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Improving state estimation in smart distribution grid using synchrophasor technology: a comparison study

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Abstract: Both the growing number of dispersed generation plants and storage systems and the new roles and functions on the demand side (e.g. demand side management) are making the operation (monitoring and control) of electrical grids more complex, especially in distribution. This paper demonstrates how to integrate phasor measurements so that state estimation in a distribution grid profits optimally from the high accuracy of PMUs. Different measurement configurations consisting of conventional and synchronous measurement units, each with different fault tolerances for the quality of the calculated system state achieved, are analyzed and compared. Weighted least squares (WLS) algorithms for conventional, linear and hybrid state estimation provide the mathematical method used in this paper. A case study of an 18-bus test grid with real measured PMU data from a 110 kV distribution grid demonstrates the improving of the system's state variable's quality by using synchrophasors. The increased requirements, which are the prerequisite for the use of PMUs in the distribution grid, are identified by extensively analyzing the inaccuracy of measurement and subsequently employed to weight the measured quantities.

Key words: accuracy analysis, case study, distribution grid state estimation, phasor measurement units, weighted least squares

1. Introduction

1.1. Motivation

As the number of distributed generation plants in Germany rises, capabilities to provide static and dynamic ancillary services are shifting further from the transmission grid to the distribution grid [1]. At the same time, electrical grid operation is growing complex in general, not only because of new components (storage systems) and actors but also because of increasingly shorter-term actions in the market and grid, like active demand side management [2]. Continuing to ensure a reliable supply of electricity and stable operation of the synchronous grid on all of its levels necessitates making full use of the available control capabilities [3, 4] spanning the voltage levels.

Systematically controlling the operation of distributed generation plants rather than conventional actions like providing reactive power in large power plants or adjusting transformer tap changers when regulating voltage will be a potential future solution. Such an approach is already being tested in pilot projects [5, 6]. Given the high number of potential manipulated variables and the direct local impact, it promises to rectify or eliminate critical grid situations with a minimum of intervention in day-to-day grid operation and the liberal electricity market.

The aforementioned approaches require the availability of sufficiently accurate and reliable data on the electrical grid in order to respond to critical situations optimally, though. Optimal monitoring and suitable methods of state estimation are consequently essential to ensuring system reliability [7]. This paper therefore demonstrates that phasor measurement units (PMU) used in state estimation in distribution grids are a technology key to establishing such conditions and rendering monitoring of the electrical grid viable for the future.

1.2. Synchrophasors in electrical grids

PMUs were originally developed for use in transmission grids to improve stability analysis in power grids by using synchronized readings. Improvements in performance and accuracy of state estimation have been demonstrated [8]. Korres [9] and Bi [10] implemented hybrid state estimators to analyze the effect phasor measurements added to SCADA have on the reconstruction of system states. Glavic [11] and Das [12] also corroborated the positive effect additional PMUs have on precision, computation time and topology error detection.

Since use cases and results are not easily transferred to distribution grids, phasor measurements are still not widely used in the field. Sexauer [13] and Hurtgen [14] first demonstrated the necessity and benefits of PMU use in the distribution grid. Since the measurement infrastructure that has evolved over time is minimal, future thoughts about generally overhauling the monitoring system ought to include the use of PMUs. Applying optimal meter placement algorithms as in [15] or [16] increases the level of observability while minimizing the number of measurement units required. According to [17], compromises inevitably have to be entered when using PMUs, e.g. modeling methods from the used state estimator in the transmission grid have to be modified slightly for use in the distribution grid. The smaller differences in voltage magnitude and angle between substations particularly necessitate expanded error management and higher standards for the measurement system [18]. Moreover, voltage and current asymmetries increase as the voltage level drops, thus necessitating factorization of the system into symmetrical components [19]. Improvements through distributed approaches to state estimation have nevertheless been demonstrated in [20] and [21]. The linear relationship between the phasor measured and the elements of the state vector particularly boosts the performance of state estimators [22].

