Assessment of Errors in the Measurement Chain of Distribution Grids for Feasibility Study of a PMU Application

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***Abstract*—This paper presents the results of tests done to review and discuss required levels of accuracy in the entire instrumentation and measurement chain of PMU-applications for distribution grids. Specific grid monitoring and estimation applications could have different requirements in terms of accuracy and resolution of the PMU estimates. Apart from the PMU's own accuracy, the overall accuracy of PMU estimates are dependent on accuracy level of the entire instrumentation channel and the grid's physical parameters. The results and discussions presented in this paper are in the context of a PMU-based line parameter estimation and Dynamic Line Rating (DLR) algorithm for medium voltage lines. These tests could be used to check feasibility of the DLR application on existing instrumentation infrastructure as well as to select the instrumentation equipment for futuristic applications in grids. The same methodology could be utilized to investigate the feasibility of other PMU-based applications for distribution grids.**

***Index Terms*—Distribution Grid Monitoring, Line Parameter Estimation, PMU, Power System Instrumentation**

I. Introduction and Background

Modern distribution grids are changing rapidly with increasing deployment of distributed energy resources, bi-directional power flows and inclusion of new customer devices like electric vehicles. To better observe such grids, there is a growing interest in better monitoring tools for the distribution grids. Phasor Measurement Unit (PMU)-based comprehensive realtime monitoring could enable grid operators to better observe, understand and react to power system events in the grid [1].

Some of the potential PMU applications in the distribution grid are [1]:

- Event detection and classification.
- Aggregated load models and line impedance estimation.
- Distribution grid state estimation.

In recent times, distribution grid operators have installed commercial PMUs in their network to investigate and gain insight on possible PMU applications for their grids. One such example is mentioned in [2]. From the measurement and instrumentation point of view, these applications require varying range of accuracy of the PMU estimates. For several reasons, these accuracy requirements are more challenging for a distribution grid when compared to a transmission grid. A typical distribution grid is smaller in terms of power flows and shorter in line-lengths. This means the voltage magnitude and phase differences between different measurement points are lower. Over-all measured voltage and current signals to noise ratio is also lower.

Due to such small signal to noise ratio and small magnitude and angle differences for voltage and current signals at different points, the PMU-based application would require very high accuracy and resolution to accurately measure and resolve measurements from two different locations in the grid. Apart from errors associated with PMU's measurement and estimation process, the accuracy of the PMU estimates are dependent on the accuracy of the instrument (current and voltage) transformers (CTs and VTs) of the grid [3]. On the other hand, the accuracy of the measurements would also depend on the type and length of the line (example: overhead or cable, type of conductors).

For any application based on high quality measurements, it is quite important to assess the accuracy of the measured data and check if they comply with the required accuracy. Similarly for any grid operator, it is important to investigate the required accuracy of the entire measurement chain for any PMU based application. Prior investigations could help them to:

- Select and work on possible applications depending upon the existing measurement infrastructure.
- Design the whole measurement chain and select appropriate equipment based on the application's requirement.
- If required, select appropriate data pre-processing and curing techniques to make the data suitable for the application.

This paper presents the results of a study done to gain

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insights on the accuracy requirements of the entire measurement and instrumentation chain for a PMU-based application. The PMU application studied for this purpose was: Dynamic Line Rating of a line segment using accurate line parameter estimates [4].

The remainder of this paper is arranged as follows. Section II presents the idea and accuracy requirements of the application. Section III investigates the effect of various types of inaccuracies present in the instrumentation channel on the performance of the application. In the end, conclusions are drawn in section IV.

II. Dynamic Line Rating (DLR) based on line parameter estimates

DLR establishes dynamic loading levels of power lines based on accurate measurements and estimation of necessary parameters. Authors in [5] shows that effective application of DLR could enable extra connection of wind resourvecs up to 20%-50% on an existing line infrastructure of a particular 132kV line segment. Looking into the future with rapidly increasing distributed renewable generation, DLR may be able to solve or at least alleviate te problem of generation or load curtailment due to line overloading [6].

