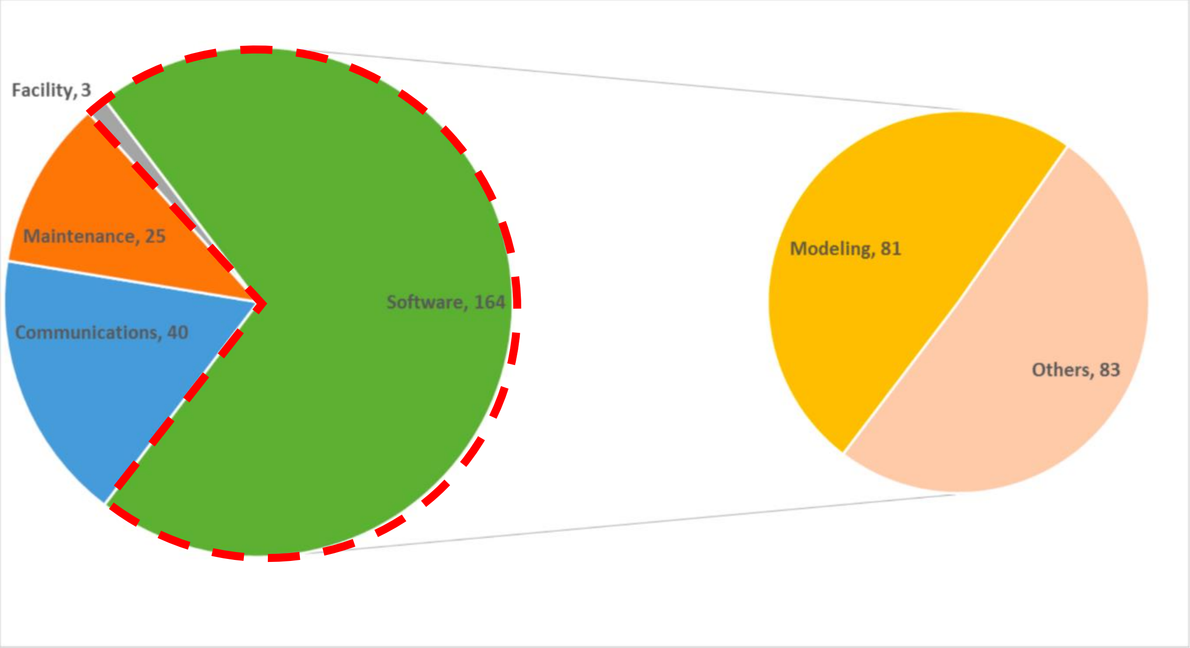
Bad data is Inevitable in power systems applications, so WLS SE is not suitable.

The North American Electric Reliability Corporation (NERC) Survey in Mar 2020

Table 1: Contributors to Loss of EMS functions					
Failure	**Software**	**Communications**	**Maintenance**	**Facility**	**Total**
Loss of SE	164	40	25	3	232
Loss of ability to monitor or control	32	48	45	57	182
Loss of ICCP	0	47	2	2	51
Loss of RTU	2	35	4	3	44
Loss of AGC	9	2	1	0	12
Total	**207**	**172**	**77**	**65**	**521**

This survey only covers the **severe failures** (continuous loss of function ≥30 minutes)

A power utility company has **11% divergence rate of SE** per month (31 times divergence everyday)



Why Some Power Utility Companies Do Not Use State Estimator in Their Control Room?

The Facts:

1. High percentage of bad data.
2. Low measurement redundancy ratio.

The Performance of their SE:

1. Has high divergence rate.
2. They do not trust the results of their SE. For example, they do not trust the voltage magnitudes of the SE solution.
3. They directly use the measurements in the control room.

State Estimator Plus (SE+)

Some definitions:

1). *Basis set* Z_B : a subset of measurements which can just solve the system

2). *Redundant set* Z_R : the remaining measurements.

3). *Feasible space* Φ : a set formed by all possible basis sets.

4). The residual vector r_R (absolute value) of Redundant Set Z_R.

The objective function:

To minimize the number of abnormal measurement residuals in r_R .

$$Min \qquad \left\| r_R - threshold^{\xi} \right\|_0$$

$$S.T. \qquad r_R = Z_R - h_R(v) = Z_R - h_R(h_B^{-1}(Z_B))$$

The Goal: to find a basis set Z_B which is formed by the most consistent measurements

ξ Weibiao Wu, Maggic Chen, Bei Gou, "Hypothesis Testing Approach for Topology Error Detection in Power Grids." *IEEE Internet of Things Journal*, Vol. 3, No. 6, Dec. 2016

State Estimator Plus (SE+)

Physics understanding:

Why such a minimum set of the most consistent measurements always exists?

Let us select a basis set Z_B^i from the feasible space Φ, and we can solve all bus voltages and calculate r_R^i. After we repeat this calculation for all basis sets in the feasible space, we obtain r_R^i, $i = 1,2,\cdots,N_{all}$.

Among all r_R^i, there must exist an j such that $\left\| r_R^j - threshold_j \right\|_0$ is minimum, and the corresponding Z_B^j is our solution.

State Estimator Plus (SE+)

Why such a minimum set of the most consistent measurements always exists?

$$
\Phi \left\{ \begin{array}{lllll}
Z_B^1 & \xrightarrow{v_1} r_R^1 & \longrightarrow \left\| r_R^1 - threshold_1 \right\|_0 & \longrightarrow & n_B^1 \\
Z_B^2 & \xrightarrow{v_2} r_R^2 & \longrightarrow \left\| r_R^2 - threshold_2 \right\|_0 & \longrightarrow & n_B^2 \\
Z_B^3 & \xrightarrow{v_3} r_R^3 & \longrightarrow \left\| r_R^2 - threshold_2 \right\|_0 & \longrightarrow & n_B^3 \\
\vdots & \quad \vdots & \qquad \vdots & & \vdots \\
\vdots & \quad \vdots & \qquad \vdots & & \vdots \\
\vdots & \quad \vdots & \qquad \vdots & & \vdots \\
Z_B^{N_{all}} & \xrightarrow{v_{N_{all}}} r_R^{N_{all}} & \longrightarrow \left\| r_R^{N_{all}} - threshold_{N_{all}} \right\|_0 & \longrightarrow & n_B^{N_{all}}
\end{array} \right\} Z_B^{min}
$$

State Estimator Plus (SE+): Background

The Data:

- ➢ Bad data is inevitable in power system model and real-time measurements.
- ➢ Measurement redundancy ratio is relatively low.

The Algorithm:

- ➢ WLS algorithm is prefect for data with only noise.
- ➢ WLS algorithm is Not a good choice for applications with gross errors.

SE+:

- ➢ Based on the realistic situation of the data, SE+ is developed on a completely different philosophy.
- ➢ Select the minimum set of the most consistent measurements.

State Estimator Plus (SE+): Unique Features

1. The minimum set of the most consistent measurements always exist. A solution is guaranteed by SE+.

2. The bad data (outliers) are naturally rejected by SE+. The open-problem of leverage point has been solved.

3. SE+ is Not sensitive to bad data, it is robust.

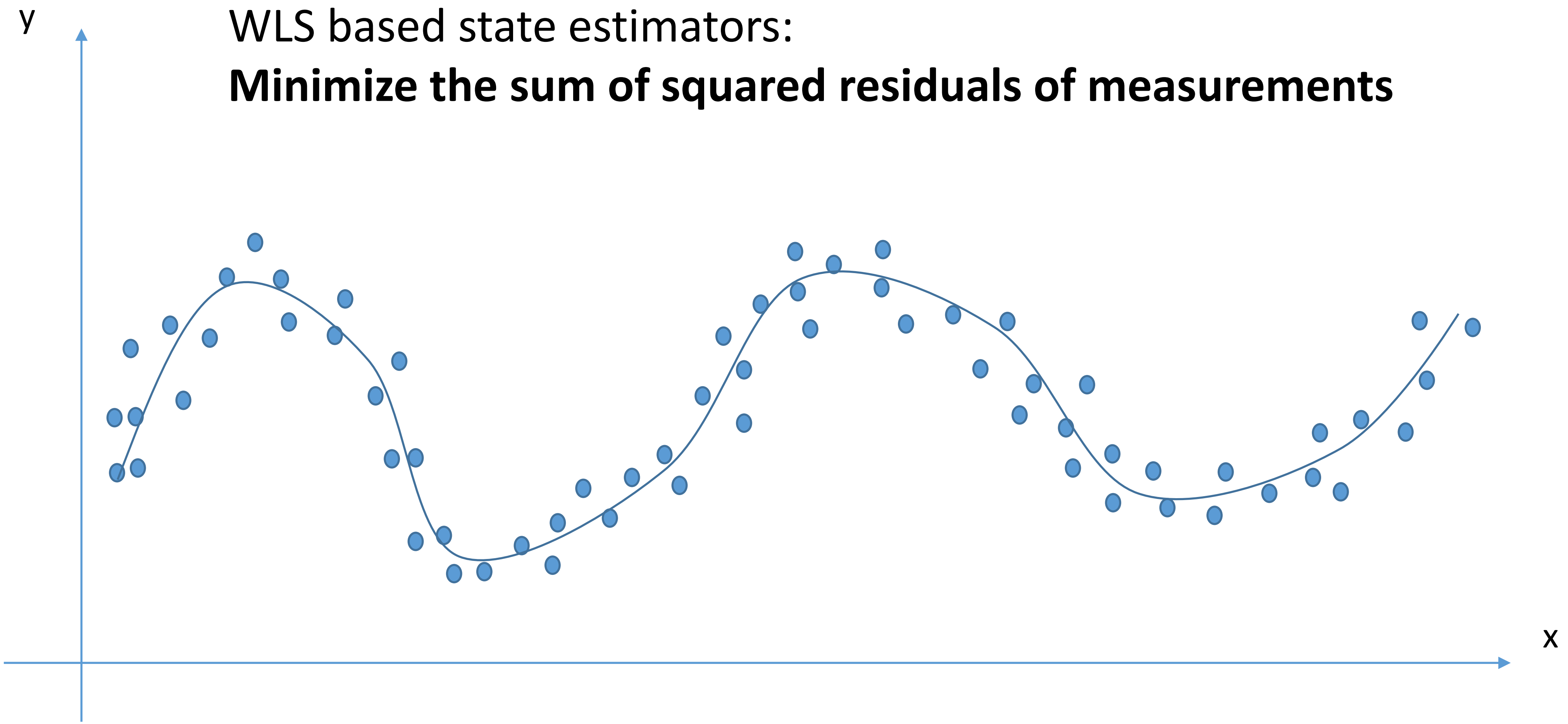
4. Comparing with WLS SE & LAV SE, SE+ reaches a more accurate voltage solution with a much faster speed.

Minimizing Square Residuals by WLS based SE

1. No bad data, noise only. WLS SE obtains the optimal solution.

WLS based state estimators:

Minimize the sum of squared residuals of measurements

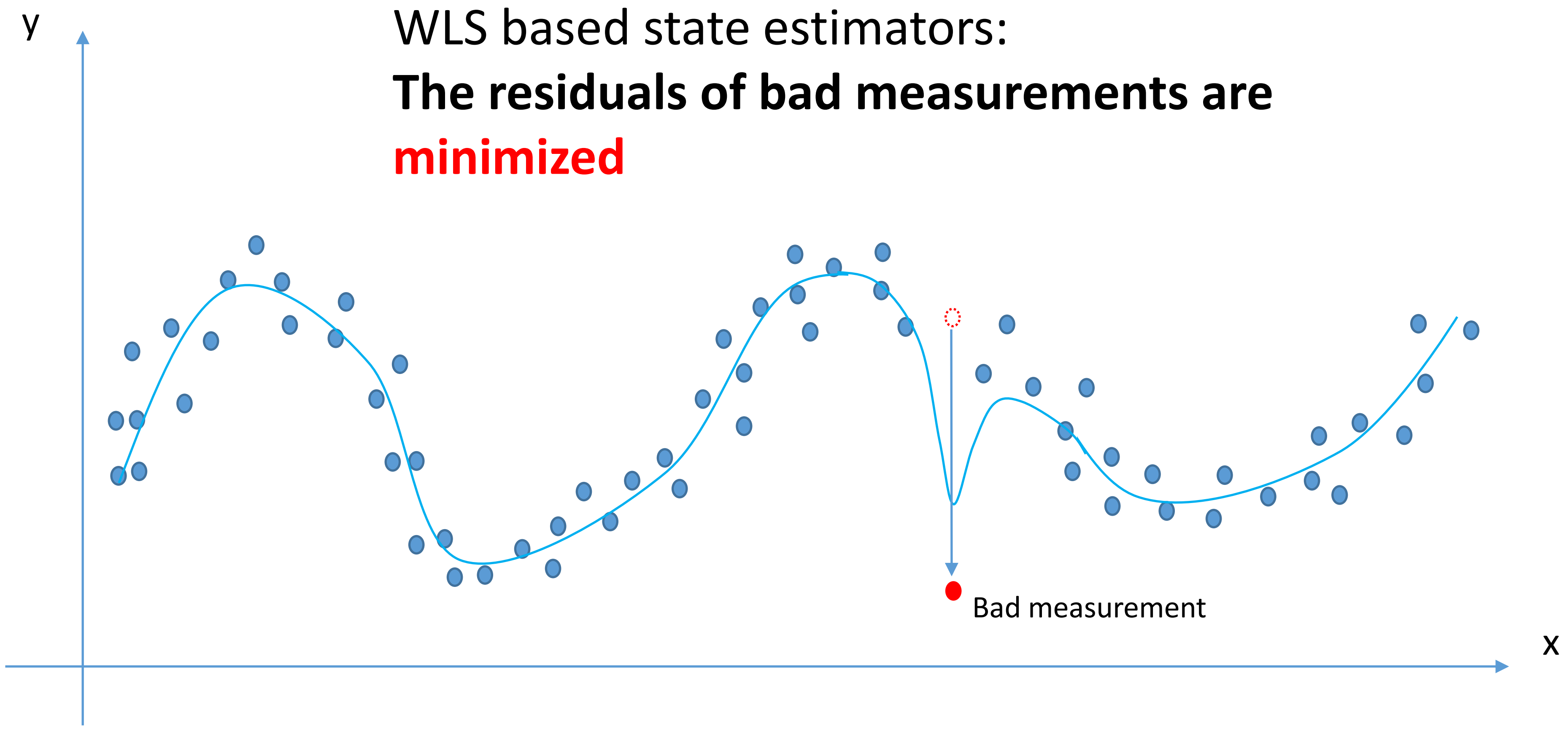


Minimizing Square Residuals by WLS based SE

2. Bad data. WLS SE obtains a biased solution.

WLS based state estimators:

The residuals of bad measurements are **minimized**

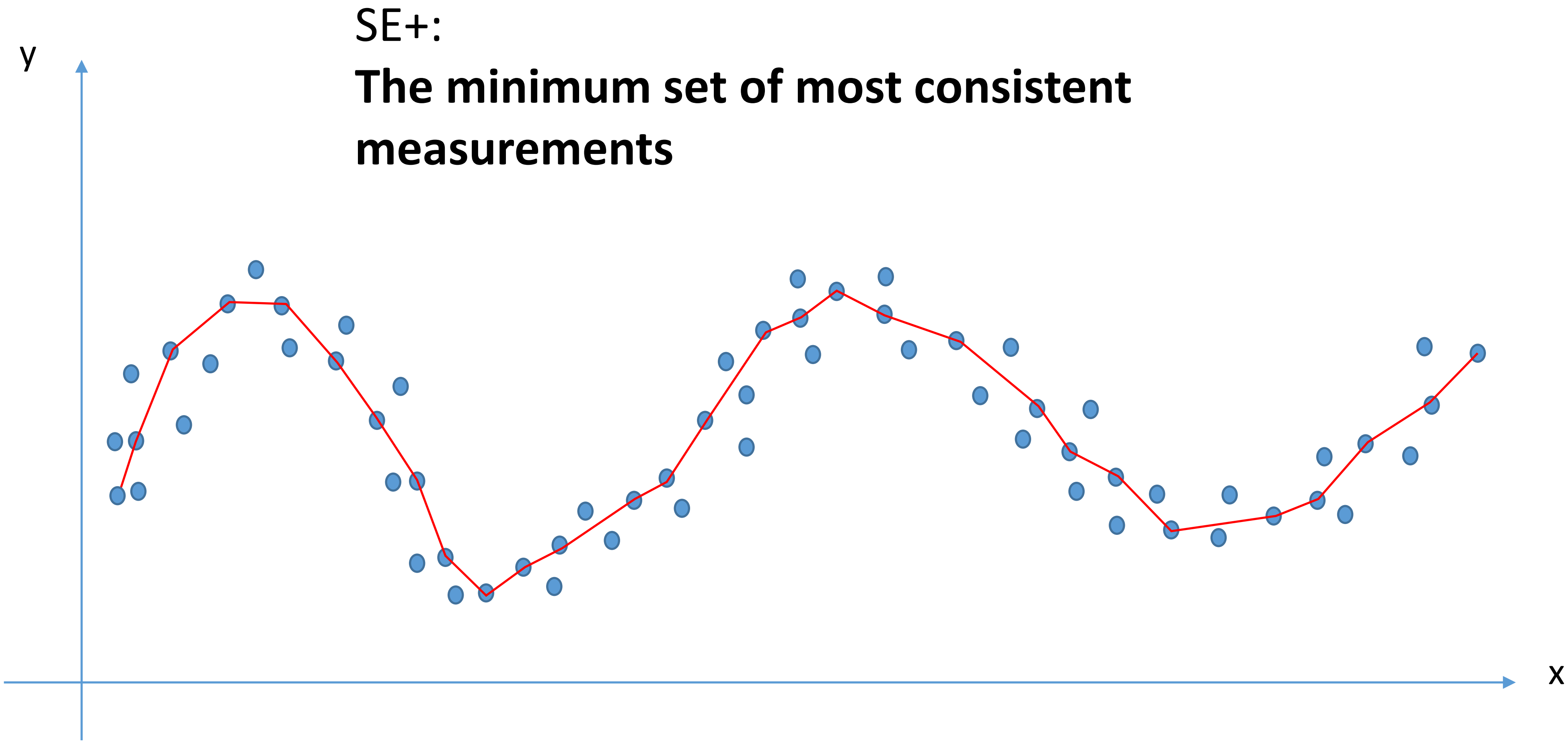


Bad measurements:

Small residual -> hide the bad measurements and make it very hard to detect

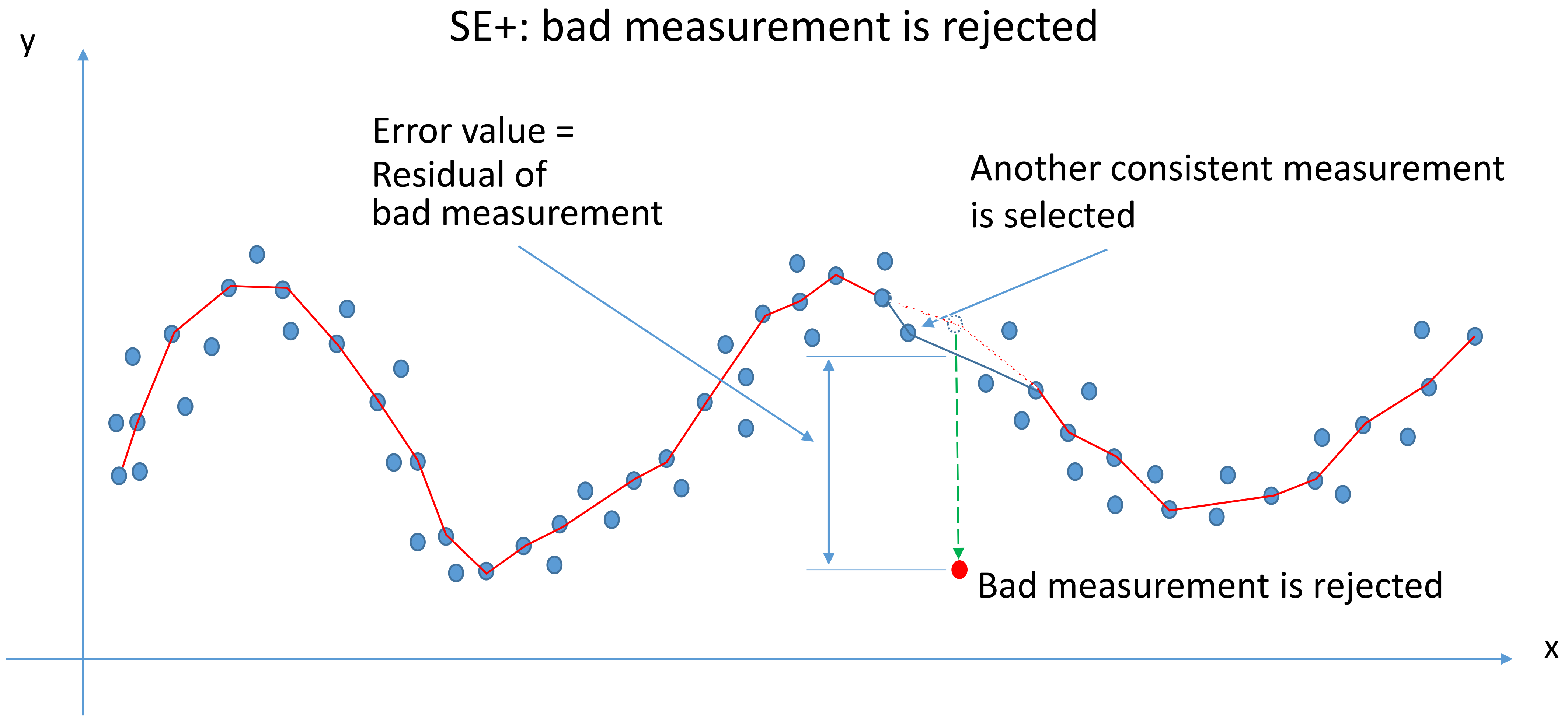
SE+: minimum set of the most consistent measurements

1. No bad data, noise only. SE+ obtains the good solution.

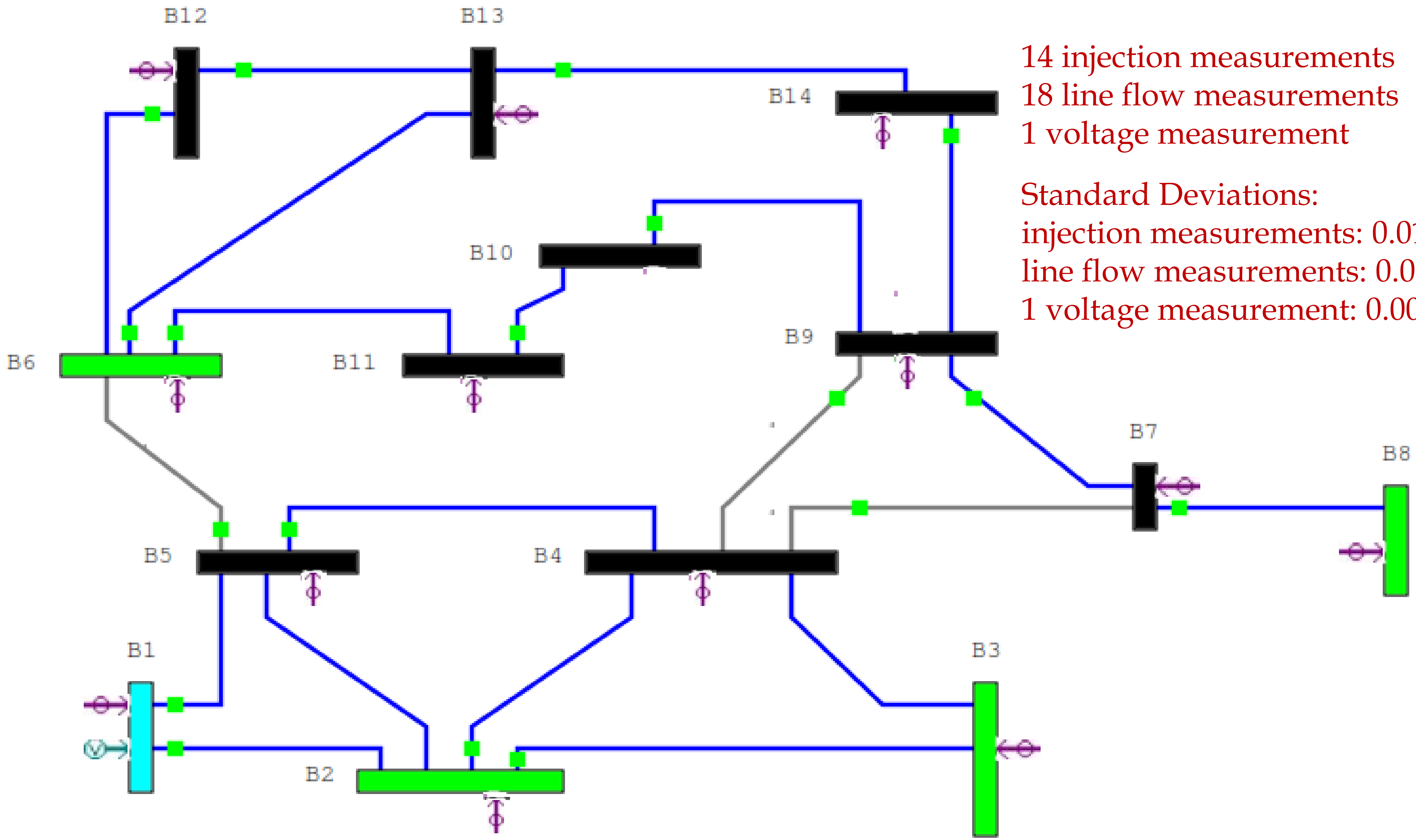


SE+: minimum set of the most consistent measurements

2. Bad data. SE+ obtains a robust solution by rejecting bad data.



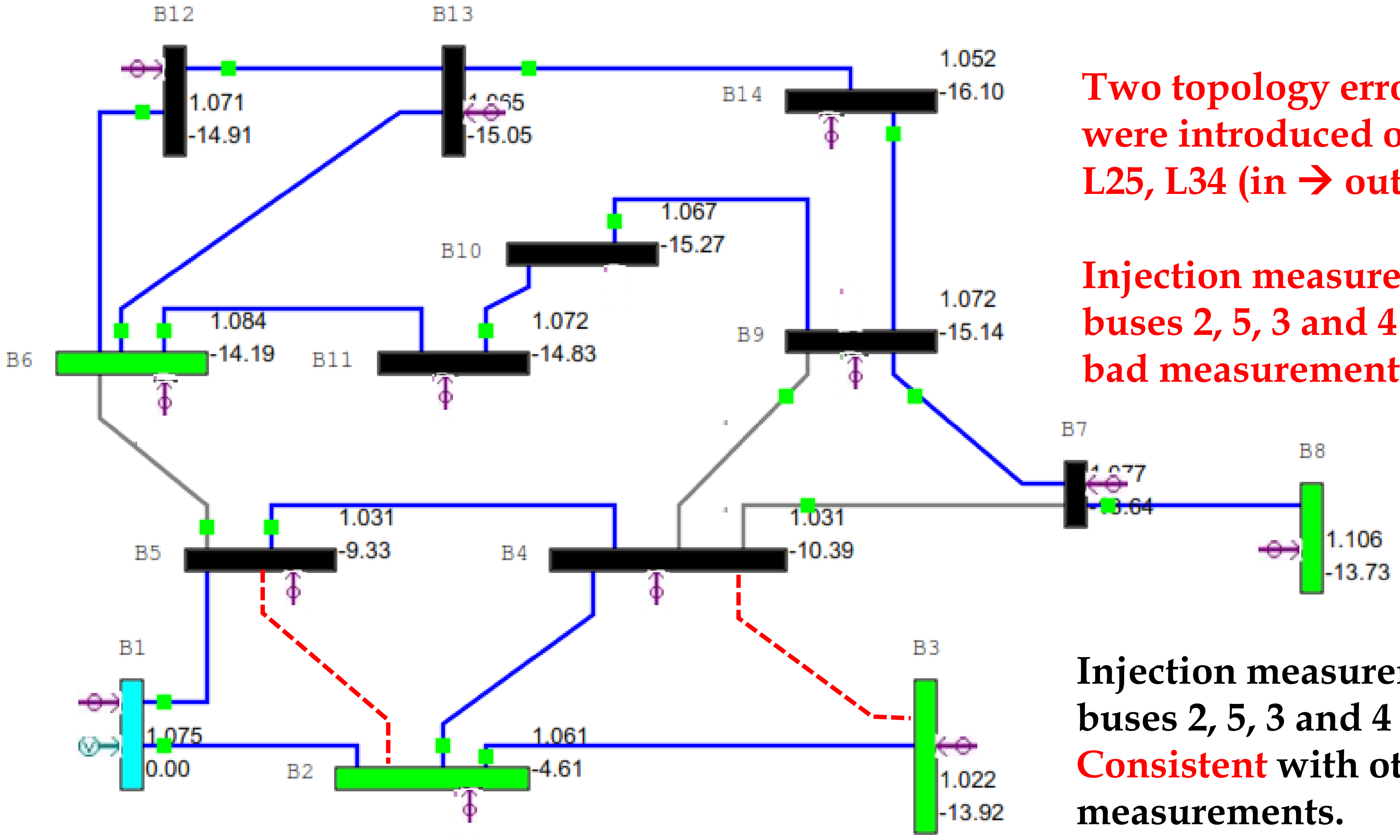
An Example: IEEE 14 Bus System



14 injection measurements
18 line flow measurements
1 voltage measurement

Standard Deviations:
injection measurements: 0.01
line flow measurements: 0.001
1 voltage measurement: 0.001

An Example: IEEE 14 Bus System



Two topology errors were introduced on L25, L34 (in → out)

Injection measurements at buses 2, 5, 3 and 4 become bad measurements

Injection measurements at buses 2, 5, 3 and 4 are Not Consistent with other measurements.

An Example: IEEE 14 Bus System

Results of Weighted Least Square (WLS) approach:

rn.dat - Notepad

File Edit Format View Help

4	P54	5	4	238.0578	0
4	P23	2	3	224.1321	0
2	P5	5		179.6015	0
2	P2	2		175.0047	0
2	P4	4		126.5547	0
4	P12	1	2	96.6068	0
2	P3	3		91.2902	0
4	P24	2	4	76.8391	0
4	P15	1	5	75.2030	0
2	P6	6		45.7369	0
4	P56	5	6	45.2509	0
2	P7	7		36.7061	0
3	Q4	4		34.2411	0
4	P47	4	7	30.6485	0
2	P9	9		25.1518	0
1	V1	1		24.0522	0
3	Q5	5		23.6218	0
2	P12	12		18.7487	0
2	P13	13		18.4671	0
5	Q56	5	6	18.3916	0
5	Q47	4	7	16.2474	0
2	P1	1		15.5892	0

Largest Normalized Residuals occur on P54 and P23, which are error-free measurements.

An Example: IEEE 14 Bus System

Results of Least Absolute Value (LAV)approach:

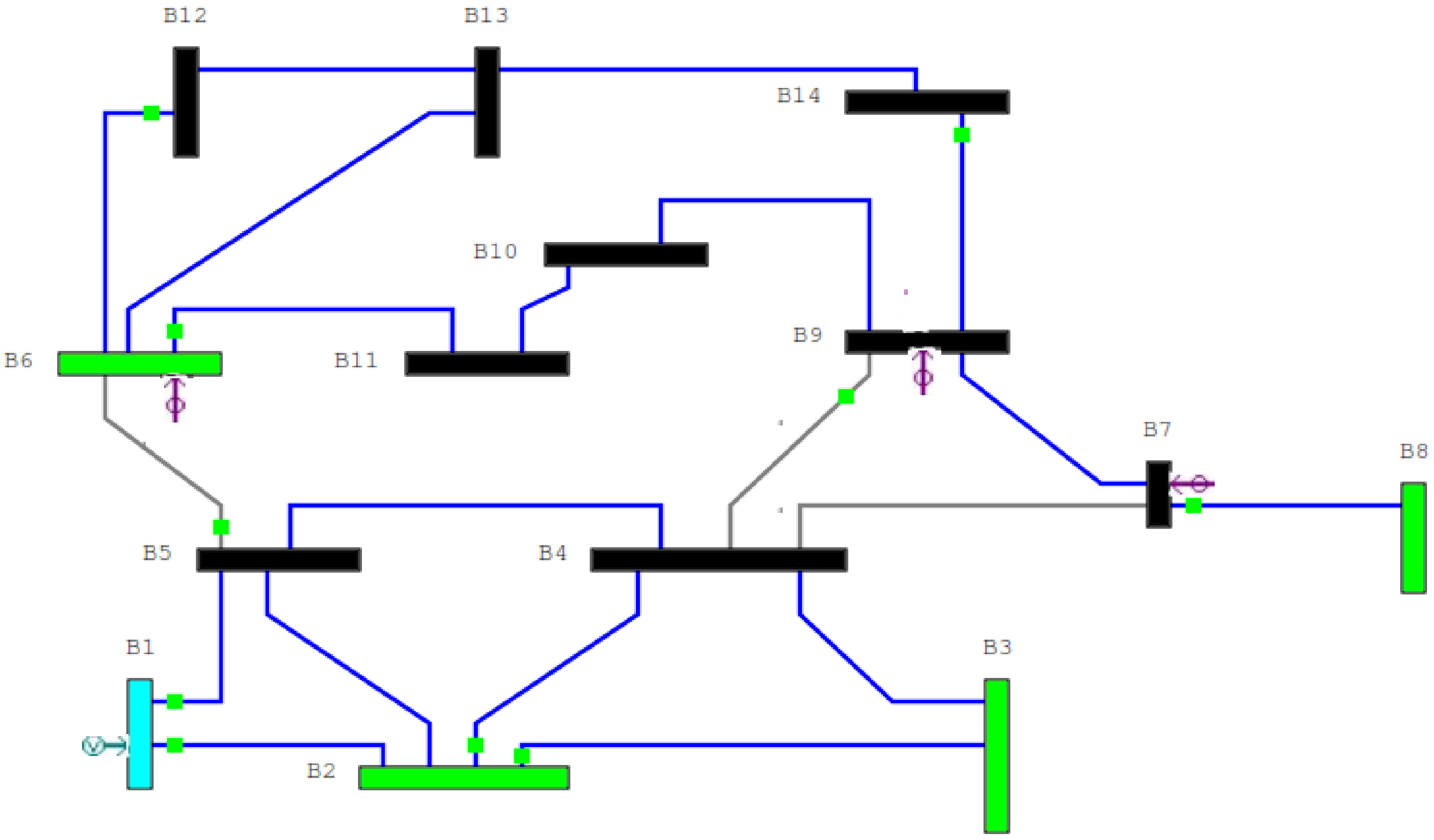
Type	Meas	From	To	Telemetry	Estimated	Residual
4	P23	2	3	0.73235	0.98354	0.25119
4	P54	5	4	0.61832	0.37783	0.24049
2	P2	2	0	0.18355	0.05502	0.12853
2	P5	5	0	-0.07588	0.01402	0.0899
4	P56	5	6	0.44077	0.39777	0.043
3	Q3	3	0	0.044	0.08613	0.04213
3	Q4	4	0	0.03956	0.07918	0.03962
2	P6	6	0	-0.11189	-0.07258	0.03931
4	p12	1	2	1.5691	1.53105	0.03805
4	P15	1	5	0.75646	0.79193	0.03547
5	Q56	5	6	0.1288	0.11018	0.01862
5	Q23	2	3	0.03591	0.04334	0.00743
3	Q6	6	0	0.0481	0.05515	0.00705
5	Q12	1	2	-0.20302	-0.20995	0.00693
5	Q15	1	5	0.03584	0.04204	0.0062
3	Q5	5	0	-0.01559	-0.01262	0.00297
5	Q47	4	7	-0.09412	-0.096	0.00188
5	Q78	7	8	-0.16817	-0.16994	0.00177
4	P6-11	6	11	0.07353	0.07184	0.00169
4	P6-13	6	13	0.17773	0.17608	0.00165
4	P13-14	13	14	0.05675	0.05547	0.00128
4	P11-10	11	10	0.03792	0.03672	0.0012
5	Q6-13	6	13	0.07225	0.07105	0.0012
3	Q12	12	0	-0.0156	-0.0146	0.001

Largest Residuals occur on P23 and P54, which are error-free measurements.