Initial experiences have been made with micro PMUs (μPMUs) on lower voltage levels. McCamish uses μPMUs in [23] in a small campus testbed and demonstrates advantages in time when estimating unmeasured bus power. Even standard industrial PMUs employed on lower voltage levels are beneficial [24]. Other important technical advantages apart from highly accurate measurements are the improved observability of distributions grids, advanced modeling approaches and better power system diagnostics. These functions have been analyzed in theory and in practice on medium [25] and even low voltage levels in microgrids [26] and industrial networks [27].

1.3. Article scope and structure

With its high voltage level and concomitant characteristic performance of a distribution grid, the German 110 kV grid plays a special role in system state estimation. The existing metering infrastructure closes the gap between the level of the transmission grid and the medium voltage grid. Field tests in [18] have already demonstrated that industrially available PMUs are definitely able to control the slighter voltage differences between the stations. Furthermore, the asymmetries occurring in the 110 kV grid are still so comparatively small that modeling the system state in the positive sequence component is sufficient.

Taking this as its point of departure, this paper examines the influence of different measurement configurations and accuracies on the quality and performance of the modeled system state in the 110 kV distribution grid. Conventional state estimation, linear state estimation based solely on PMUs and hybrid state estimation are compared. The latter utilizes both conventional voltage and power data and synchronous PMU data. Unlike in [28, 29] and [30], analysis is not limited to additional PMUs in the grid. Instead, the extent to which upgrades of existing SCADA systems affect the quality of the modeled state vector is analyzed in comparison with a PMU rollout. To this end, the accuracy and penetration of the measurement configurations compared vary. They are analyzed using a broad range of scenarios, thus keeping the case study from being limited to specific use cases. Based on statistical parameters and the distribution parameters derived, it provides global conclusions about a particular measurement configuration's suitability and accuracy.

First and taking an extensive literature survey in section 2 as its starting point, the accuracy of the synchronous independent variables and their impacts on the modeled system state are analyzed. A state estimator specially developed in MATLAB subsequently employs weighted least squares (WLS) to solve the system of overdetermined equations in the distribution grid (section 3). In section 4, this method's suitability for state estimation is analyzed in a case study employing different measurement configurations and varying accuracies. Since the underlying load time series with a resolution of 1 second were recorded with PMUs in a real 110 kV distribution grid, they reflect characteristic performance optimally.

2. Qualifying PMUs for distribution grids

2.1. Characteristics of distribution grid phasors

The distribution grid's significant differences in characteristics and operation from the transmission grid have to be factored in when PMUs are used. A distribution grid is generally designed for lower transmission capacity because of the rated voltage levels are lower. Moreover, the lines' higher R-to-X-ratio precludes decoupled power flow studies since active and reactive power are no longer solely a function of differences in amplitude or angle. The resulting slight differences of voltage angles and amplitudes between buses are crucial to the use of PMUs (see section 1.2). If the total vector error (TVE) renders the tolerance range unduly larger than the difference between two buses or the complex-valued solution spaces even overlap, then the mathematical solution of the modeled active and reactive power flows is meaningless for grid operators because it is highly inaccurate.

Structurally, this differs on the transmission level, too. The limited meshing of the structure requires greater penetration with measurement units while maintaining the level of monitoring. Standard metering infrastructures are generally minimal, though. Moreover, since dynamic effects and asymmetries increase as the voltage level drops, measurements have to be taken at higher frequency and methods of grid modeling may have to be applied modally.

2.2. Fault analysis

Table 1 presents an overview of the independent variables that detract from accuracy when quantities measured by phasors are established. These are used to assess the suitability of high-precision PMU technology for state estimation in distribution grids. The inaccuracies identified represent worst case analyses based on currently available technologies.