The presented method estimates the real-time temperature of the conductor (overhead line and underground cable) based on real-time estimates of its resistance [4]. The resistance of a conductor is directly proportional to the temperature of the conductor. Correct real-time resistance estimates could be used to estimate the conductor temperature by fitting the resistance-temperature curve of the conductor. Knowing the correct line temperature, distribution operators can set higher yet safer loading levels for the lines. This application could be particularly suited for existing cable/overhead line infrastructure with increasing power transfer demand. PMU-based line parameter estimation is discussed in details in [7].

To investigate the accuracy requirement of the entire instrumentation chain, the deciding factor is the accuracy of the application's final output. For the case of DLR, this is the required accuracy of the line temperature estimates. This temperature range could then be translated into the accuracy range for resistance estimates. These estimates depend on PMU estimates which in turn are dependent on the performance of instrument transformers and the grid's physical parameters.

Neglecting the skin effect, the resistance and resistivity of a conductor is given by:

$$R_1 = R_0(1 + \alpha(T_1 - T_0)) \tag{1}$$

where α is the temperature coefficient ($^\circ C^{-1}$) of the resistance for a given material, T_0 is 20°, R_0 is the DC resistance of the conductor at T_0 and R_1 is the new resistance at temperature T_1.Using (1), and assuming the pure linear relationship between copper resistance and temperature in the range 20 °C - 80 °C, it can be found that the rate of change of resistance per unit change in the temperature is 0.394% of the actual resistance. Table I presents the required accuracy of resistance estimates corresponding to desired accuracy in temperature estimate. So, to determine the line temperature with an accuracy of ± 5 °C, the errors in resistance estimates should be less than 2% of the line resistance.

TABLE I
Accuracy requirements of resistance estimates based on the required accuracy of temperature estimates.

Temperature Estimation Accuracy	Resistance Estimates Error
± 3 °C	< 1.2 (%)
± 5 °C	< 2.0 (%)
± 10 °C	< 4.0 (%)

The accuracy of estimates of resistance depends upon the accuracy of the measurement system. In particular, as shown in [7], real and imaginary components of voltage and current differences between two points ($re(\triangle V)$, $im(\triangle V)$, $re(\triangle I)$ *and* $im(\triangle I)$) are critical measurements. The importance of these measurements could also depend on the application and operating conditions. For instance, the accuracy of resistance estimates is affected more by the voltage phase and magnitude errors in VTs when compared to similar errors in CTs. Hence, accurate measurement of $re(\triangle V)$, $im(\triangle V)$ is more critical than $re(\triangle I)$, $im(\triangle I)$. Fig. 1 illustrates this with an example.

The following section tests the feasibility of obtaining better accuracy line resistance estimates in various test conditions.

III. Simulation Results

A cable and an overhead medium-voltage (24 kV l-l) line were simulated. The base power (S_b) and base voltage (V_b) for our simulated system was set to be 10 MVA and 24 kV, the base current (I_b) was 240.56 A. Voltage and current measurement at receiving and sending ends were obtained. The time-domain signals are then converted into phasor estimates by a PMU algorithm. Accuracy of the line parameter estimates

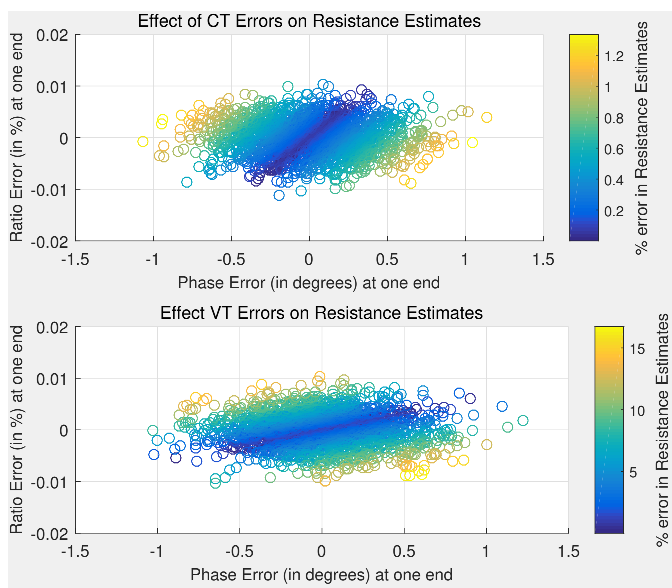

Fig. 1. Comparison of the effect of CT and VT errors on Resistance Estimates.