An Example: IEEE 14 Bus System

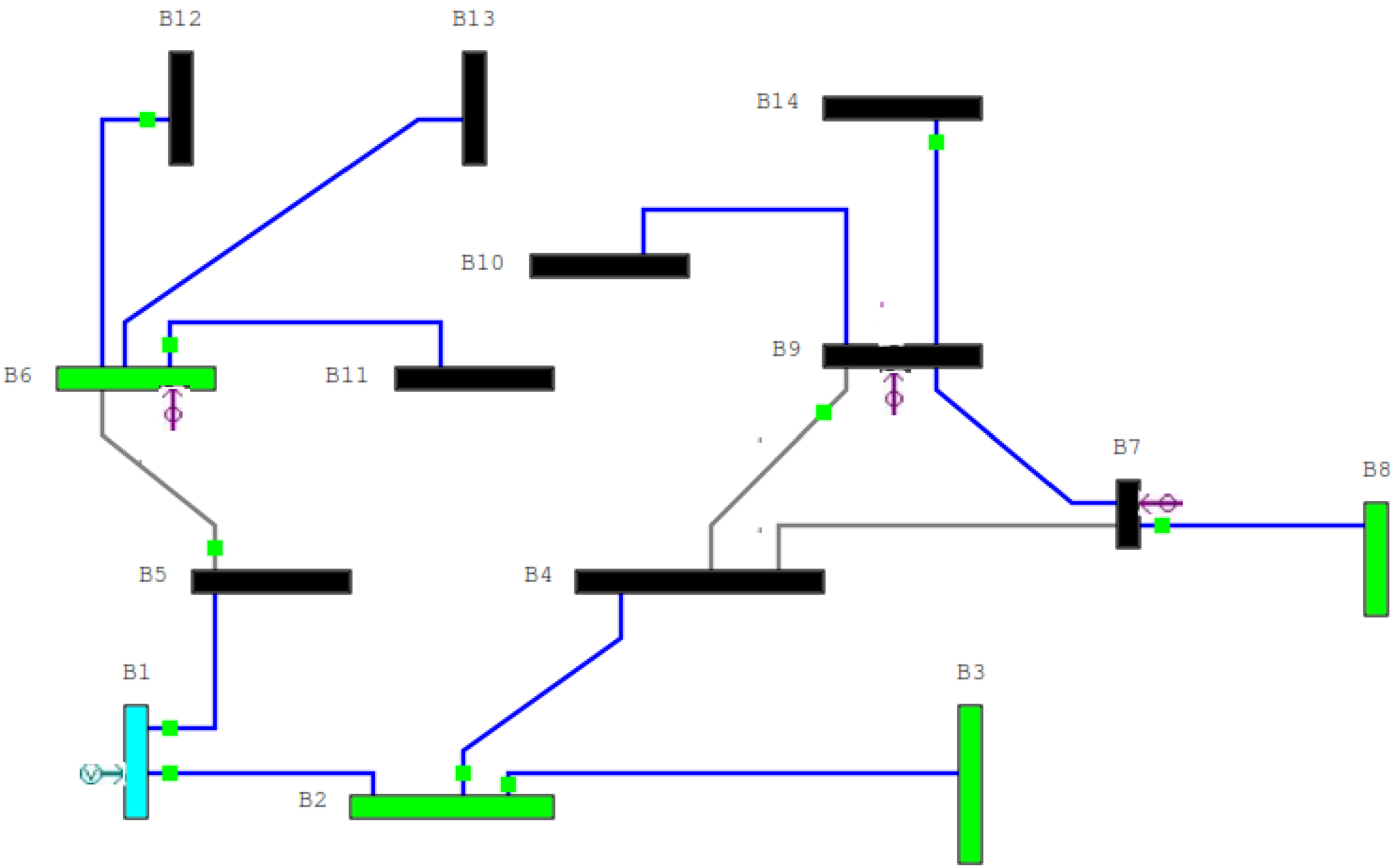
Results of SE+:

The basis set is formed by 10 line flow and 3 injections plus a voltage measurement, and injection measurements at buses 2, 5, 3 and 4 were rejected.



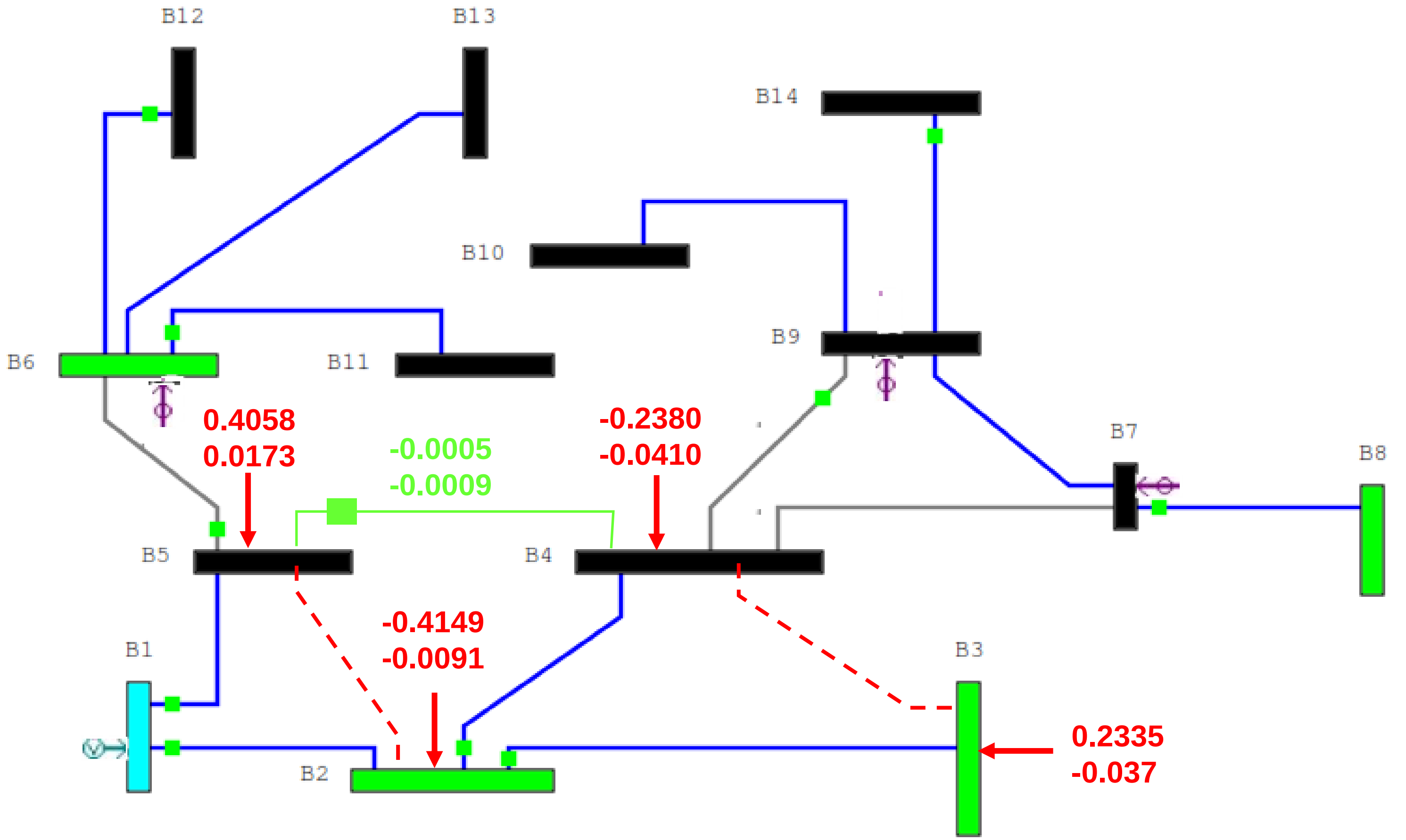
An Example: IEEE 14 Bus System

The basis set is given as follows:



An Example: IEEE 14 Bus System

Injections (redundant) at buses 2, 3, 4 and 5 have big residuals.
The redundant flow measurement on line 4-5 has small residual which implies basis set measurements on lines 1-2, 1-5, 2-4 are all error free.



Threshold was derived to judge abnormal residuals

Ψ Weibiao Wu, Maggic Chen, Bei Gou, "Hypothesis Testing Approach for Topology Error Detection in Power Grids." *IEEE Internet of Things Journal*, Vol. 3, No. 6, Dec. 2016

Philosophy of WLS SE and SE+: Objective Function

Objective function of WLS SE:
minimize the sum of squares of all residuals

1. Hard to converge when big inconsistency exists among measurements.
2. Adjusting the weights in order to reach a solution. Human involvement is needed. Oncor engineer: It is an "Art" other than Science.
3. Minimizing the residuals of Bad Measurements implies voltage biases and difficulty to detect the bad data.
4. Recovery of bad measurements is impossible.

Philosophy of WLS SE and SE+: Objective Function

Objective function of SE+:
find the minimum set of the most consistent measurements

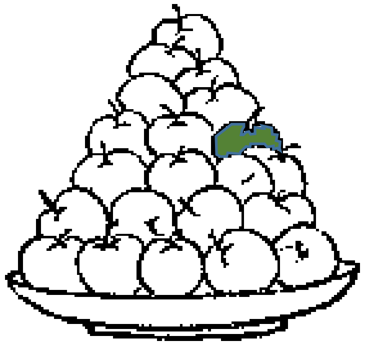
1. A solution is guaranteed.
2. Rejecting the **bad measurements** by selecting a minimum set of the most consistent measurements.
3. SE+ has a more accurate solution when bad data are present.
4. SE+ is robust because it is insensitive to all types of bad data.
5. The voltage solution is 100% decided by the measurements and system model. Human involvement is not needed.

Philosophy of WLS SE and SE+: Bad Data

WLS SE

Try to detect the bad measurements and remove one by one from the measurement set.

Disadvantage: it is hard because of the low measurement redundancy ratio and high percentage of bad data.



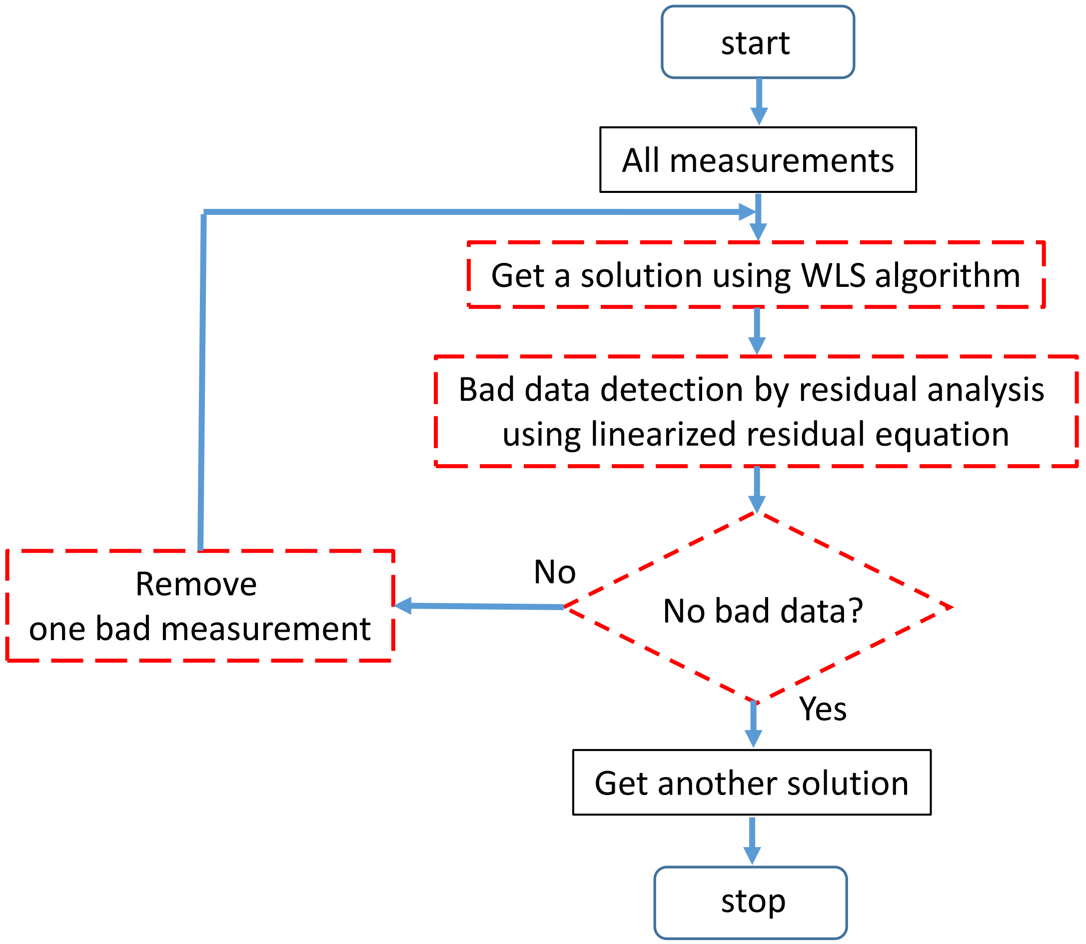
SE+

Try to select the error-free measurements so that the entire system can be solved.

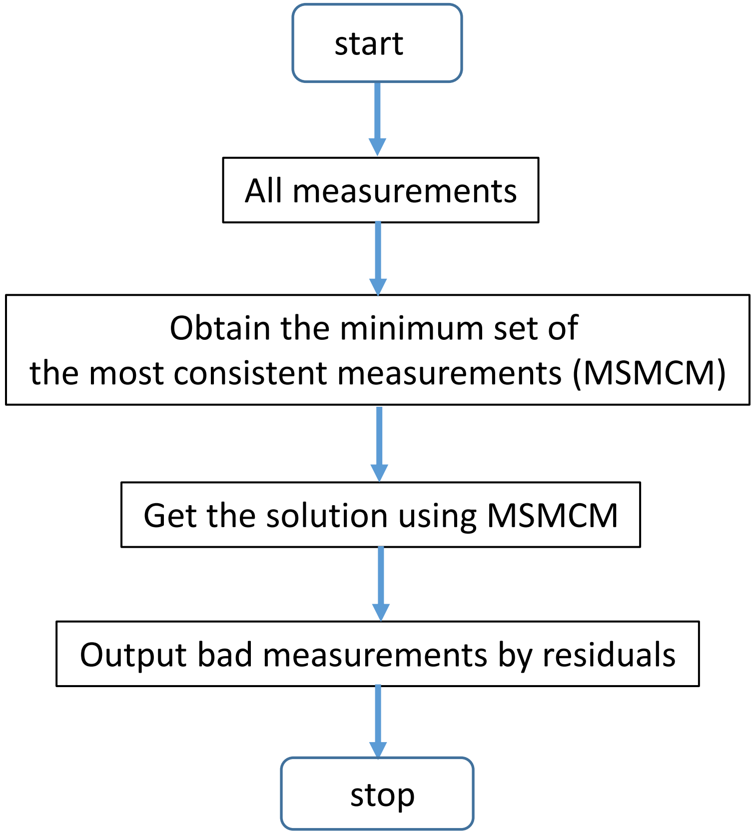
Advantage:

1) It is much easier
2) The convergence to a solution is guaranteed
3) Solution is more accurate
4) Bad data are kept in the redundant set, SE+ is robust.

Comparison of Philosophy between WLS SE and SE+



Weighted Least Square based SE by r^N_{max}-test



SE+

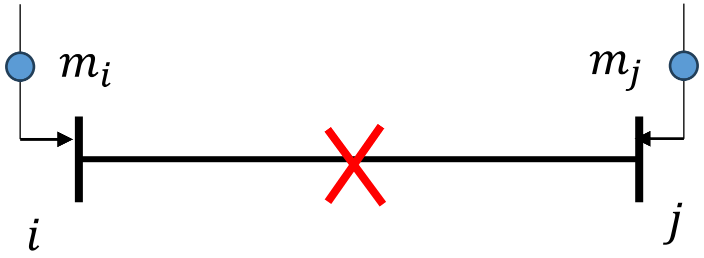
Note: steps in red are **vulnerable** or **incorrect** due to linear approximation.

About SE+ Software Package

1. SE+ is designed for the Offline backup state estimator. No risk.
2. The input files are PSSE raw file (system model) and the concurrent real-time measurements.
3. SE+ installation needs less than 1 minute.
4. We have a converter in the package to convert your PSSE file and concurrent measurements to the format of SE+.

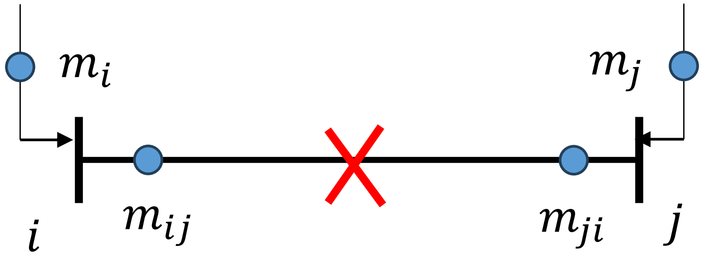
Bad Data vs Measurements

1. Topology Errors



The injection measurements at both terminals become bad measurements

2. Parameter Errors



All 4 measurements become bad measurements

Bad Data Rejection: Topology Errors

In 3120 system, we added the following topology errors.