Table 1. Quantification of PMU inaccuracies

Error source	**Parameter**	**Characteristic value range**	**Potential inaccuracy of magnitude**	**Potential inaccuracy of angle**
Potential transformers	IEC 61869 accuracy class [31]	0.1, . . . , 3.0 [32, 33]	$3\%^1$	$> 0.7^{\circ 1}$
Current transformers	IEC 61869 accuracy class [31]	0.1, . . . , 3.0 [32, 33]	$> 1.5\%^2$	$> 1.5^{\circ 2}$
GPS sender	Delay	< 1 µs (40 ns) [34]	–	$< 0.018^{\circ}$
GPS receiver	Delay	1 µs [35, 36]	–	0.018°
Power system characteristics	Frequency deviation	± 27.4 mHz^3 [37]	–	$< 10^{\circ 4}$
Digital-to-analog converter	Resolution	12, . . . , 16 bit [38, 35]	≈ 0	≈ 0

[1] between 0.8 and 1.2 times the nominal voltage
[2] at 0.2 times the nominal current
[3] maximum standard deviation of German grid frequency between 2011 and 2014
[4] global influence on frequency

Both voltage and current measurement devices are based on the principle of a transformer. The equivalent circuit diagram reveals that the magnetization branch and longitudinal flows cause additional voltage drops and current paths in the form of leakage reactance and winding resistance. They prevent primary and secondary variables from being in-phase and (incorporating the transformation ratio) equal in amplitude. While calibration for specific operating points minimizes variation in practice [39], sensitivity to the adjacent load remains. Percentage accuracy generally increases as the operating point comes closer to the measurement transformer's nominal range.

Voltage and current transformers' maximum deviations are usually quantified on a data sheet by their accuracy classes, which specify deviations in the range of rated operation. Rather uncritical in voltage transformers, the tolerance for amplitude and angle increases one and a half fold in current transformers at just 20% of the rated current. This is why advanced PMUs provide the option of storing correction curves or lookup tables (LUT) to preprocess input variables mathematically in order to minimize transformer influence [35]. Alternatively, measurement systems can be calibrated for particular operating ranges. Practical experience with this has been presented in [40].

PMUs make use of the global positioning system (GPS) for time synchronization. Minimal influences on senders and receivers are chiefly dominated by relativistic effects. Deviations from the rated frequency, on the other hand, may indicate that the phasors measured are highly inaccurate in part. When the frequency is assumed to be a constant variable (especially in a distribution grid constrained by space), relative effects fail to materialize, though.

Inaccuracy can largely be minimized here when current transmission and processing standards for digital data are used. Quantization also has comparatively little influence. Since advanced systems have resolutions higher than 12 bit, quantization errors are insignificant when other larger independent variables are factored in.

2.3. Increased measurement accuracy requirements for state estimation in distribution grids

The preceding observations demonstrated that the transformer systems used primarily affects the quality of the phasors measured. By contrast, the errors caused by further signal processing and transmission are insignificantly minor. It is therefore essential to define increased requirements of measurement transformer systems in the distribution grid in conjunction with the identified characteristics of phasor values in a distribution grid. Only then can synchronism be used optimally as key advantage of a Distribution Area Monitoring System with PMUs. The potential and current transformer systems used in distribution grids therefore have to have a high accuracy class of 0.1. Only then can measurement accuracies lower than 0.2% of the amplitude and 0.1° of the angle be guaranteed [41].

Since exact measurement of phase angles is essential for conventional active and reactive power measurements, too, industrially available measurement transformer systems already have the capacity to provide the accuracy required by [32] and [33]. What is more, saving a measurement transformers' characteristic load curve when digital data is processed additionally improves quality.

Measurement unit accuracies are entered together with transformer properties as weighting factors in the calculation when the WLS algorithm is used for state estimation in distribution grids (see section 3.3). What time inaccuracy has only enabled stochastic parameters to specify when quantities are measured conventionally (asynchronously) directly affects the accuracy of the state vector obtained when values come from synchrophasors. The mathematical relationships among measured quantities, measurement errors and state variables of the WLS algorithm are identified in the following section in order to underscore this correlation.