were calculated for different line lengths. The effect of various random and systematic (bias) errors associated with different accuracy classes of CTs and VTs on the accuracy of line parameter estimates and hence on DLR were also studied.

Per kilometer impedance (in ohms) and susceptance (in siemens) of three phase lines simulated were:

- Overhead Line

$$Z_{ABC} : \begin{bmatrix} .1663 + .7374j & .1636 + .1772j & .1634 + .7374j \end{bmatrix}$$
$$B_{ABC} : 10e^{-6} \begin{bmatrix} 2.7660j & 2.7597j & 2.7358j \end{bmatrix}$$

- Underground Cable

$$Z_{ABC} : \begin{bmatrix} .2549 + .1736j & .2547 + .1736j & .2551 + .1735j \end{bmatrix}$$
$$B_{ABC} : 10e^{-4} \begin{bmatrix} 1.1548j & 1.1549j & 1.1547j \end{bmatrix}$$

In a distribution grid, magnitude and phase difference between voltage and current signals could be very small. The errors of overall measurement chain could be higher than the voltage and current differences. The voltage and current difference depend majorly on parameters like, line type, line length and power flow. Similarly, the accuracy of the entire measurement chain is built up of factors like, ratio and phase accuracy of CTs and VTs (CT VT accuracy class), calibration errors in CTs and VTs, noise in the measurement system, and accuracy of PMU estimation process. As opposed to the random measurment noise, the ratio and phase errors of CTs and VTs are considered to be a systematic bias. Depending on their accuracy class or previous calibration tests, the errors are known for the new or calibrated CTs and VTs [9]. On the other hand, calibration errors depict the on-field condition where the errors of CTs and VTs drift from the last calibration. The accuracy of PMU estimates also depend on the time-synchronization of PMUs [3]. An example of accuracy limits for a commercial PMU can be found in [8]. Estimation errors for voltage magnitude rms is 0.02% of the reading and for current magnitude rms is 0.03% of the reading. Phase error is up to 0.01°.

Following part of the paper presents some case studies to investigate the effect of various random and bias errors in the measurement system. To begin, errors in resistance estimates without any kind of measurement errors for 10 km length of lines is presented in Table II. The errors are about nine orders lower than the required 2% limit suitable for DLR application.

In presence of no calibration or random noise error, the per-unit difference in voltage measurements (time domain complex signals) between two ends is shown in Fig. 2. As shown above, the accuracy of current measurement is not as critical as the voltage measurement. Hence, voltage measurements are chosen for the analysis. Circle *deltaV* (*deltaV*=△V) is the per-unit voltage drop between two end points for the mentioned underground cable of length 500 meter at a particular power flow (5 MW, 2.4 MVA). Radius of this circle increases with increase in the magnitude and phase difference between the two ends. The radius of the circle could be considered as the absolute maximum error which the total measurement chain can afford. Three other concentric circles are the per-unit voltage measurement error caused by the instrument transformers based on their accuracy class. All the CTs and VTs at one end are of same accuracy class. Combination of accuracy class of CTs and VTs at both (sending-receiving) ends are mentioned for each circle.

For any operating scenario, if the circle depicting the total error of the measurement chain for voltage or current signals is bigger than the *deltaV* circle, then the minimum observable difference in phase and magnitude of voltage measurements would be limited to a value higher than the actual difference. This means the resolution of the measurement system would be inadequate for the DLR application for that particular operating condition. The radius of this difference should always be greater than the addictive effect of all the errors. It can be observed from Fig. 2 that, in presence of no calibration or random noise error, CTs VTs having same accuracy class at both ends have a very small error circle. The error circle for 0.5-1 class arrangement is bigger than the *deltaV* circle. So it can be inferred that, even without calibration and random errors, this arrangement of CT VT accuracy class is not suitable for the required resolution.