Branch ID	From Bus	To Bus	Status	Status_error
42	188	26	In service	Out of service
45	203	98	In service	Out of service
180	196	191	In service	Out of service
201	217	221	In service	Out of service
303	1941	130	In service	Out of service
323	2317	162	In service	Out of service
382	3095	236	In service	Out of service
2304	2727	2534	In service	Out of service
2375	2294	2496	In service	Out of service
2458	2374	2259	In service	Out of service
2944	3103	1105	In service	Out of service

Injection measurements related to these top errors become Bad measurements.

Bad Data Rejection: Topology Errors

Before adding the top errors, 22 injection measurements were in the basis set.

Bus ID	Type	Selected in Base Set	Type	Selected in Base Set
26	MW	Yes	Mvar	Yes
98	MW	Yes	Mvar	Yes
196	MW	Yes	Mvar	Yes
221	MW	Yes	Mvar	Yes
1105	MW	Yes	Mvar	Yes
1941	MW	Yes	Mvar	Yes
2294	MW	Yes	Mvar	Yes
2317	MW	Yes	Mvar	Yes
2374	MW	Yes	Mvar	Yes
2534	MW	Yes	Mvar	Yes
3095	MW	Yes	Mvar	Yes
130	MW	No	Mvar	No
162	MW	No	Mvar	No
188	MW	No	Mvar	No
191	MW	No	Mvar	No
203	MW	No	Mvar	No
217	MW	No	Mvar	No
236	MW	No	Mvar	No
2259	MW	No	Mvar	No
2496	MW	No	Mvar	No
2727	MW	No	Mvar	No
3103	MW	No	Mvar	No

Bad Data Rejection: Topology Errors

After adding the top errors, 4 injection measurements were in the basis set.

Bus ID	Type	Selected in Base Set	Type	Selected in Base Set
2374	MW	Yes	Mvar	Yes
3103	MW	Yes	Mvar	Yes
26	MW	No	Mvar	No
98	MW	No	Mvar	No
130	MW	No	Mvar	No
162	MW	No	Mvar	No
188	MW	No	Mvar	No
191	MW	No	Mvar	No
196	MW	No	Mvar	No
203	MW	No	Mvar	No
217	MW	No	Mvar	No
221	MW	No	Mvar	No
236	MW	No	Mvar	No
1105	MW	No	Mvar	No
1941	MW	No	Mvar	No
2259	MW	No	Mvar	No
2294	MW	No	Mvar	No
2317	MW	No	Mvar	No
2496	MW	No	Mvar	No
2534	MW	No	Mvar	No
2727	MW	No	Mvar	No
3095	MW	No	Mvar	No

Bad Data Rejection: Topology Errors

The impact of topology errors on the solution accuracy

	Before Top Errors	After Top Errors	% of impact
Sum of |v_residual|	106.13 Volt	105.53 Volt	0.56 %

Bad Data Rejection: Parameter Errors

In 3120 system, we added the following parameter errors.

Branch ID	From Bus	To Bus	x	x_errors
1	9	11	0.0305	0.5305
7	53	54	0.02097	0.52097
14	177	180	0.023	0.523
26	3116	181	0.00326	0.50326
43	53	124	0.08161	0.58161
55	210	171	0.03484	0.53484
70	35	7	0.05052	0.55052

Bad Data Rejection: Parameter Errors

Branch ID	From Bus	To Bus	x	x_errors	In Base set (MW)	In Base set (Mvar)
1	9	11	0.0305	0.5305	No	No
7	53	54	0.02097	0.52097	Yes	Yes
14	177	180	0.023	0.523	Yes	Yes
26	3116	181	0.00326	0.50326	Yes	Yes
43	53	124	0.08161	0.58161	Yes	Yes
55	210	171	0.03484	0.53484	Yes	Yes
70	35	7	0.05052	0.55052	No	No

Branch ID	From Bus	To Bus	x	x_errors	In Base set (MW)	In Base set (Mvar)
1	9	11	0.0305	0.5305	No	No
7	53	54	0.02097	0.52097	No	No
14	177	180	0.023	0.523	No	No
26	3116	181	0.00326	0.50326	No	No
43	53	124	0.08161	0.58161	Yes	Yes
55	210	171	0.03484	0.53484	No	No
70	35	7	0.05052	0.55052	No	No

	Before Par Errors	After Par Errors	% of impact
Sum of |v_residual|	106.13 Volt	106.17 Volt	0.038 %

Bad Data Recovery: Measurement Value Errors

In 3120 system, we added the following errors on line flow measurements.

Line ID	From bus	To bus	Bad data added (real value)	Type
1	11	9	500	MW
3	20	18	500	MVar
16	185	184	500	MVar
20	213	211	500	MVar
23	227	225	500	MW
23	227	225	500	MVar
25	3116	180	500	MW
29	3114	120	500	MW

In 3120 system, we added the following errors on injection measurements.

Bus ID	Bad data added (real value)	Type
1	1000	MW
4	1000	MVar
6	1000	MW
8	1000	MW
11	1000	MW
11	1000	MVar
14	1000	MVar
21	1000	MVar

Bad Data Recovery: Measurement Value Errors

Recovery of line flow measurements:

Line ID	From bus	To bus	Bad data added (real value)	Type	True value	Recovered
1	11	9	500	MW	5.932	5.581
3	20	18	500	MVar	0.140	0.144
16	185	184	500	MVar	-0.181	2.123
20	213	211	500	MVar	0.331	-0.033
23	227	225	500	MW	0.107	0.062
23	227	225	500	MVar	0.246	-0.188
25	3116	180	500	MW	0.019	0.108
29	3114	120	500	MW	0.111	0.301

Recovery of injection measurements:

Bus ID	Bad data added (real value)	Type	True value	Recovered
1	1000	MW	0.250	0.201
4	1000	MVar	32.632	32.406
6	1000	MW	0.557	0.293
8	1000	MW	0.028	0.106
11	1000	MW	5.845	4.371
11	1000	MVar	215.380	205.715
14	1000	MW	2.996	2.771
21	1000	MVar	132.340	130.567

Massive Testing SE+ on 13659 Bus System

Table 2. Measurement configuration of 13659 bus system

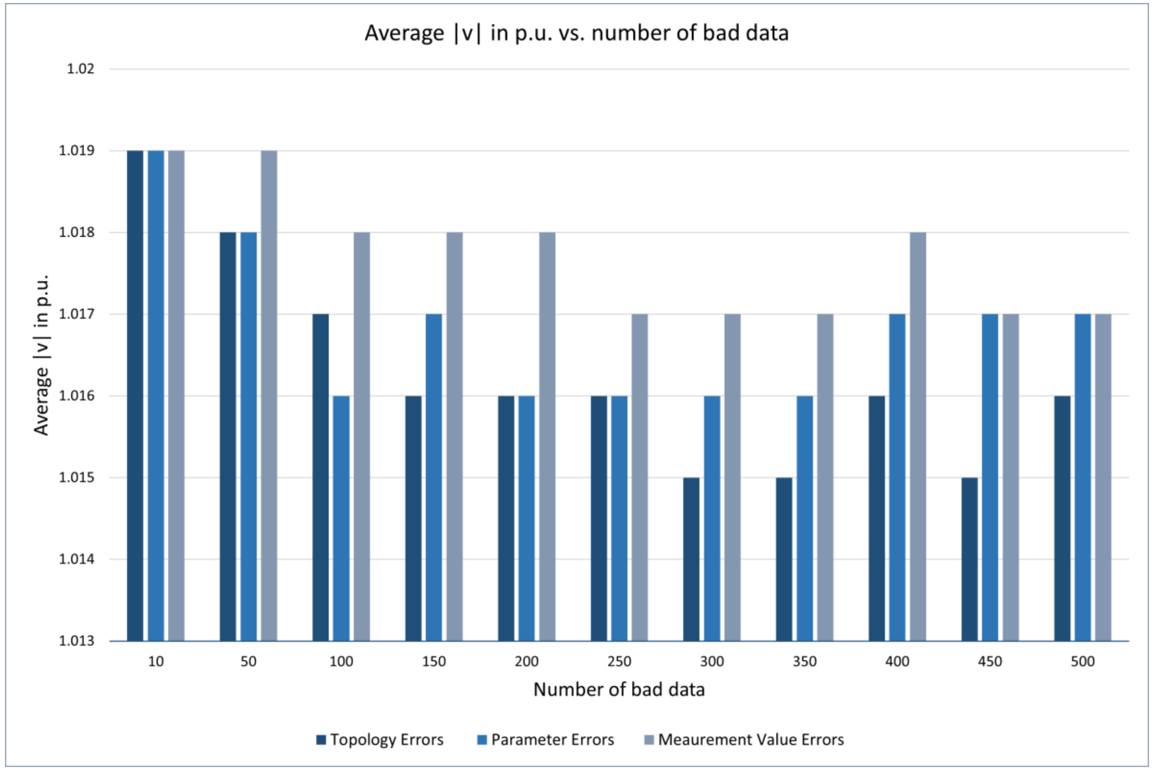
	Total # of buses	Total # of lines	Total # of line flow measurements (p_{ij}^m, q_{ij}^m)	Total # of bus injection measurements (p_i^m, q_i^m)	Total # of voltage Magnitude $(\lvert v_i \rvert^m)$	Measurement redundancy ratio	Total # of short lines $(x \leq 1.0^{-3}\ p.u.)$
Configuration	13659	20467	35510	27318	5772	2.51	1231

The topology errors and parameter errors were set up on branches with big line flows (> 80MW)

Severe topology and parameter errors

Rejection rate for three types of bad data

Massive Testing SE+ on 13659 Bus System



<u>Convergence Rate</u> of All above testing cases: **100%**

Testing SE+ on 25 Real Cases

1. System sizes

2500 ~ 6500 buses

2. Measurement redundancy ratios

1.4 ~ 2.1

3. Converged on all cases

Some cases are highly inconsistent due to mistakes in the convert code

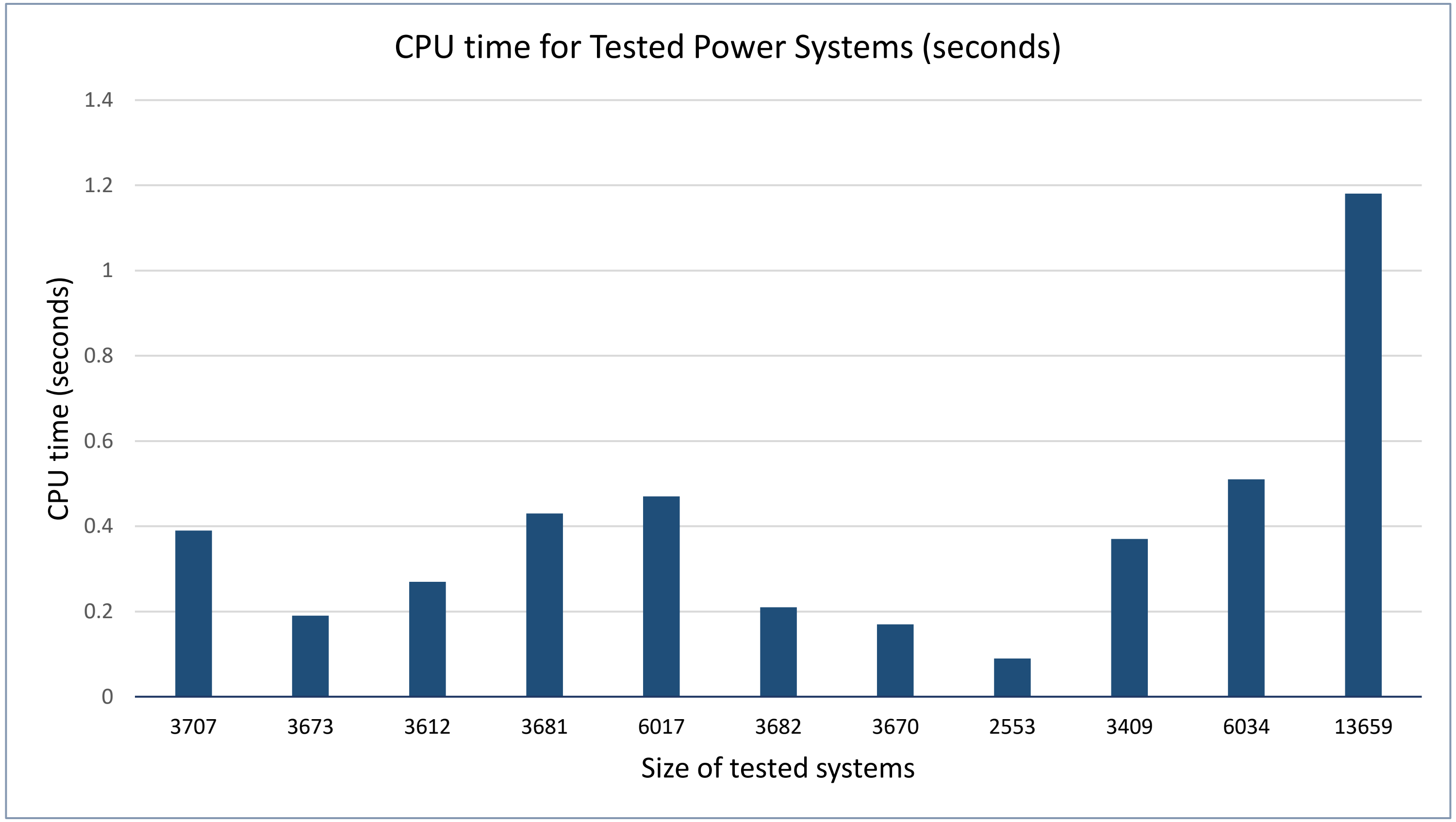
4. Residuals of Voltage magnitude measurements

SE+ is smaller than their SE (PSSE file)

5. Recovery of bad measurements

Large percentage of significant bad measurements can be recovered.

CPU Time for Different Systems



CPU time (in seconds) spent by different systems (on Dell Inspiron 7500 2n1, 4 cores)

Does SE+ reach the same speed level as Linear State Estimator (LSE)?

It becomes possible to run SE in a shorter period, say, every 15 seconds.

The CPU time has been significantly improved after our article* was published.

*Bei Gou, David Shue, "Advances in Algorithms for Power System Static State Estimators: An Improved Solution for Bad Data Management and State Estimator Convergence". Vol 21, No 1, Jan.-Feb. 2023, IEEE Power and Energy Magazine.

A Real-time Case: Bad data recovery

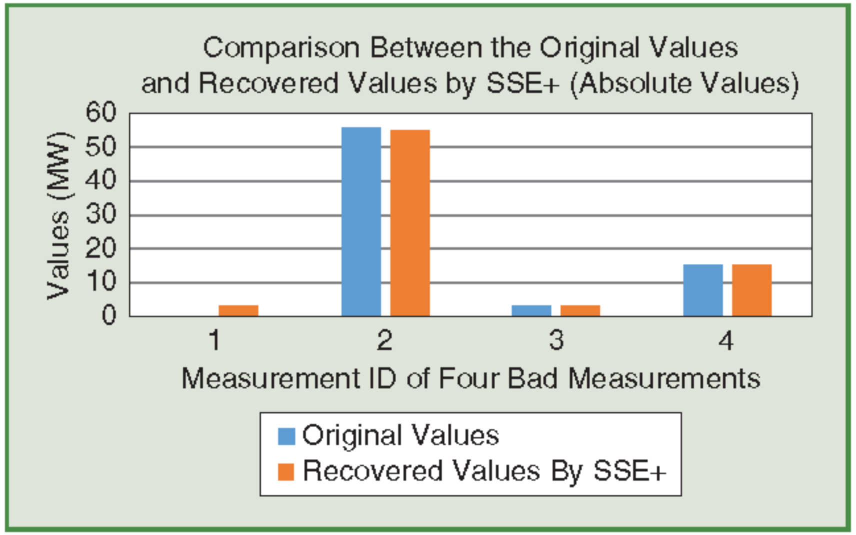
Recovery of Bad Measurements

Situation #1:

1) Added 10.0 p.u. on randomly selected 10 injection measurements.

Results of SE+:

- Converged in 0.25 seconds with a solution
- 64 bad line flow and injection measurements were detected
- 4 out of 10 bad injection measurements were precisely recovered
- 1 bad data detected but not precisely recovered (big residual) due to 5 bad data in the base set



A Real-time Case: Bad data recovery

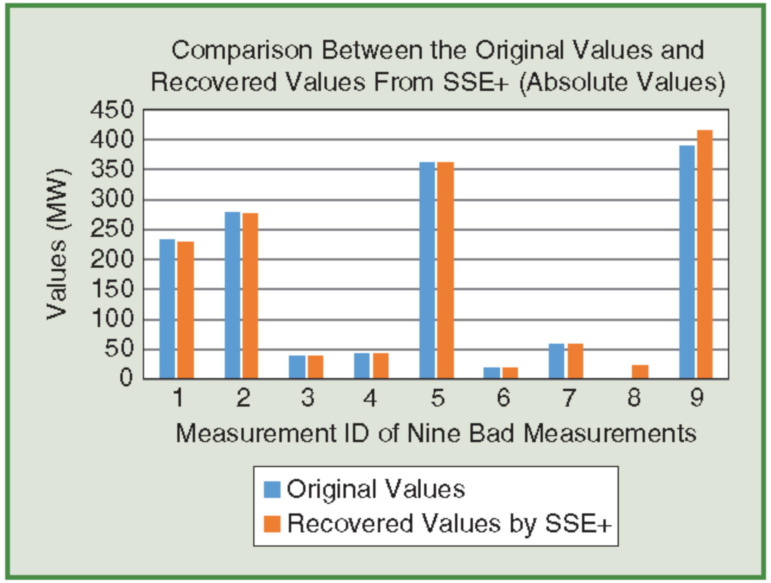
Recovery of Bad Measurements

Situation #2:

2) Added 5.0 p.u. gross errors on randomly selected 10 line flow measurements.