3. State estimation in distribution grids

3.1. Weighted least squares algorithm

Methods of state estimation based on the weighted least squares (WLS) algorithm calculate the state vector $\boldsymbol{x}$ from an overdetermined set of imperfect measurements $\boldsymbol{z}$. The state vector in (1) is defined as the minimum set of variables that describe a system's state in terms of its complex bus voltages.

$$\boldsymbol{x} = [\boldsymbol{e}_{\mathrm{K}} \quad \boldsymbol{f}_{\mathrm{K}}]^{\mathrm{T}} = [e_1 \quad \cdots \quad e_{n\mathrm{K}} \quad f_1 \quad \cdots \quad f_{n\mathrm{K}}]^{\mathrm{T}}, \tag{1}$$

where e_1 is the real and f_1 the imaginary part of the complex voltage of bus 1. Since for conventional state estimation bus 1 usually serves as a reference with a voltage angle of zero, f_1 is assumed to be known and is therefore removed from the state vector.

Equation (2) defines the mathematical relationship between $\boldsymbol{x}$ and z by introducing the measurement function $\boldsymbol{h}(\boldsymbol{x})$.

$$z = \boldsymbol{h}(\boldsymbol{x}) + \boldsymbol{\varepsilon}. \tag{2}$$

The target function in (3) is formulated as follows in order to minimize the (unknown) inaccuracies in ε to obtain an optimal assessment.

$$\min\left((z - \boldsymbol{h}(\boldsymbol{x}))^{\mathrm{T}} \cdot \boldsymbol{R}^{-1} \cdot (z - \boldsymbol{h}(\boldsymbol{x}))\right), \tag{3}$$

where $\boldsymbol{R}$ is the measurements' weighting matrix composed of the standard deviations.

The synchronism of phasor measurements guarantees better error management, (known) measurement tolerances superseding standard deviations as the indicator of measurement quality. Combining these two approaches nevertheless presents major challenges described in section 3.3.

The Jacobian matrix of measurements $\boldsymbol{H}$, which contains the partial derivatives of the measurement matrix $\boldsymbol{h}$ based on the state variables in $\boldsymbol{x}$, is introduced in the next step. Linearization by means of a Taylor series makes it possible to solve the minimization problem iteratively with (4).

$$\boldsymbol{H}^{\mathrm{T}}\left(\boldsymbol{x}^{(k)}\right) \cdot \boldsymbol{R}^{-1} \cdot \boldsymbol{H}\left(\boldsymbol{x}^{(k)}\right) \cdot \left(\boldsymbol{x}^{(k+1)} - \boldsymbol{x}^{(k)}\right) = \boldsymbol{H}^{\mathrm{T}}\left(\boldsymbol{x}^{(k)}\right) \cdot \boldsymbol{R}^{-1} \cdot \left(z - h\left(\boldsymbol{x}^{(k)}\right)\right), \tag{4}$$

where k indicates the iteration step. A convergence criteria that terminates the iteration has to be defined.

3.2. Conventional, linear and hybrid data processing

Conventional state estimation algorithms utilize asynchronous measurements, whereas a linear state estimation (LSE) algorithm can be employed when only PMU measurements are used. The direct relationship between measurements and state variables creates a system of linear equations, thus simplifying and expediting calculation. The use of both asynchronous and phasor measurements is referred to as hybrid state estimation (HSE). Drawing on (2), Table 2 juxtaposes the mathematical relations underlying each method of state estimation.

Table 2. Conventional, linear and hybrid state estimation approach

Conventional state estimation	**Linear state estimation**	**One-step hybrid state estimation**
$z_{\mathrm{conv.}} = \boldsymbol{h}_{\mathrm{conv.}}(\boldsymbol{x}) + \boldsymbol{\varepsilon}_{\mathrm{conv.}}, \quad (5)$	$z_{\mathrm{PMU}} = \boldsymbol{H}_{\mathrm{PMU}}\boldsymbol{x} + \boldsymbol{\varepsilon}_{\mathrm{PMU}}, \quad (6)$	$\begin{bmatrix} z_{\mathrm{conv.}} \\ z_{\mathrm{PMU}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{h}_{\mathrm{conv.}}(\boldsymbol{x}) \\ \boldsymbol{H}_{\mathrm{PMU}}\boldsymbol{x} \end{bmatrix} + \begin{bmatrix} \boldsymbol{\varepsilon}_{\mathrm{conv.}} \\ \boldsymbol{\varepsilon}_{\mathrm{PMU}} \end{bmatrix}. \quad (7)$