Fig. 3 presents the effect of calibration errors and random measurement noise. The accuracy class of CTs and VTs at both ends were same (0.5 Class). Different calibration error factors up to 25% of the factory calibrated 0.5 Class accuracy were randomly assigned to each of the CTs and VTs. The red circle showing the total error in this case is much bigger than the error circle of 0.5-0.5 class arrangement in Fig. 2. This shows that, it is important to select same accuracy class of instrument transformers at both ends of the line and also maintain the the calibration. The errors caused by difference in accuracy classes and lack of calibration were bigger than the errors caused by less accurate but same accuracy class.

TABLE II
ERRORS IN ESTIMATES WITHOUT ANY MEASUREMENT ERRORS

Line Type	Resistance Estimation Errors (%)		
	A	B	C
Overhead Line	$3.882e^{-9}$	$6.734e^{-9}$	$4.237e^{-9}$
Underground Cable	$1.5934e^{-8}$	$1.3691e^{-8}$	$2.0075e^{-10}$

TABLE III
FACTORS AFFECTING PERFORMANCE OF THE DLR APPLICATION

Factors	Test Conditions		
Power Flow	5 MW, 2.4 MVA		
Max Noise PMU	0.1%		
Max Noise CT VT	1%		
Calibration Error	0%	10%	
Line Length	3 km	10 km	
Line-Type	Underground Cable	Overhead Line	
CT VT Class	0.1	0.5	1

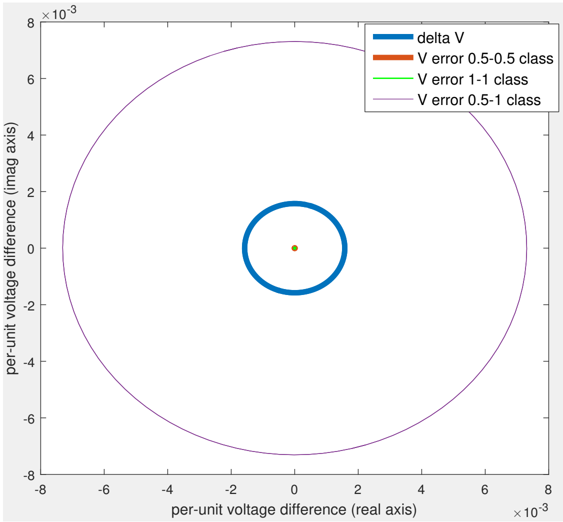

Fig. 2. Comparison of voltage difference (△V in time domain) between two measurement points and errors due to CT VT accuracy class at both ends of an underground cable of length 500 m.

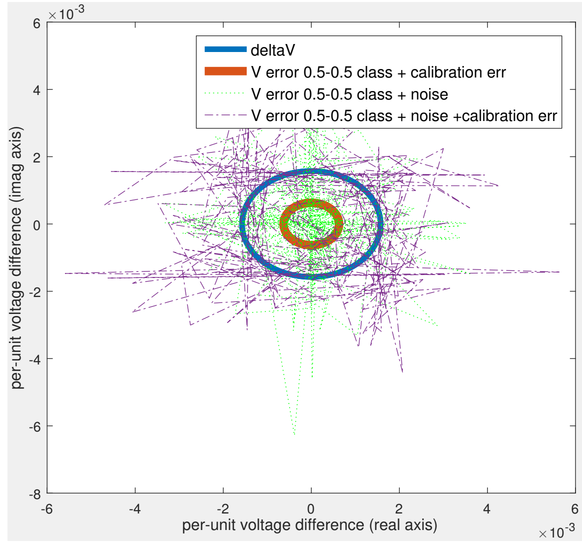

Fig. 3. Comparison of voltage difference (△V in time domain) between two measurement points and errors due to measurement noise and calibration error for 0.5 class CTs and VTs at both ends of an underground cable of length 500 m.