Results of SE+:

- Converged with a solution
- 69 bad data detected including line flow and injection measurements
- 9 out of 10 bad line flow measurements were accurately recovered



Why SE+ ?

1. You will have a good name memorized in PES history.
2. can provide a more accurate voltage solution.
3. can accurately reject bad measurements and **recover** their true values.
4. Insensitive to all types of bad data. SE+ is robust.
5. 10+ time faster than the existing state estimators.
6. An ideal offline supplement tool to improve the performance of your state estimator.

Appendices

State Estimator Plus (SE+)

The process of R&D:

1. Started the research since 2005, and fully focusing since 2013 by resigning my associate professor.

2. Financial supports by NSF since 2013 to 2020.

3. Industry supports by 4 big power companies including ISONE.

4. Consulting from statistics professors from Univ. of Chicago (20+ years), Stanford, UCLA, Georgia Tech, UTD, Purdue. None of them has background of power systems, but I have to understand their approaches and find a way to apply them in power systems.

5. We developed various approaches to solve vulnerability of SE before 2018.

6. We have studied hundreds of research papers in Compressive Sensing (Sparse Recovery Theory). I took an online course on it.

7. We have developed more than 22 versions of algorithms & codes. Experience: it is very hard to find the “best” way among all solutions to solve all problems at one shot.

Comparison of Voltage Solution between Customer SE and SE+ on Two Real Cases

3612 Real-time Case: Voltage solution quality

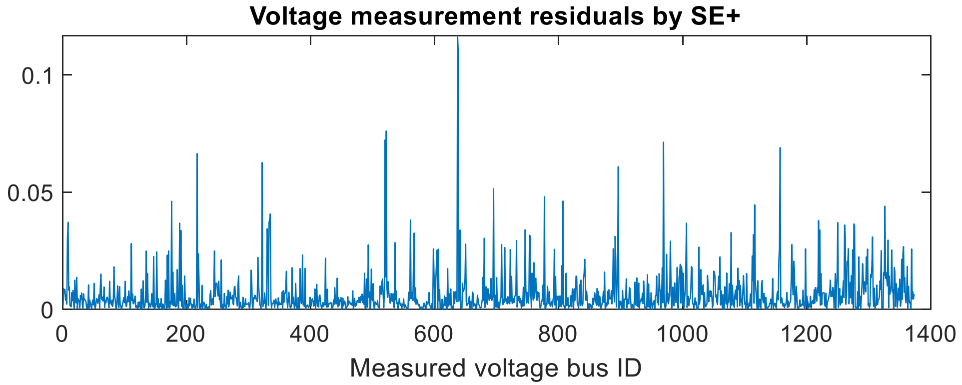
Raw data information:

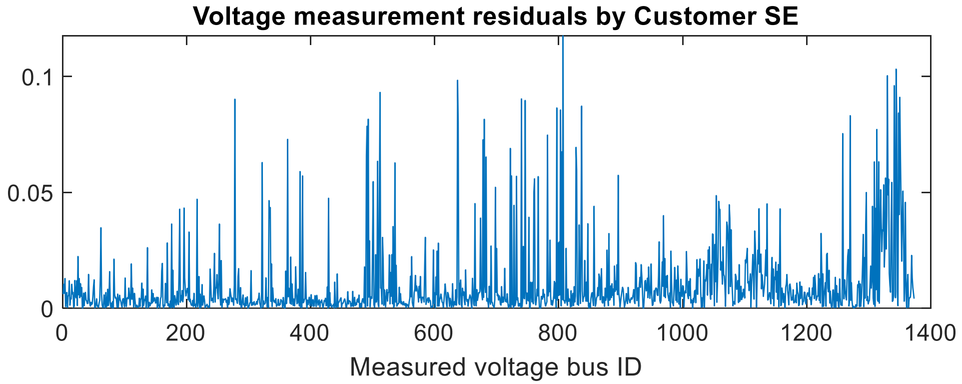
Total number of buses:	3612
Total number of branches:	4170
Total number of line flow measurements:	3521
Total number of injection measurements:	3588
Total number of voltage magnitude measurements:	1401

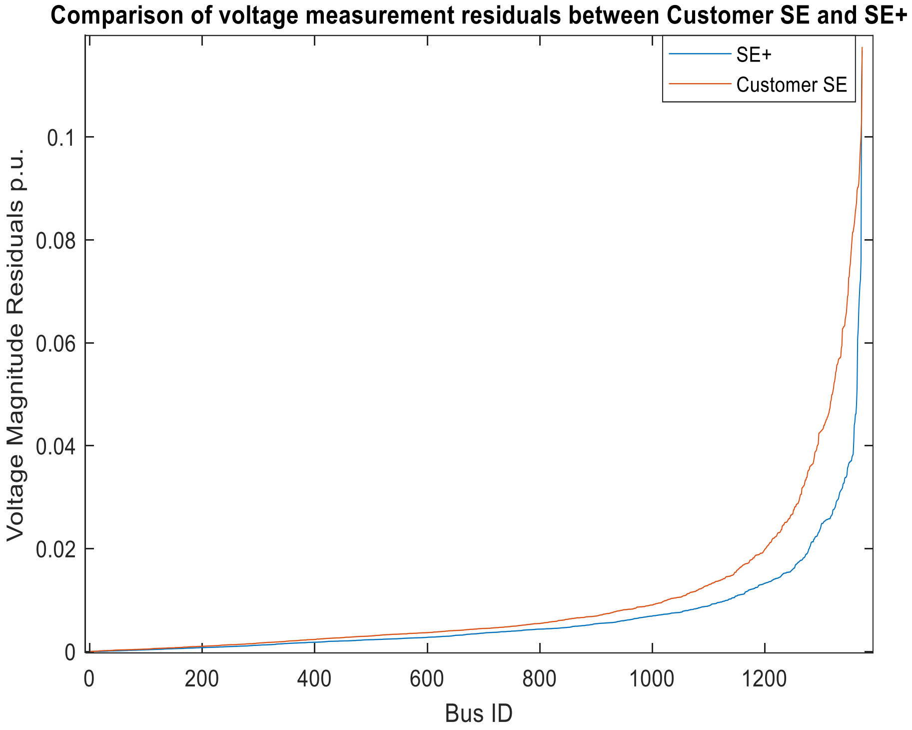
Main observable island:

Total number of buses:	3349
Total number of branches:	4170
Total number of line flow measurements:	3512
Total number of injection measurements:	3327
Total number of voltage magnitude measurements:	1373

3612 Real-time Case: Voltage solution quality







Voltage residuals are reduced by 34.98%

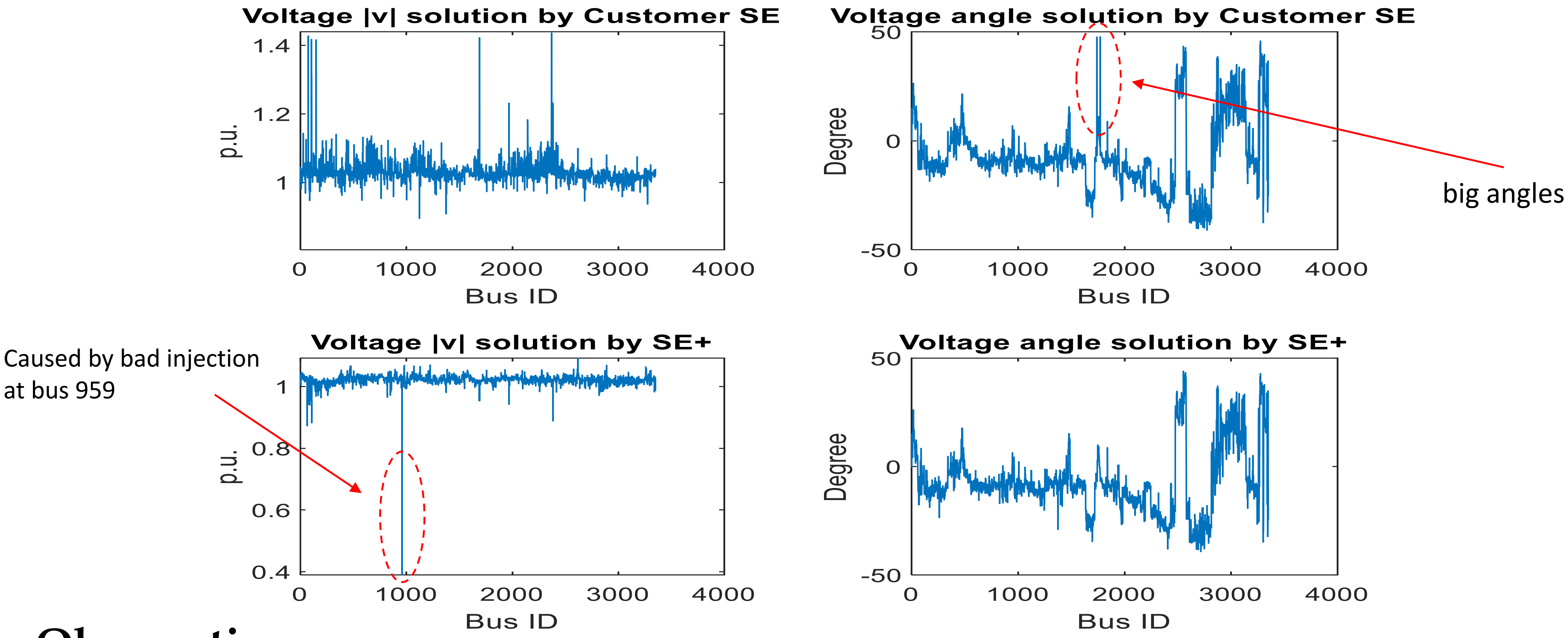
$\sum_{i=1}^{M_v} \left| v_i^{meas} - v_i^{SE+} \right|$ = 8.8866 p.u.

$\sum_{i=1}^{M_v} \left| v_i^{meas} - v_i^{WLS} \right|$ = 13.6677 p.u.

Observation:

- The bus voltage solution obtained by SE+ is closer to the voltage measurements than that of Customer SE (WLS)

3612 Real-time Case: Voltage solution quality

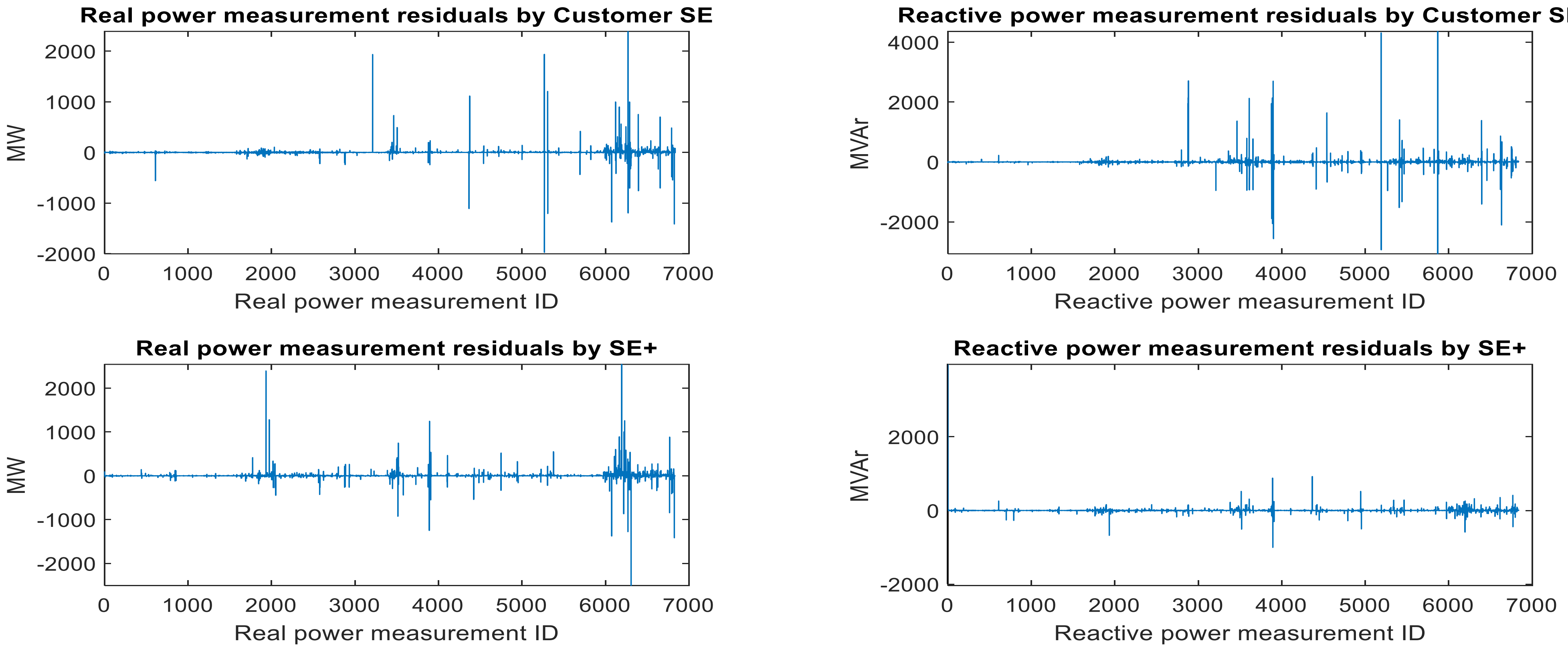


Observation:

1. All voltage magnitude measurements are < 1.1 p.u., but a few Customer SE > 1.2.
2. Customer SE has big angles at a few buses.
3. SE+ has a low |v| solution at bus 959 due to a bad injection measurement at 959.

3612 Real-time Case: Voltage solution quality

Residuals of real power and reactive power measurements:



Observation:

- The residuals of reactive power measurements are obviously much smaller for SE+

3612 Real-time Case:
Top Errors Detected

Lines having line flow measurements are detected to be out-of-service: 39 lines

Threshold: 0.1 W

Line ID	From Bus	To Bus	Meas_P (MW)	Meas_Q (MVAr)	Recovered_P (MW)	Recovered_Q (MVAr)
1194	1770	1739	2.6104	-5.6361	0	0
2576	3326	3332	56.405	2.754	3.24E-13	1.68E-13
2577	3326	3332	0	0	3.24E-13	1.68E-13
2579	3324	3327	-9.2	-0.9	0	0
2858	343	345	8	-0.4	0	0
2920	428	425	0	0	-5.65E-15	2.22E-14
2921	427	425	0	0	0	0
2937	455	457	6.6608	1.8502	1.88E-15	2.35E-14
3071	662	663	18.455	-1.0791	0	0
3090	707	710	21.287	0.77867	-1.85E-19	9.07E-14
3129	771	772	13.9	-1.4	5.73E-15	2.99E-16
3292	1014	1012	-11.579	1.1103	0	0
3297	1015	1016	4.9175	-3.564	0	0
3345	1098	1099	10.327	-1.5576	0	0
3367	1126	1131	9.6205	-3.9808	1.68E-15	2.30E-14
3369	1136	1139	9.0062	1.3925	5.65E-15	1.70E-16
3393	1170	1173	12.411	-0.97797	0	0
3428	1214	1217	6.1375	-0.2569	1.10E-15	2.28E-14
3452	1252	1256	14.469	0.61804	0	0
3455	1251	1253	7.9779	1.9302	-7.85E-15	4.48E-14
3497	1317	1319	8.905	-0.77496	0	0
3511	1333	1336	10.596	-0.90637	0	0
3525	1351	1355	12.05	1.75	0	0
3622	1511	1514	18.169	1.1432	-1.41E-15	-3.71E-18
3664	1586	1588	9.6125	-3.6244	0	0
3706	1651	1649	-6.747	0.55371	-9.46E-15	-4.41E-14
3718	1661	1660	-15.348	-0.025635	-1.18E-14	-9.01E-14
3763	1716	1713	-11.198	0.75881	0	0
3780	1739	1740	2.6368	-0.31696	3.25E-15	-2.25E-14
3796	1769	1770	0	0	0	0
3801	1784	1781	-1.465	1.4131	0	0
3859	1871	1875	0.0050049	-0.015015	0	0
3866	1893	1896	11.223	0.11536	0	0
3867	1893	1895	10.498	0.47791	2.44E-15	-4.55E-14
4238	2426	2428	12.733	1.5948	0	0
4239	2426	2429	11.957	2.8397	1.29E-14	4.36E-14
4249	2441	2443	5.8059	0.15234	0	0
4384	2671	2670	0	0	-4.26E-14	1.66E-14
4459	2798	2796	-57.245	0.7914	-2.65E-14	-3.72E-13

3612 Real-time Case: Top Errors Detected

Lines without line flow measurements are detected to be out-of-service: 270 lines