Since the measurement equations in the distribution grid are only slightly overdetermined anyway, this paper focuses on one-step HSE. Two-step HSE first process every conventional measurement. Afterward, the resulting state vector is subjected to linear post-processing together with the measured phasor data [42].

3.3. Consistent measurement weighting

Every measurement in the WLS algorithm must be assigned a weighting factor quantifying its significance in the calculation of the state vector. Missing the absence of synchronism in measurements can be managed by analyzing past measurements $z_i - h_i(\boldsymbol{x})$ and their normal distribution parameters. The weighting elements are calculated as the reciprocal of the squared standard deviation σ_i based on (3) and (4). σ_i specifies the standard deviation of the i-th measurement from the measurement vector so that around 63% of all past measurements are within the tolerance of σ_i.

Unlike this statistical approach, error analysis can quantify phasors concretely (see section 2.2). Without restricting their generality, a uniform distribution of inaccurate phasors within the tolerances initially has to be assumed. These authors nevertheless propose treating the quantified inaccuracies just like standard deviation parameters for linear and hybrid state estimation. Although the accuracy of the phasor measurements is underestimated by a factor of 1.5 then, this makes it possible to factor in other unknown influences, e.g. dynamic effects.

Generally, every PMU must meet the requirements of the standard IEEE C37.118-1 [43]. Advanced PMUs are far more accurate and can display each fault tolerance for magnitude and angle separately [35]. Table 3 presents typical accuracy parameters for conventional and synchronized measurements for use in state estimation in distribution grids.

Table 3. Measurement accuracy for weighting [10, 35, 38, 43–45]

Conv. measurements	**Min. standard deviation σ_{min}**	**Max. standard deviation σ_{max}**
Voltage	0.008 p.u.	0.02 p.u.
Power	0.008 p.u.	0.02 p.u.
Phasor measurements	**Min. absolute error Δ_{min}**	**Max. absolute error Δ_{max}**
Magnitude	0.0002 p.u.	0.002 p.u.
Angle	0.01°	0.1°

Since inaccuracy is described based on magnitude and angle (see Table 3) and the system's state is characterized based on real and imaginary parts, the weighting factors have to be converted. Error propagation theory delivers the mathematical relationships in (8) and (9).

$$\sigma_{\Re} = |\cos\phi_{\mathrm{meas}}| \cdot \sigma_X + |X_{\mathrm{meas}} \sin\phi_{\mathrm{meas}}| \cdot \sigma_\phi\,, \tag{8}$$

$$\sigma_{\Im} = |\sin\phi_{\mathrm{meas}}| \cdot \sigma_X + |X_{\mathrm{meas}} \cos\phi_{\mathrm{meas}}| \cdot \sigma_\phi\,, \tag{9}$$

where X and ϕ are magnitude and phase angles of a general phasor measurement (voltage or current), σ_X and σ_ϕ the standard deviations for polar coordinates, and $\sigma_{\Re}$ and $\sigma_{\Im}$ the standard deviations for the real and imaginary parts.

4. Case study

4.1. Methodology

Fig. 1 presents the methodology used to analyze the measurement unit infrastructures, accuracies and algorithms of different methods of state estimation.