The effect of random measurement noise (up to 1% of the measured quantity) is also shown in Fig. 3. It shows that presence of random noise renders the measurement system unsuitable for accurately differentiating between the voltage measurements at two ends. This make the measurement system unsuitable for the application. Hence is is also critical to pre-process the acquired PMU data to extract accurate estimates of the measured signals.

Same strategy was used to assess the feasibility of the DLR application under different conditions. Various critical factors and there assumed values are mention in Table III. The random measurement noise for CTs and VTs are assumed to have Gaussian distribution with zero mean error (μ) and 0.0033 standard deviation of the errors (σ). For a given set of (μ, σ), the error is limited to $\pm 3\sigma$ from the mean value. So for CTs and VTs, the maximum error percentage was 1% of the measured value. Similarly, the maximum error percentage for PMU estimates was assumed to be 0.1% of the measured phase and magnitude.

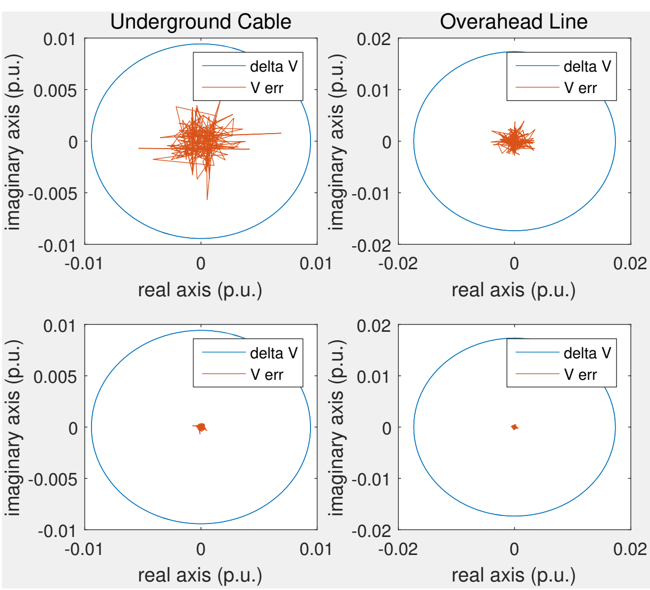

Fig. 4. Analyzing of the effect of measurement noise, CT and VT errors (accuracy class and calibration error) for 3 km long underground cable and overhead line. Bottom row plots show the benefit of data pre-processing to filter out noise and correct the calibration error.

The same analysis for some combinations of factors mentioned in Table III are presented in Fig. 4 which shows the voltage difference and measurement errors in case of the underground cable and the overhead line respectively of length 3 km. Accuracy class 1 CTs and VTs at both line ends were used. Two test cases for top and bottom rows respectively are:

- Calibration error: ±25%, random error: ± 1%
- Calibration error: ±2.5%, random error: ± 0.1%

The figures confirm that effective filtering of random noise and correction of calibration errors using accurate correction coefficients help increasing the resolution of the measurement chain. Accuracy of resistance estimates were checked by running tests using some of the factors as shown in the

TABLE IV
ERRORS IN RESISTANCE ESTIMATES IN PRESENCE OF MEASUREMENT NOISE AND CALIBRATION ERRORS FOR AN UNDERGROUND CABLE

Accuracy Class (End1/End2)	Three Phase Errors					
	Length 3 km			Length 10 km		
	A	B	C	A	B	C
0.1 / 0.1	37.2%	22.2%	25.4%	7.55%	5.97%	4.59%
0.5 / 0.5	111.6%	14.7%	32.9%	11.9%	31.2%	9.75%
1 / 1	250.9%	88.8%	128.2%	22.7%	28.7%	47.3%
0.1 / 1	139.5%	32.6%	88.7%	30.8%	11.1%	1.82%