Threshold: 0.1 W

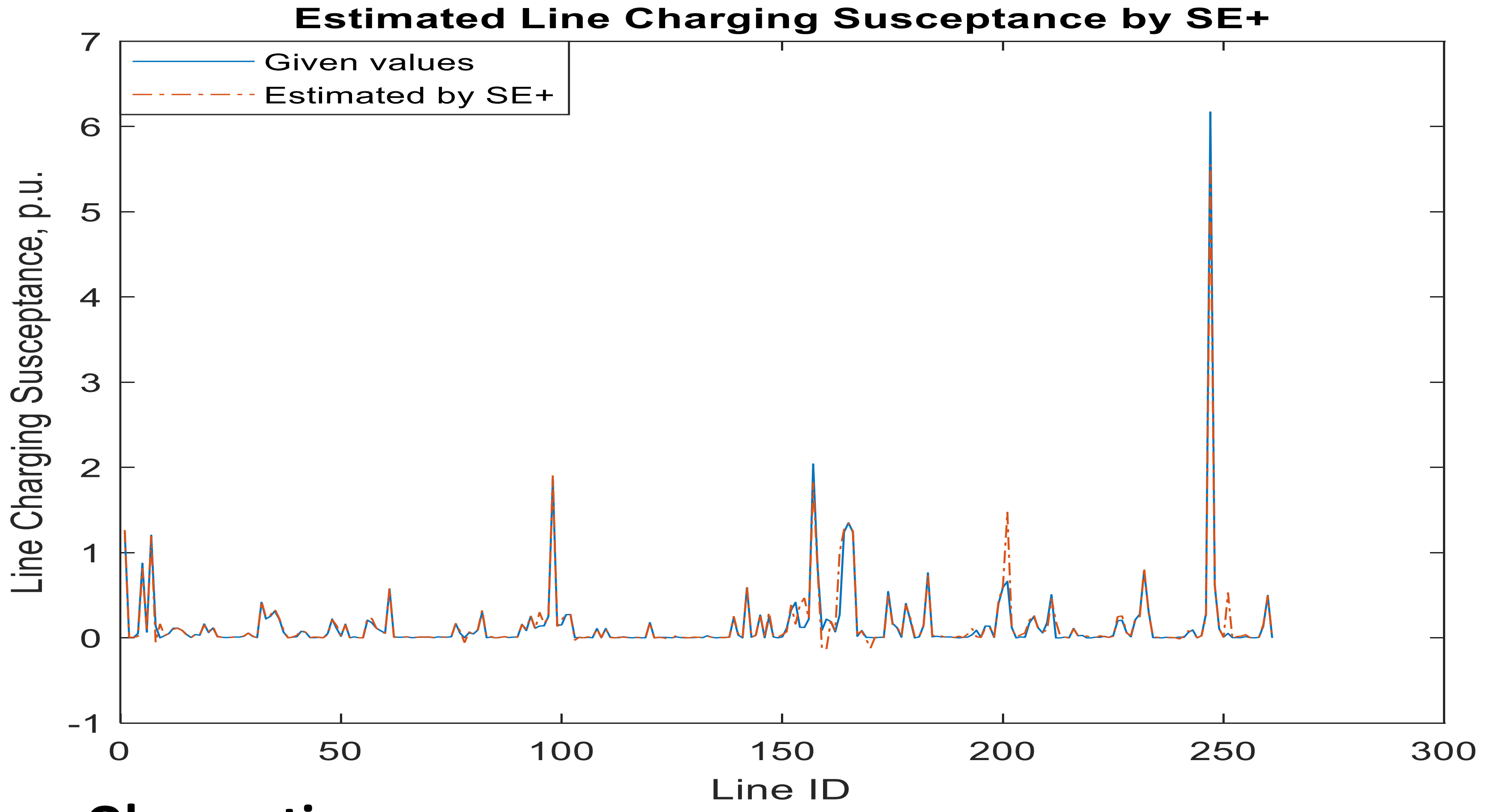
Line ID	From Bus	To Bus	Recovered_P (MW)	Recovered_Q (MVAr)
64	314	311	2.41E-13	-1.16E-11
91	298	297	-5.76E-12	-5.70E-14
91	297	298	5.76E-12	5.70E-14
206	353	352	1.54E-11	4.97E-11
323	449	450	3.59E-13	5.73E-14
336	489	488	-5.43E-11	1.79E-10
336	488	489	5.43E-11	-1.79E-10
465	822	823	0	0
571	1191	1190	1.99E-13	7.24E-13
586	1193	2022	-1.83E-13	1.01E-15
691	999	998	-5.36E-13	-2.93E-12
884	1412	1409	-8.45E-15	3.58E-13
1351	2193	1637	4.45E-14	7.30E-13
1448	2070	2068	1.46E-12	-5.12E-14
1450	2069	2068	1.46E-12	-5.12E-14
1457	2449	2450	0	0
1461	2444	2450	4.68E-12	2.27E-11
1464	2448	2450	1.42E-12	-2.93E-13
1474	1687	1691	-1.06E-11	2.41E-12
1578	1990	1989	0	0
1581	1991	1988	2.52E-12	-9.36E-11
1593	2085	2090	0	0
1593	2090	2085	0	0
1630	2529	2530	-7.39E-14	-5.27E-14
1668	2577	2499	1.20E-13	-1.38E-13
1691	2515	2517	0	0
1691	2517	2515	0	0
1868	2643	2648	0	0
1868	2648	2643	0	0
2044	2874	2873	-8.90E-14	1.05E-12
2044	2873	2874	8.90E-14	-1.05E-12
2459	3241	3242	4.47E-14	-2.73E-16
2591	3341	2861	1.12E-11	2.57E-12
2834	301	297	2.81E-15	2.78E-17
2834	297	301	-2.81E-15	-2.78E-17
2854	336	332	-2.99E-15	4.50E-14
2854	332	336	2.99E-15	-4.50E-14
2858	345	343	0	0
2866	354	356	5.88E-14	-3.59E-13
2866	356	354	-5.88E-14	3.59E-13
2869	361	358	7.35E-15	-4.51E-14
2869	358	361	-7.35E-15	4.51E-14
2870	359	357	0	0
2870	357	359	0	0
2871	360	358	0	0
2871	358	360	0	0
2875	370	371	-4.17E-14	1.79E-13
2875	371	370	4.17E-14	-1.79E-13
2882	380	381	9.84E-14	-3.60E-13
2882	381	380	-9.84E-14	3.60E-13
2905	410	408	0	0
2905	408	410	0	0
2906	410	408	0	0
2906	408	410	0	0
2909	411	408	0	0
2909	408	411	0	0
2914	417	415	9.30E-15	-2.15E-14
2914	415	417	-9.30E-15	2.15E-14
2916	419	418	5.62E-15	9.21E-16
2916	418	419	-5.62E-15	-9.21E-16
2920	425	428	5.65E-15	-2.22E-14
2921	425	427	0	0
2937	457	455	-1.88E-15	-2.35E-14
2947	468	465	2.73E-15	9.02E-16
2947	465	468	-2.73E-15	-9.02E-16
2961	490	488	-6.04E-15	1.01E-14
2961	488	490	6.04E-15	-1.01E-14
2981	527	525	2.99E-15	2.33E-14
2981	525	527	-2.99E-15	-2.33E-14
3071	663	662	0	0
3082	692	690	-6.23E-15	-9.03E-14
3082	690	692	6.23E-15	9.03E-14
3083	691	689	1.41E-15	-2.49E-17
3083	689	691	-1.41E-15	2.49E-17
3090	710	707	1.85E-19	-9.07E-14
3105	732	729	-3.60E-15	-4.51E-14
3105	729	732	3.60E-15	4.51E-14
3106	731	729	-2.82E-15	4.85E-17
3106	729	731	2.82E-15	-4.85E-17
3107	730	729	0	0
3107	729	730	0	0
3129	772	771	-5.73E-15	-2.99E-16
3130	773	775	1.65E-15	-2.28E-14
3130	775	773	-1.65E-15	2.28E-14
3181	863	865	-1.13E-14	-1.12E-15
3181	865	863	1.13E-14	1.12E-15
3184	864	866	4.51E-14	4.52E-15
3184	866	864	-4.51E-14	-4.52E-15
3207	898	900	0	0
3207	900	898	0	0

Line ID	From Bus	To Bus	Recovered_P (MW)	Recovered_Q (MVAr)
3284	999	1000	-1.38E-13	2.16E-12
3284	1000	999	1.38E-13	-2.16E-12
3292	1012	1014	0	0
3297	1016	1015	0	0
3309	1037	1038	-9.44E-15	1.83E-13
3309	1038	1037	9.44E-15	-1.83E-13
3313	1036	1039	7.74E-15	-1.82E-13
3313	1039	1036	-7.74E-15	1.82E-13
3345	1099	1098	0	0
3358	1122	1125	0	0
3358	1125	1122	0	0
3359	1124	1125	0	0
3359	1125	1124	0	0
3360	1123	1121	-1.22E-15	-2.29E-14
3360	1121	1123	1.22E-15	2.29E-14
3363	1132	1133	-1.15E-14	-4.76E-16
3363	1133	1132	1.15E-14	4.76E-16
3366	1129	1134	7.47E-16	2.30E-14
3366	1134	1129	-7.47E-16	-2.30E-14
3367	1131	1126	-1.68E-15	-2.30E-14
3369	1139	1136	-5.65E-15	-1.70E-16
3393	1173	1170	0	0
3395	1171	1174	0	0
3395	1174	1171	0	0
3396	1172	1174	-8.88E-14	3.63E-13
3396	1174	1172	8.88E-14	-3.63E-13
3405	1192	1191	-1.23E-15	-2.27E-14
3405	1191	1192	1.23E-15	2.27E-14
3428	1217	1214	-1.10E-15	-2.28E-14
3452	1256	1252	0	0
3455	1253	1251	7.85E-15	-4.48E-14
3479	1291	1294	0	0
3479	1294	1291	0	0
3480	1291	1293	0	0
3480	1293	1291	0	0
3481	1291	1292	0	0
3481	1292	1291	0	0
3482	1291	1296	0	0
3482	1296	1291	0	0
3483	1291	1295	-4.10E-15	4.49E-14
3483	1295	1291	4.10E-15	-4.49E-14
3488	1305	1302	1.83E-14	4.67E-14
3488	1302	1305	-1.83E-14	-4.67E-14
3489	1305	1302	1.42E-14	9.14E-14
3489	1302	1305	-1.42E-14	-9.14E-14
3490	1305	1302	2.94E-14	4.77E-14
3490	1302	1305	-2.94E-14	-4.77E-14
3491	1305	1302	2.23E-14	2.04E-15
3491	1302	1305	-2.23E-14	-2.04E-15
3494	1311	1313	0	0
3494	1313	1311	0	0
3497	1319	1317	0	0
3499	1316	1320	0	0
3499	1320	1316	0	0
3511	1336	1333	0	0
3525	1355	1351	0	0
3549	1391	1393	0	0
3549	1393	1391	0	0
3550	1390	1392	0	0
3550	1392	1390	0	0
3551	1394	1396	1.11E-14	1.86E-15
3551	1396	1394	-1.11E-14	-1.86E-15
3579	1446	1449	-5.55E-15	3.72E-13
3579	1449	1446	5.55E-15	-3.72E-13
3610	1495	1494	0	0
3610	1494	1495	0	0
3622	1514	1511	1.41E-15	3.71E-18
3637	1534	1533	-1.42E-15	-4.88E-17
3637	1533	1534	1.42E-15	4.88E-17
3651	1559	1560	0	0
3651	1560	1559	0	0
3664	1588	1586	0	0
3673	1608	1606	0	0
3673	1606	1608	0	0
3687	1633	1629	0	0
3687	1629	1633	0	0
3688	1632	1629	0	0
3688	1629	1632	0	0
3689	1630	1629	0	0
3689	1629	1630	0	0
3690	1631	1629	-5.40E-16	-4.57E-14
3690	1629	1631	5.40E-16	4.57E-14
3692	1637	1640	-1.79E-13	2.98E-12
3692	1640	1637	1.79E-13	-2.98E-12
3706	1649	1651	9.46E-15	4.41E-14
3713	1659	1657	0	0
3713	1657	1659	0	0
3718	1660	1661	1.18E-14	9.01E-14
3763	1713	1716	0	0
3780	1740	1739	-3.25E-15	2.25E-14

Line ID	From Bus	To Bus	Recovered_P (MW)	Recovered_Q (MVAr)
3796	1770	1769	0	0
3801	1781	1784	0	0
3840	1850	1848	0	0
3840	1848	1850	0	0
3841	1848	1849	-8.75E-15	-1.81E-13
3841	1849	1848	8.75E-15	1.81E-13
3846	1862	1857	2.83E-15	1.42E-16
3846	1857	1862	-2.83E-15	-1.42E-16
3847	1861	1860	0	0
3847	1860	1861	0	0
3848	1866	1864	0	0
3848	1864	1866	0	0
3849	1865	1864	-5.99E-16	-4.56E-14
3849	1864	1865	5.99E-16	4.56E-14
3859	1875	1871	0	0
3860	1885	1882	0	0
3860	1882	1885	0	0
3861	1884	1881	-9.06E-16	-4.56E-14
3861	1881	1884	9.06E-16	4.56E-14
3862	1881	1883	0	0
3862	1883	1881	0	0
3863	1892	1889	0	0
3863	1889	1892	0	0
3864	1891	1886	0	0
3864	1886	1891	0	0
3865	1890	1886	0	0
3865	1886	1890	0	0
3866	1896	1893	0	0
3867	1895	1893	-2.44E-15	4.55E-14
3919	1951	1952	-4.17E-15	-1.82E-13
3919	1952	1951	4.17E-15	1.82E-13
3922	1951	1953	0	0
3922	1953	1951	0	0
3942	1974	1975	-5.65E-15	5.15E-16
3942	1975	1974	5.65E-15	-5.15E-16
3945	1980	1979	0	0
3945	1979	1980	0	0
3951	1985	1986	4.92E-15	-1.83E-13
3951	1986	1985	-4.92E-15	1.83E-13
3984	2052	2051	3.69E-15	4.54E-14
3984	2051	2052	-3.69E-15	-4.54E-14
3985	2053	2051	-5.97E-15	-9.08E-14
3985	2051	2053	5.97E-15	9.08E-14
4029	2112	2117	-1.81E-13	1.60E-14
4029	2117	2112	1.81E-13	-1.60E-14
4032	2112	2118	0	0
4032	2118	2112	0	0
4079	2187	2186	0	0
4079	2186	2187	0	0
4089	2204	2203	0	0
4089	2203	2204	0	0
4090	2203	2204	0	0
4090	2204	2203	0	0
4091	2204	2203	0	0
4091	2203	2204	0	0
4214	2399	2397	0	0
4214	2397	2399	0	0
4215	2398	2396	0	0
4215	2396	2398	0	0
4226	2411	2410	0	0
4226	2410	2411	0	0
4238	2428	2426	0	0
4239	2429	2426	-1.29E-14	-4.36E-14
4249	2443	2441	0	0
4267	2462	2464	-1.54E-13	-7.06E-13
4267	2464	2462	1.54E-13	7.06E-13
4270	2462	2463	0	0
4270	2463	2462	0	0
4283	2479	2480	-2.13E-13	2.95E-13
4283	2480	2479	2.13E-13	-2.95E-13
4296	2503	2504	0	0
4296	2504	2503	0	0
4307	2525	2528	-5.49E-14	7.20E-14
4307	2528	2525	5.49E-14	-7.20E-14
4328	2570	2571	-2.55E-15	-1.30E-13
4328	2571	2570	2.55E-15	1.30E-13
4384	2670	2671	4.26E-14	-1.66E-14
4404	2722	2727	-3.34E-14	-8.49E-14
4404	2727	2722	3.34E-14	8.49E-14
4409	2719	2728	0	0
4409	2728	2719	0	0
4415	2721	2726	0	0
4415	2726	2721	0	0
4418	2720	2723	0	0
4418	2723	2720	0	0
4458	2798	2796	-1.13E-13	-3.44E-13
4458	2796	2798	1.13E-13	3.44E-13
4459	2796	2798	2.65E-14	3.72E-13
4601	3313	3314	0	0
4601	3314	3313	0	0

3612 Real-time Case: Parameter Estimate

Number of lines having enough measurements redundancy for parameter estimation: 261 lines

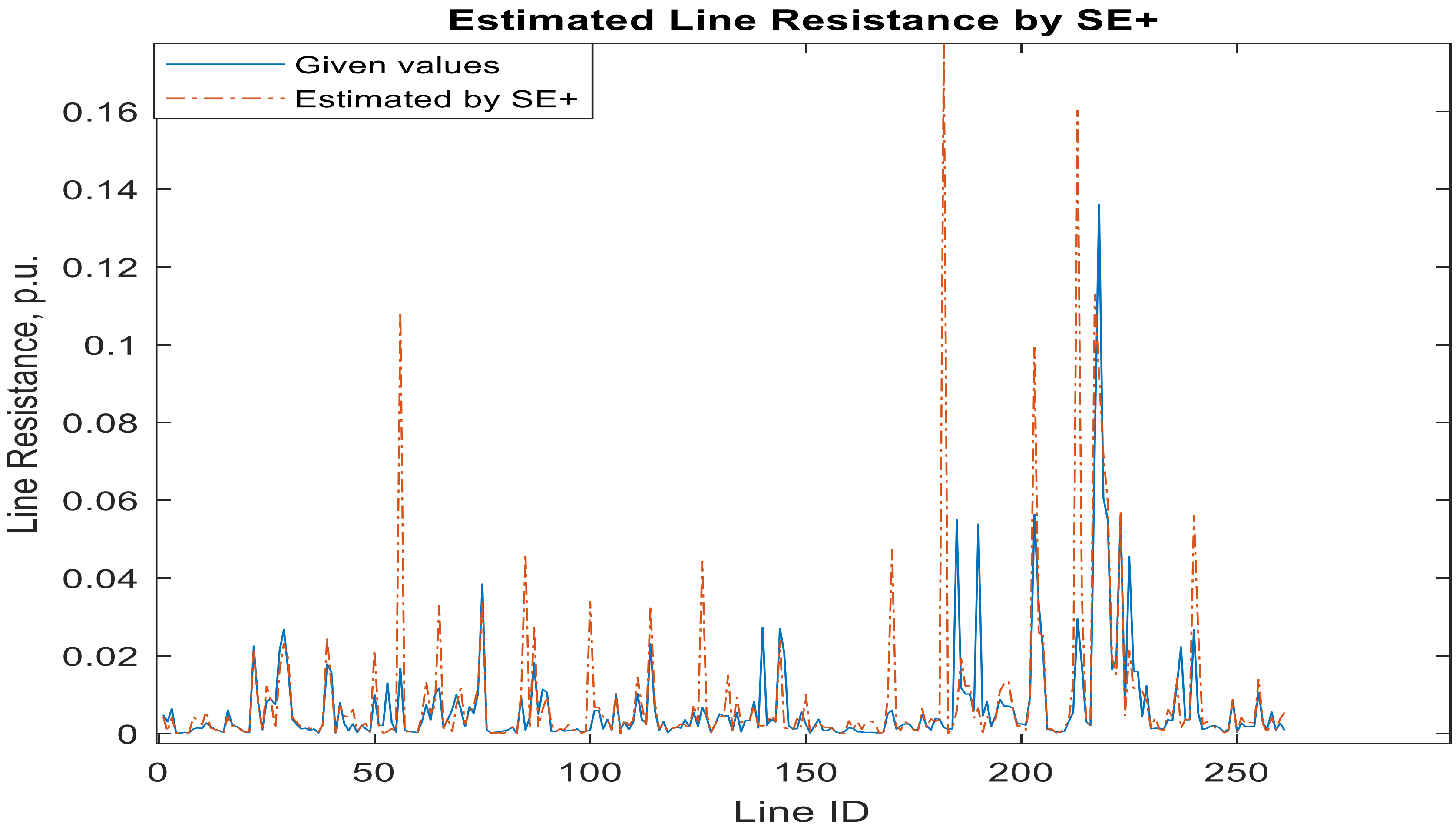


Observations:

1. The given values and SE+ estimated values are close.
2. The comparison implies that the obtained voltage solution by SE+ is accurate.