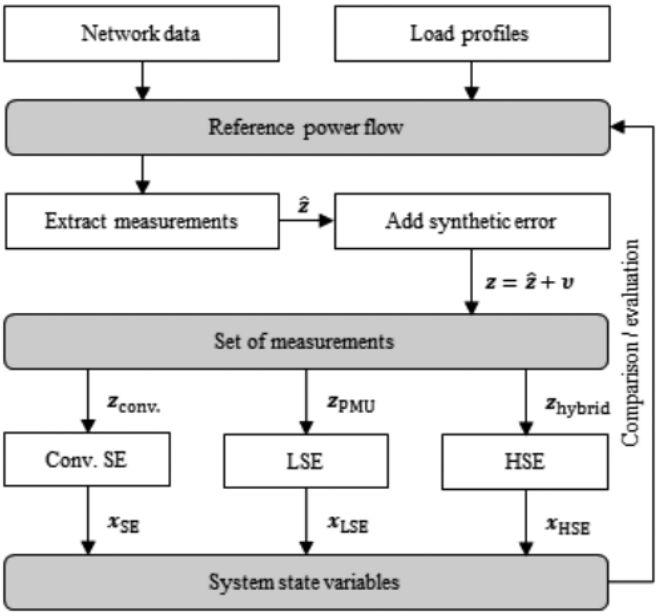

Fig. 1. Case study methodology

A reference power flow used to ascertain the correct reference values for the complex-valued bus voltages, the outgoing active and reactive power at the stations and the current prevalent in the lines initially serve as the basis for analyses. It is recalculated every second in every data set or every time step. Load time series recorded in a real German 110 kV distribution grid structure serve as the basis.

In the next step, a virtual measured data set is extracted from the power flow variables. Depending on the type, a synthetic error is applied to the correct value within the scenario's precision limits. The measured quantity z_i is formed by adding the correct value with correspondingly distributed random numbers in the tolerance range. The three methods analyzed (conventional, linear and hybrid state estimation) make use of the measured data set compiled in keeping with the underlying types of measurement they take.

The modeled system states and their derived variables (including conduction current) are subsequently compared with the reference value. The large base of data from time series analysis and very high variations of load and generation in the grid region analyzed over the period of analysis ensure the representativeness of results over a large power flow range. The mean absolute deviation of the values calculated as a function of every bus or line based on (10) and (11) is used as an indicator to assess the quality of each of the modeled state variables.

$$\Delta u_{\text{avg}} = \frac{1}{n_{\text{K}}} \sum_{i=1}^{n_{\text{K}}} |u_i - \hat{u}_i| , \tag{10}$$

$$\Delta I_{\text{avg}} = \frac{1}{n_{\text{L}}} \sum_{l=1}^{n_L} \left| I_l - \hat{I}_l \right| , \tag{11}$$

where n_{K} is the number of busses and n_{L} represents the number of lines. The circonflex accent indicates the reference values from the load flow calculation.

The distribution of these variables as a function of the time series can be approximated subsequently with the parameters of a normal distribution (expected value μ and variance σ) and the accuracy can be quantified as a result.

4.2. Description of the grid and scenario

The model is based on an original German 110 kV distribution grid with eighteen buses (see Fig. 2) with an altogether low level of meshing and cable lengths of less than 50 km.

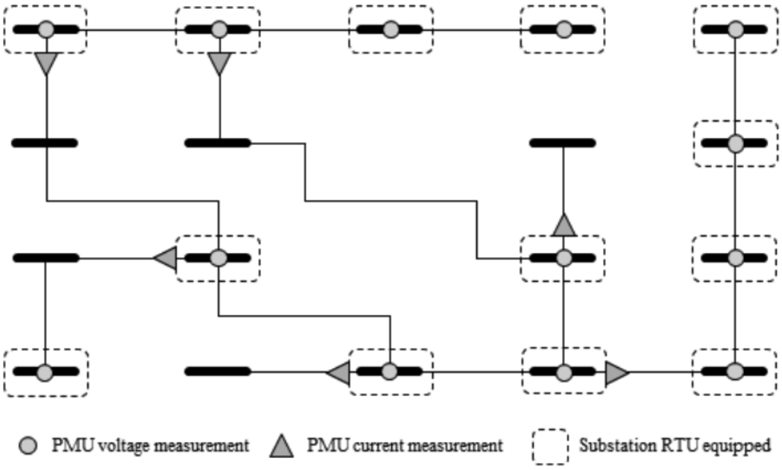

Fig. 2. German 110 kV distribution grid with scenario 2 measurement configuration