TABLE V

ERRORS IN RESISTANCE ESTIMATES IN PRESENCE OF MEASUREMENT NOISE AND CALIBRATION ERRORS FOR AN OVERHEAD LINE

Accuracy Class	Three Phase Errors					
	Length 3 km			Length 10 km		
End1/End2	A	B	C	A	B	C
0.1 / 0.1	13.0%	2.1%	27.4%	12.7%	23.5%	13.4%
0.5 / 0.5	11.1%	96.2%	38.7%	8.10%	9.29%	18.4%
1 / 1	250%	455%	855%	7.45%	25.6%	24.1%
0.1 / 1	17.0%	59.3%	51.7%	43.2%	52.9%	47.2%

Table III. For first case, the maximum measurement noise was assumed to be 1% of the measured value and calibration error in CTs and VTs up to 25% from the known ratio and phase errors. The results for the same underground cable and overhead line are presented in Tables IV and V respectively. As expected the resistance estimates were not accurate in the presence of calibration errors and measurement noise.

Second case was tested to see the benefits of PMU data filtering and CT, VT calibration error correction. The maximum noise here was assumed to be 0.1% and calibration error up to 2.5%. The results are presented in Tables VI and VII respectively. From the resistance estimates, it was again confirmed that measurement noise, calibration error and using different class CTs VTs at two ends are the major error sources. Without these errors, the estimates of resistance for the underground cable are suitable for the DLR application. The accuracy class of CTs and VTs did not metter so much especially for the longer 10 km cable. The resistance estimates for overhead line are in general less accurate than the underground cable. Hence for DLR application, accuracy class 0.1 at both ends was the only suitable option for the overhead cable.

TABLE VI

ERRORS IN RESISTANCE ESTIMATES ERRORS AFTER FILTERING DOWN MEASUREMENT NOISE AND USING ACCURATE CT VT CORRECTION FACTOR FOR AN UNDERGROUND CABLE

Accuracy Class	Three Phase Errors					
	Length 3 km			Length 10 km		
(End1/End2)	A	B	C	A	B	C
0.1 / 0.1	0.38%	0.46%	0.58%	0.35%	1.13%	0.58%
0.5 / 0.5	5.83%	2.76%	1.63%	0.71%	0.48%	0.27%
1 / 1	0.28%	4.07%	1.72%	0.37%	1.82%	1.61%
0.1 / 1	20.6%	39.9%	14.4%	10.3%	3.38%	9.61%

TABLE VII

ERRORS IN RESISTANCE ESTIMATES ERRORS AFTER FILTERING DOWN MEASUREMENT NOISE AND USING ACCURATE CT VT CORRECTION FACTOR FOR AN OVERHEAD LINE

Accuracy Class	Three Phase Errors					
	Length 3 km			Length 10 km		
End1/End2	A	B	C	A	B	C
0.1 / 0.1	0.54%	2.87%	0.19%	1.33%	1.35%	2.21%
0.5 / 0.5	7.92%	11.7%	15.0%	7.12%	8.98%	7.44%
1 / 1	46.6%	32.1%	25.6%	16.7%	2.35%	21.2%
0.1 / 1	45.7%	57.1%	81.6%	16.3%	5.03%	5.51%

IV. CONCLUSION

The paper discussed and presented some tests to check performance and feasibility of a PMU based application in a distribution grid. Errors associated with the power system measurement chain were studied along with their impact on the measured data. It was shown that accuracy of critical measurements could influence the final application's output. From the perspective of DLR application it was necessary to determine accurate values for $\triangle$V and $\triangle$I values. It was found out that, measurement noise and calibration errors are the main contributing factors for bad quality measurements of $\triangle$V and $\triangle$I values and hence degrading the required accuracy of resistance estimates. This showed that to apply the DLR application in such medium voltage grid, apart from using instrument transformers from same accuracy class at both ends, filtering of measurement noise and correction of calibration error is important. It was also found at for same lengths, DLR is better feasible for underground cables than for overhead lines. The analysis method shown could be used to investigate the available distribution grid measurement infrastructure for a possible accurate measurement based application. It could help the distribution grid operators to identify the bottlenecks in terms of instrument accuracy and search for possible solutions such as data processing.

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