3612 Real-time Case: Parameter Estimate

Number of lines having enough measurements redundancy for parameter estimation: 261 lines

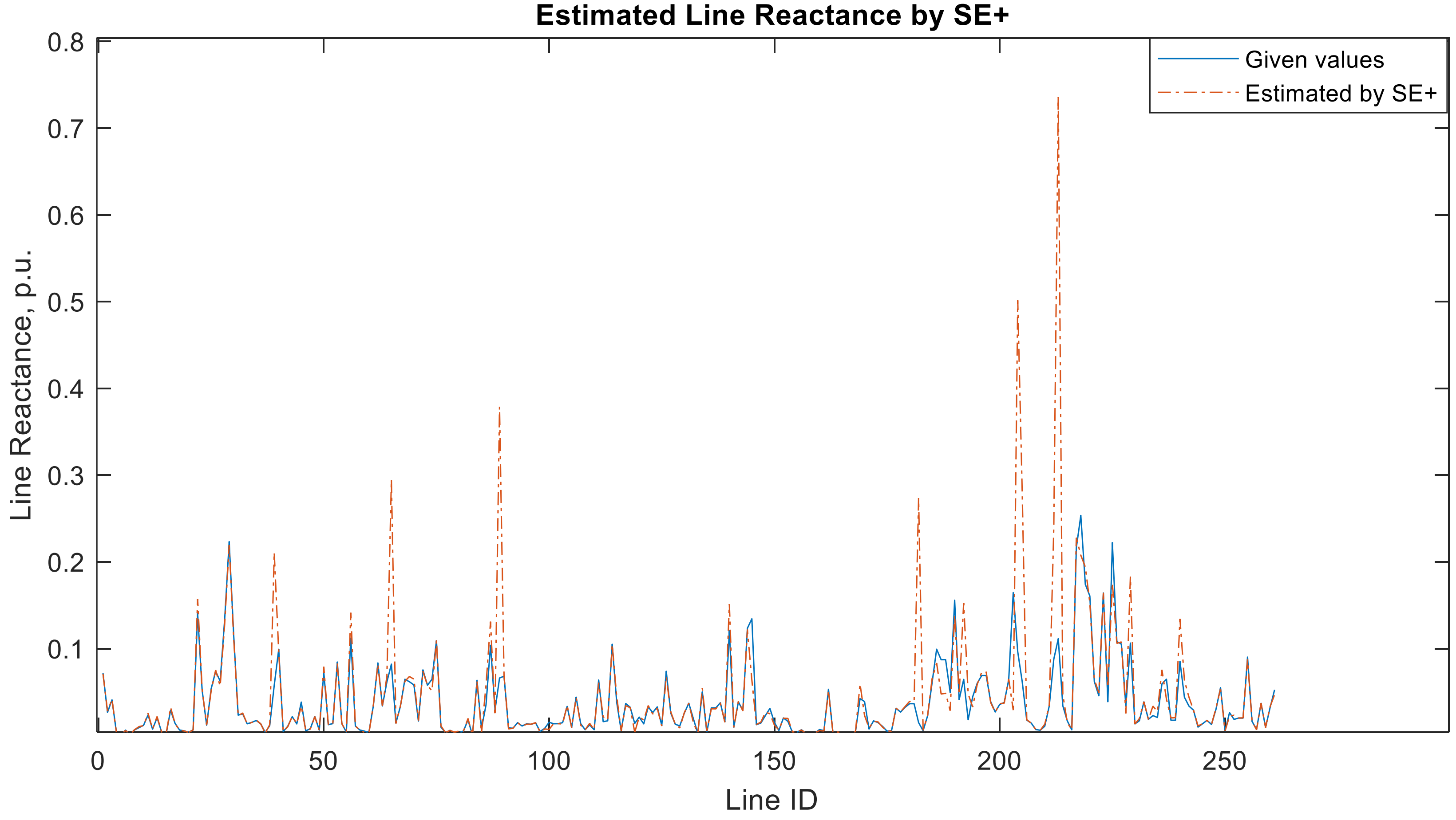


Observations:

1. There are some differences between the given values and estimated values.

3612 Real-time Case: Parameter Estimate

Number of lines having enough measurements redundancy for parameter estimation: 261 lines



Observations:

1. Most of the given values are accurate.

3409 Real-time Case: Voltage solution quality

Raw data information:

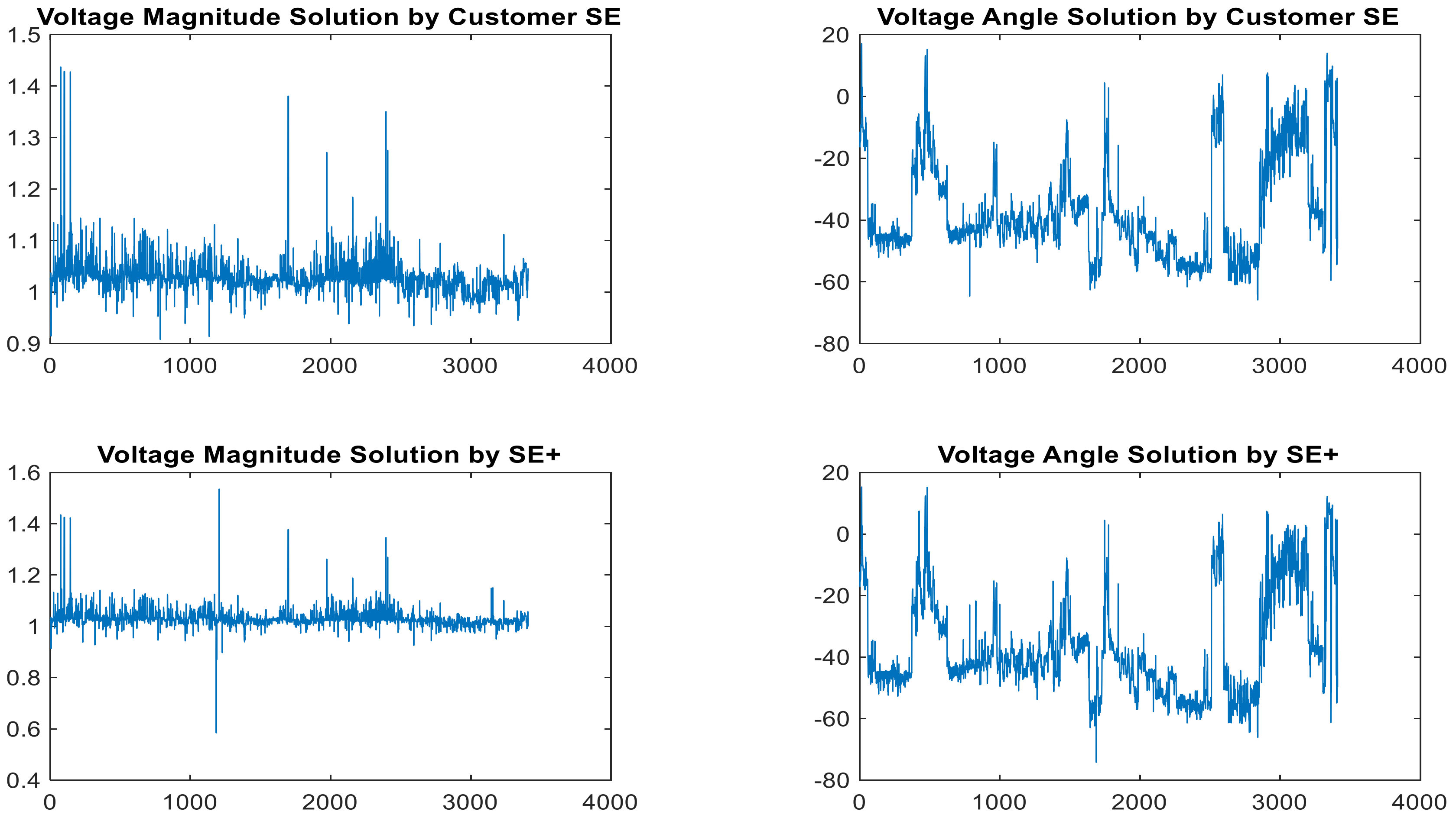
Total number of buses:	3409
Total number of branches:	4228
Total number of line flow measurements:	3571
Total number of injection measurements:	3022
Total number of voltage magnitude measurements:	1457

Main observable island:

Total number of buses:	3409
Total number of branches:	4228
Total number of line flow measurements:	3568
Total number of injection measurements:	3022
Total number of voltage magnitude measurements:	1432

3409 Real-time Case: Voltage solution quality

Voltage solutions:



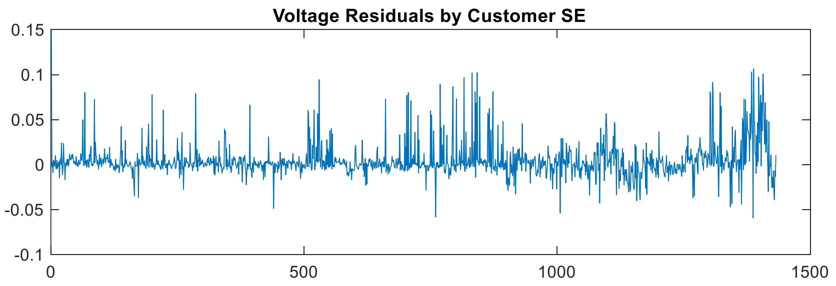
p.u.

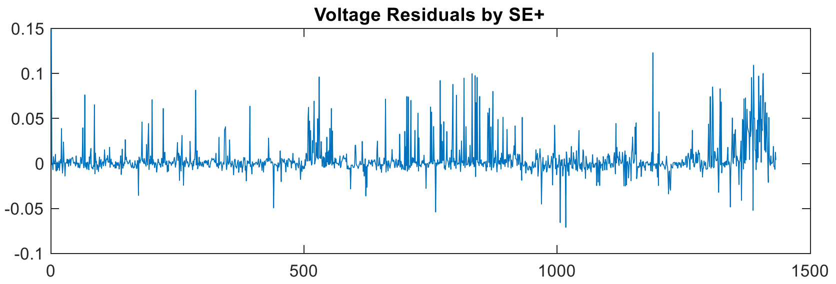
degree

3409 Real-time Case: Voltage solution quality

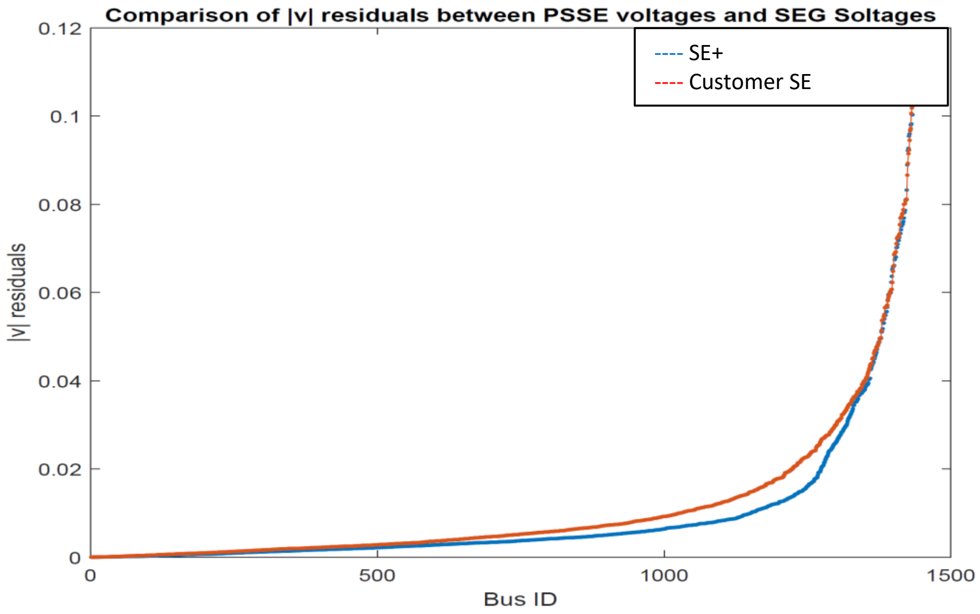
Quality of Voltage Estimate

Compare WLS SE voltage solution with SE+ voltage solution to the |v| measurements:





p.u.



Voltage residuals are reduced by 13.4%

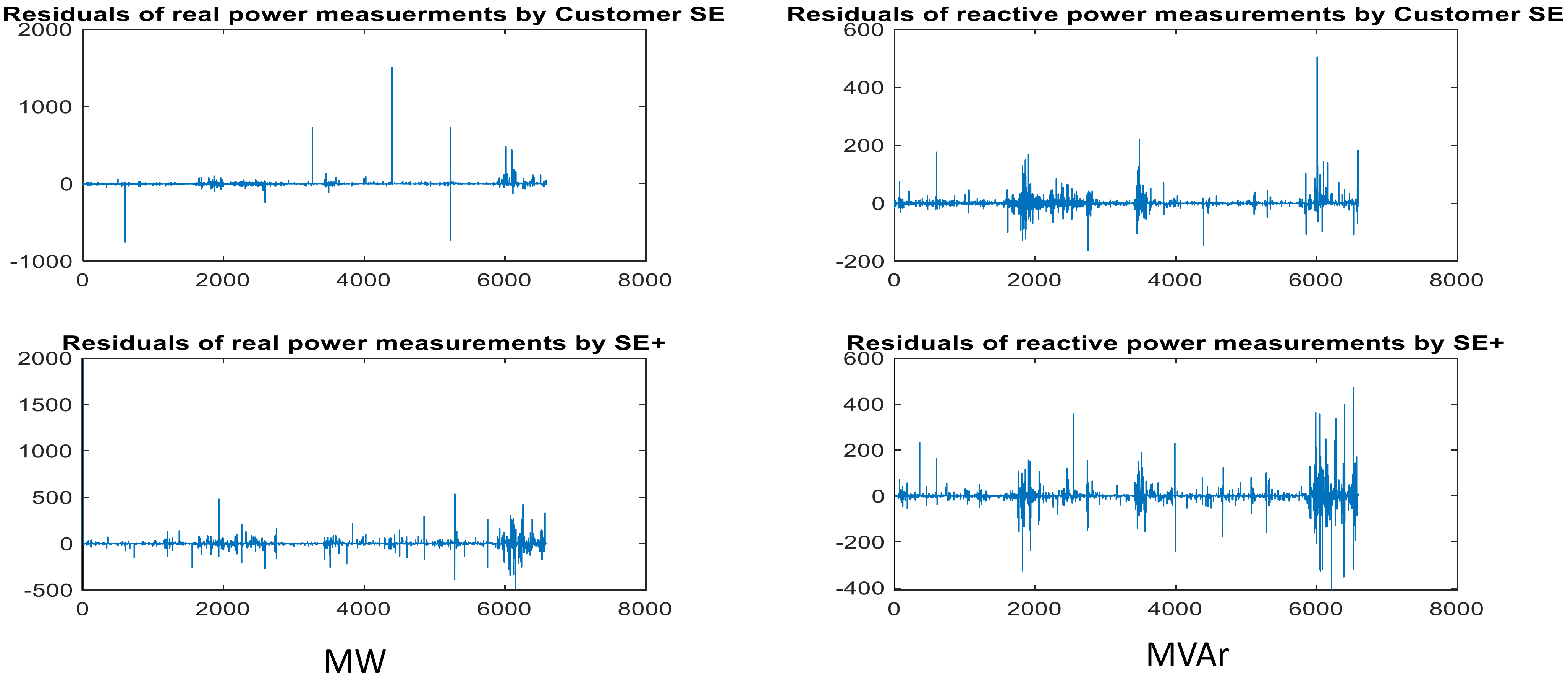
$$\sum_{i=1}^{M_v} \left| v_i^{meas} - v_i^{SE+} \right| = 13.3838 \text{ p.u.}$$
$$\sum_{i=1}^{M_v} \left| v_i^{meas} - v_i^{WLS} \right| = 15.4461 \text{ p.u.}$$

Conclusion:

- The bus voltage solution obtained by SE+ is closer to the voltage measurements than that of Customer SE (WLS)

3409 Real-time Case: Voltage solution quality

Residuals of real power and reactive power measurements:



Observation:

- The residuals of real power measurements are obviously smaller for SE+

3409 Real-time Case: Topology Errors Detected

The lines should be out-of-service:

Lines having line flow measurements: 12 lines

Line ID	From Bus	To Bus	Meas_P (MW)	Meas_Q (MVAr)	Recovered_P	Recovered_Q
308	419	422	0	0	2.81E-13	2.35E-13
544	864	78	0	0	1.77E-12	1.18E-11
1764	2633	2641	0	0	-2.30E-11	-1.86E-10
1810	2732	2634	0	0	7.21E-13	-6.48E-14
1815	2633	2632	0	0	-7.11E-13	-1.17E-11
2082	2888	2889	0	0	1.12E-13	4.91E-13
2942	419	421	0	0	0	0
2943	419	420	0	0	0	0
3207	865	868	6	-5.01	4.48E-14	8.57E-15
3508	1324	1326	9.4375	0.6418	0	0
3701	1633	1632	0	0	0	0
3990	2013	2015	0	0	-2.99E-16	1.17E-14