Real measurements taken over a period of nine hours deliver realistic load and generation performance. Higher power switching operations during this period additionally provide a very broad power flow range. The load at the buses varies between approximately 40 MW of power discharged and 20 MW of power injected. The corresponding values of cos ϕ are between +0.9 and −0.9.

The underlying measurement configurations in Table 4 vary in the three scenarios. Scenario 1 describes a measurement system with a minimum of equipment like the one actually in the test grid at this time. In scenario 2, a redundant conventional measurement system is compared with a PMU monitoring system with a minimum of equipment. Building upon this, scenario 3 analyzes the effects of both conventional and PMU rollouts over a wide area [46]. The measurement configurations are derived from real use cases and factor in the impossibility of equipping every substation because the technical requirements are lacking. The respective placement algorithms are based on linear optimization following [47].

Table 4. Scenario and sub-scenario description

Scenario		**Conv. measurement configuration**	**PMU configuration**
1	Minimal power system monitoring	Minimum (no redundancy)	Minimum (no redundancy)
2	Full SCADA vs. minimal PMU	More than one redundancy	Minimum (no redundancy)
3	Rollout	More than one redundancy	One redundancy
Sub-scenario		**Conv. measurement accuracy**	**PMU accuracy**
A	Reference	Low	Low
B	High-precision SCADA	High	Low
C	High-precision PMU	High	High

The measurement configuration in scenario 2 is presented in Fig. 3 as an example. A station conventionally equipped with RTUs measures voltage at buses and active or reactive power at every outgoing unit. Each PMU measurement (current and voltage) is represented explicitly.

In addition to the scenarios presented, the accuracies of measurement units vary in sub-scenarios in order to draw a conclusion about the increased requirements on measurement units for real characteristics of distribution grids (see Table 4). High or lower accuracies correspond to the minimum and maximum errors in measurement in Table 3.

4.3. Results and evaluation

The state variables calculated from the different methods of state estimation establish the conditions needed to calculate all other grid parameters. The buses' voltage amplitudes and current in the lines are particularly interesting for system management. In keeping with the methodology proposed in section 4.1, Fig. 3 and Fig. 4 present the calculated parameters of the normal distribution for each of the different modeling methods.

The accuracies of the voltage amplitudes in every scenario in Fig. 3 achieved with synchronous measurements (LSE and HSE) are noticeably higher than those taken with purely conventional measurement configurations. The expected values of the average errors can be reduced substantially to an extent by applying PMUs alone, even when the accuracy of conventional measurement units (sub-scenario B) is assumed to be higher. This effect intensifies when both types of measurements are drawn on to model the grid state. Yet the expected values as well as the variances are significantly smaller when methods of state estimation are based on phasors. This makes it possible to achieve errors below 0.1% of the voltage amplitudes.