Threshold is 0.1 W

3409 Real-time Case: Topology Errors Detected

The lines should be out-of-service:

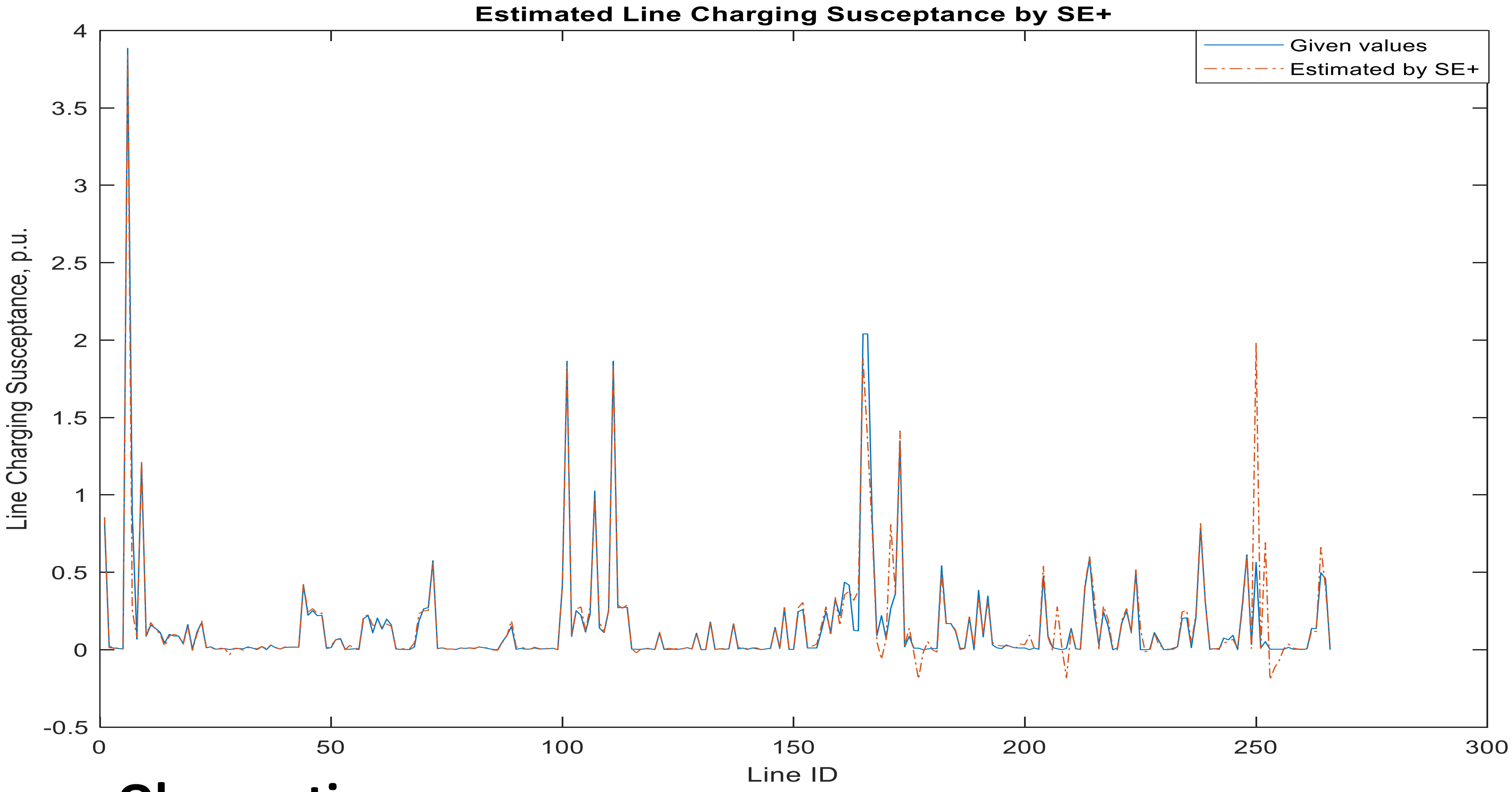
Lines having No line flow measurements: 87 lines

Line ID	From Bus	To Bus	Recovered_P (MW)	Recovered_Q (MVAr)		Line ID	From Bus	To Bus	Recovered_P (MW)	Recovered_Q (MVAr)
86	234	228	0	0		3967	1978	1979	0	0
175	1407	130	0	0		3967	1979	1978	0	0
177	1406	129	0	0		3975	1992	1994	-6.48E-14	-1.11E-13
207	368	369	-7.30E-12	4.58E-11		3975	1994	1992	6.32E-14	1.09E-13
457	629	628	0	0		3978	1992	1993	-6.23E-14	-2.99E-13
544	78	864	-1.77E-12	-1.18E-11		3978	1993	1992	6.07E-14	2.92E-13
691	1017	1016	-1.38E-12	-3.86E-13		3990	2015	2013	3.31E-15	-1.19E-14
701	1897	1044	-3.73E-13	1.39E-12		4064	2125	2131	-3.22E-13	-7.49E-13
709	1895	1896	-1.40E-11	4.44E-11		4064	2131	2125	3.22E-13	7.49E-13
1212	1913	1912	2.46E-11	-9.04E-11		4067	2125	2132	0	0
1213	1914	1912	0	0		4067	2132	2125	0	0
1259	1859	2232	-4.73E-13	6.57E-13		4319	2494	2497	0	0
1321	2060	2059	0	0		4319	2497	2494	0	0
1321	2059	2060	0	0		4322	2493	2496	0	0
1323	2493	2491	-9.31E-13	-1.86E-10		4322	2496	2493	0	0
1324	2492	2491	0	0		4325	2492	2498	-3.82E-14	1.46E-12
1325	2490	2491	-9.31E-13	-1.86E-10		4325	2498	2492	3.82E-14	-1.46E-12
1343	2494	2495	-5.59E-12	4.66E-11		4351	2536	2537	0	0
1370	2503	2495	1.17E-13	2.33E-11		4351	2537	2536	0	0
1453	2082	2081	-1.05E-12	5.74E-12		4358	2556	2557	-6.69E-14	6.16E-14
1460	2474	2475	-1.46E-12	-4.43E-14		4358	2557	2556	6.69E-14	-6.16E-14
1467	2473	2475	2.92E-12	8.86E-14		4362	2555	2558	0	0
1513	2339	2335	-3.62E-13	8.83E-16		4362	2558	2555	0	0
1764	2641	2633	2.30E-11	1.86E-10		4398	2643	2641	1.12E-11	2.30E-10
2552	3088	3041	0	0		4398	2641	2643	-1.12E-11	-2.30E-10
2915	388	389	-9.27E-14	1.52E-13		4399	2643	2642	0	0
2915	389	388	9.27E-14	-1.52E-13		4399	2642	2643	0	0
2942	421	419	-2.87E-14	3.43E-14		4416	2668	2671	0	0
2943	420	419	0	0		4416	2671	2668	0	0
3207	868	865	0	0		4419	2668	2672	0	0
3308	1017	1018	3.07E-13	1.58E-12		4419	2672	2668	0	0
3308	1018	1017	-3.07E-13	-1.58E-12		4469	2758	2763	-5.68E-15	2.23E-16
3508	1326	1324	0	0		4469	2763	2758	5.68E-15	-2.23E-16
3701	1632	1633	0	0		4474	2755	2764	0	0
3704	1640	1643	-1.55E-13	2.92E-12		4474	2764	2755	0	0
3704	1643	1640	1.55E-13	-2.92E-12		4480	2757	2762	-1.12E-14	-1.11E-15
3899	1913	1916	2.95E-12	-5.27E-12		4480	2762	2757	1.12E-14	1.11E-15
3899	1916	1913	-2.81E-12	5.02E-12		4483	2756	2759	5.66E-15	-2.77E-17
3902	1914	1917	-4.37E-12	4.88E-12		4483	2759	2756	-5.66E-15	2.77E-17
3902	1917	1914	4.16E-12	-4.65E-12		4549	2941	2942	3.25E-13	-2.05E-12
3944	1956	1957	-1.14E-14	-9.34E-16		4549	2942	2941	2.64E-13	1.59E-12
3944	1957	1956	1.14E-14	9.34E-16		4550	2941	2942	3.25E-13	-2.05E-12
3947	1956	1958	0	0		4550	2942	2941	2.64E-13	1.59E-12
3947	1958	1956	0	0						

Threshold is 0.1 W

3409 Real-time Case: Parameter Estimate

Number of lines having enough measurements redundancy for parameter estimation: 266 lines

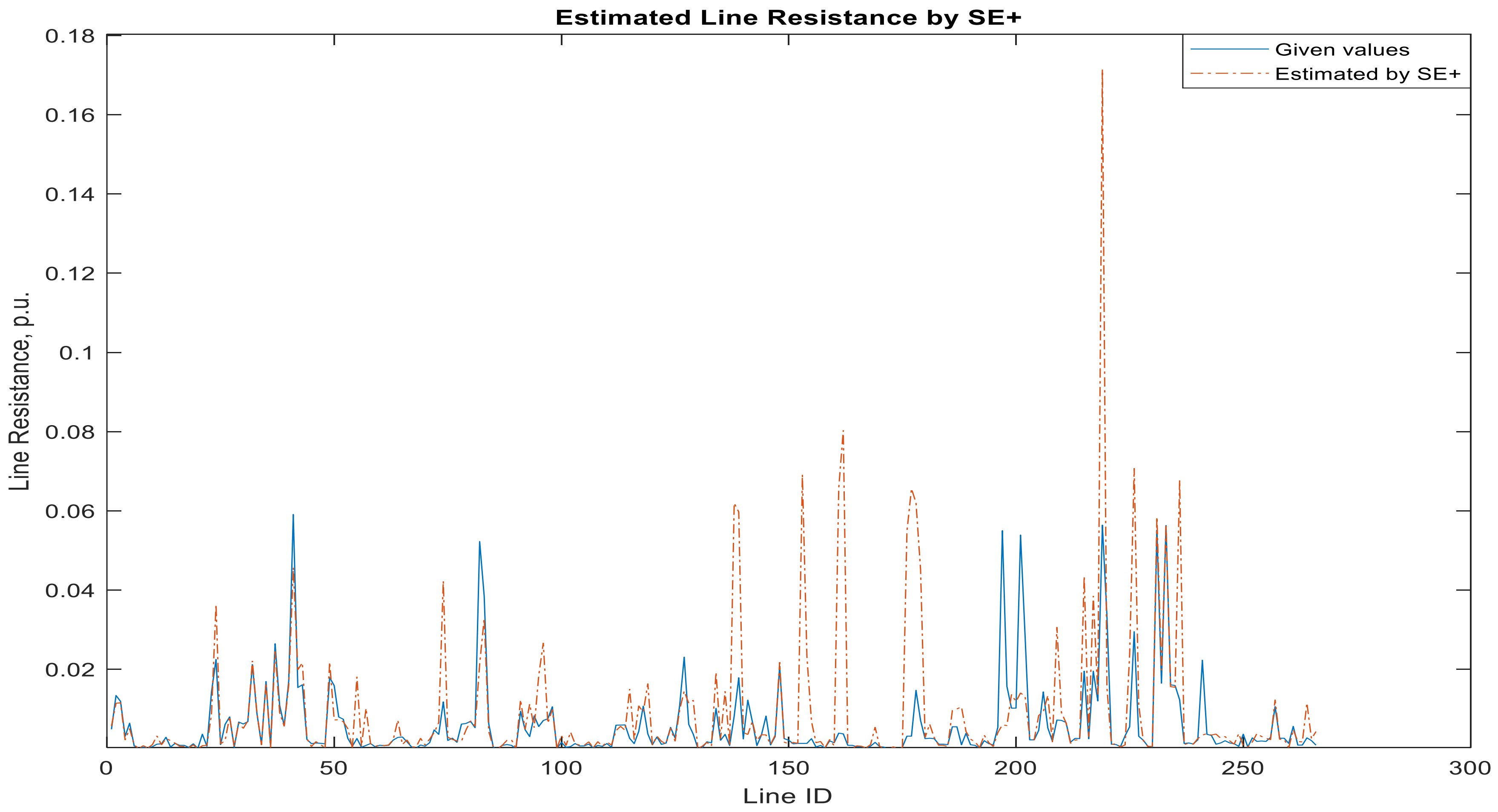


Observations:

1. The given values and SE+ estimated values are close.
2. The comparison implies that the obtained voltage solution by SE+ is accurate.

3409 Real-time Case: Parameter Estimate

Number of lines having enough measurements redundancy for parameter estimation: 266 lines

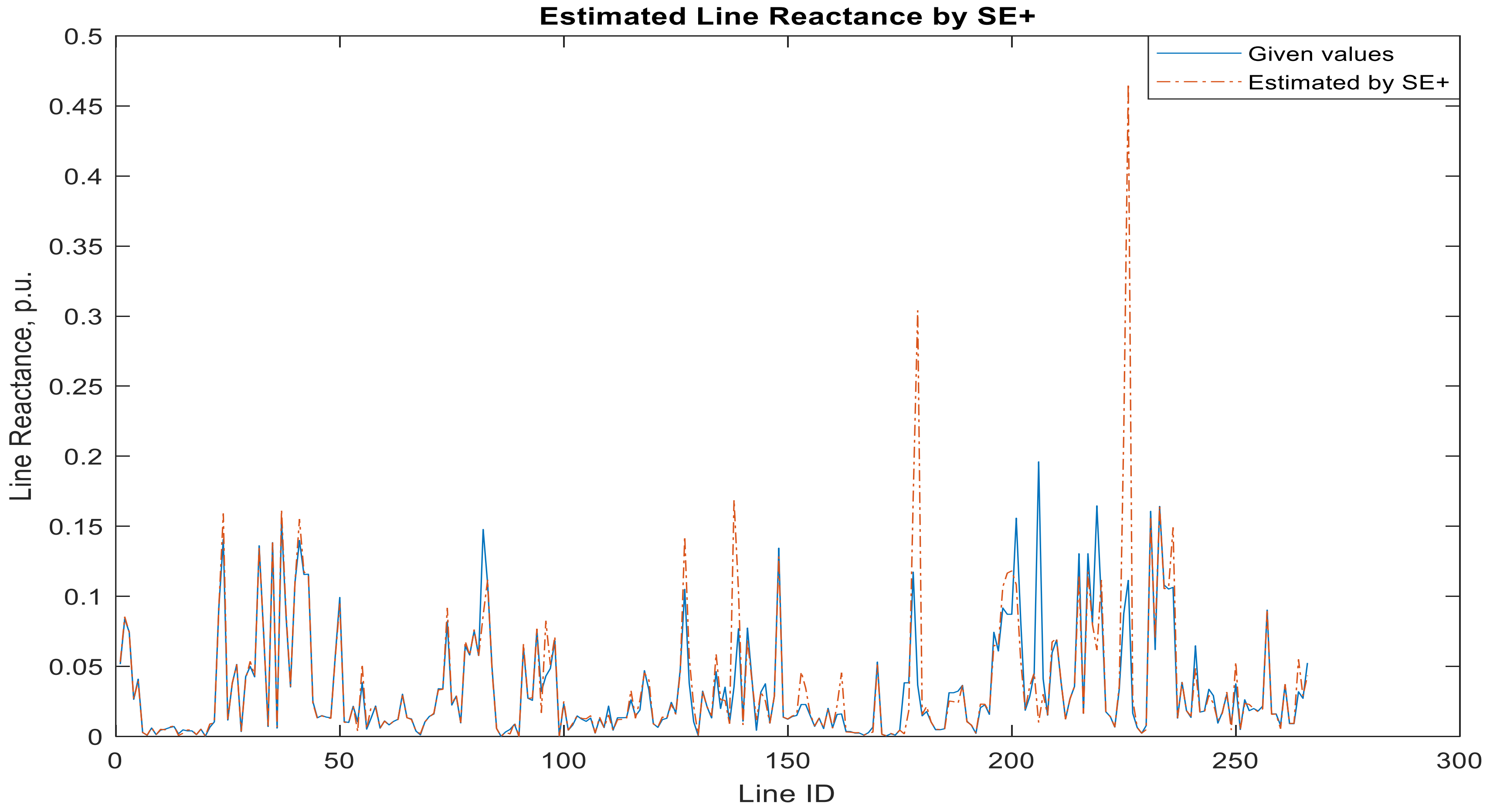


Observations:

1. There are some differences between the given values and estimated values.

3409 Real-time Case: Parameter Estimate

Number of lines having enough measurements redundancy for parameter estimation: 266 lines



Observations:

1. Most of the given values are accurate.

Definition of Leverage Point

A leverage point is **a measurement zi** that affects the state estimator in such a way that the state estimate will **satisfy closely that particular measurement.**

An example:

A zero injection measurement is assigned a Huge weight.

$$min \quad f = \sum_{i=1}^{N} w_i (z_i - h_i(x))^2 =$$

$$w_1 (z_1 - h_1(x))^2 + w_2 (z_2 - h_2(x))^2 + \ldots + w_k (z_k - h_k(x))^2 + \ldots$$

If w_k is much larger than other weights, then $(z_k - h_k(x))^2 = 0$.

WLS SE will satisfy all leverage point measurements first.

Definition of Breakdown Points (Robustness)

Breakdown point of an estimator is the proportion of incorrect measurements (e.g. arbitrarily large measurements) an estimator can handle before giving an incorrect result.

An example:

Given z_i= {0.9, 0.95, 1.05, 1.07, 1.09}, find the **breakdown point** of the WLS estimators: $f = \frac{1}{5}\sum_{i=1}^{5} z_i$

Let us replace 0.9 by ∞, $f = \infty$. Then Breakdown Point is $= \frac{0}{5} = 0$.

0 ≤ Breakdown Point ≤ 0.5

WLS SE has 0 breakdown point, while SE+ has 0.5 breakdown point.

Any Questions?

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