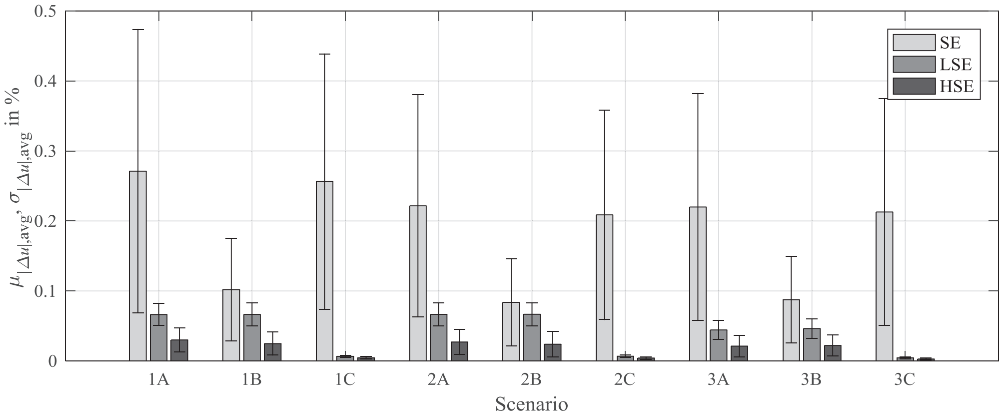

Fig. 3. Normal distribution parameter of mean absolute voltage magnitude error

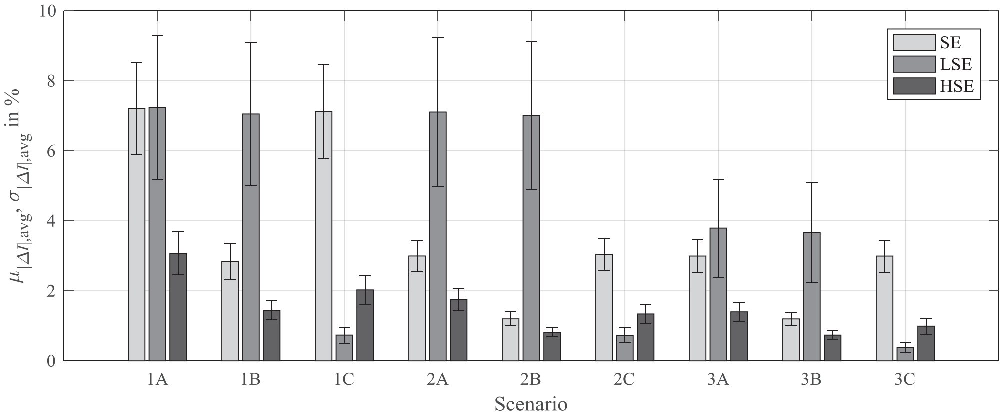

Fig. 4. Normal distribution parameter of mean absolute line current error

The characteristics of the accuracy of the calculated current loads in Fig. 4 are slightly different. When reference accuracies (sub-scenario A and B) are employed, the conventional state estimation displays better accuracy than the linear method because of the direct relationship of the measured quantities to the system variables. Measurement errors are thus incorporated directly in the calculated state vector. Given the characteristics of distribution grids explained in section 2.1, this relationship is primarily manifested in conduction current and to a lesser degree in bus voltage. This effect is correspondingly positive when PMU accuracy increases in sub-scenario C. Even advantages over combined processing (HSE) ensue since conventional measurements distort calculated state variables because they have a higher fault tolerance. Although the phasor measurements can be counteracted by assigning higher weighting factors, the influence of PMU measurement errors would increase

5. Conclusion

Simulations based on real measurements demonstrated that PMU significantly improve state estimation in the 110 kV distribution grid. Both PMUs added to existing conventional measurement systems and PMUs alone in linear state estimation reduced errors significantly. Requirements have to be increased, though, in order to calculate voltage amplitudes and current loads reliably. The technical requirements of the measurement units themselves are already met in conformance with IEEE Standard C37.118. The transformer systems used primarily affect the accuracy of the measurements taken adversely. Industrially available PMUs, however, can use stored characteristic curves to correct nonlinearities in the equipment itself. Alternatively, certain operating points can be linearized.

PMUs thus constitute a serious alternative to conventional measurement systems in an electrical distribution grid. The lower levels of the grid, which are usually monitored minimally, particularly require increased and more precise monitoring because volatile supply increases the dynamic. The faster rate at which PMUs can provide measured data sets additionally facilitates taking detailed measurements of dynamic effects and analyzing causal chains in the complete system network in-depth. Grid operators are only able to utilize and coordinate static and dynamic ancillary services of the connected distributed systems optimally when every level of the grid is monitored more thoroughly. Further studies will therefore concentrate on the implementation of the described algorithms in software tools for distribution system operation.

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