Synchrophasor Data Qualification Measures for Reliable Fault Location

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Abstract

Synchrophasor-based applications are slowly moving from the research and demonstration stage into mainstream production-grade systems in the power industry. In a production-grade environment, it is very valuable to have data quality metrics that can help manage the performance of the application that uses those data and establish a high confidence level in the end results. We discuss a goodness-of-fit (GoF) data quality metric and introduce an additional variant of it for synchrophasor data. We propose for all PMUs to provide GoF metrics together with their output synchrophasor data to enable performance quantification and improvement for all production-grade synchrophasor applications. As an example, through extensive simulations, we demonstrate how these GoF metrics can be used to qualify and improve the performance of a synchrophasor-based fault location application.

Introduction

Use of time synchronized voltage and current measurements can serve a number of functions in electric power systems. There is growing interest in using synchrophasor systems, providing voltage and current phasors time-tagged to an absolute (common) time, to enable a plurality of real-time and non-real-time applications. In the recent years, there has been a tremendous amount of research, development, and pilot demonstrations of various applications using synchrophasor data. For production grade applications, however, reliable performance is often very critical. IEEE Std. C37.118-2005 [1] and its later versions (e.g., IEEE Std C37.118.1-2011 [2] and IEEE Std C37.118.1a-2014 [3]) specify certain quality flags and performance requirements for PMUs (phasor measurement units); however, these performance requirements may not be sufficient for certain applications. For example, the accuracy of a PMU during transient conditions on a faulted line is not well defined. In fact, describing a waveform which is not a simple periodic sinusoidal waveform is not possible using the basic phasor definition. Accordingly, using synchrophasor measurements during a fault condition may lead to unreliable results as the measurements may not be reasonable representations of the voltage and current waveforms on the line.

One of the applications of interest for synchrophasor systems is fault location. Multi-terminal fault location using synchronized measurements at each end of the line has been shown to be an effective way to calculate the location of the fault [4], [5], helping speed up the *time to re-energization*. When using synchrophasor data for this purpose, however, the accuracy of the fault location is very much dependent on the accuracy of the synchrophasor data provided by the PMUs during the fault. As mentioned above, the synchrophasor data measured by the PMU may not be useful (i.e., the synchrophasor may misrepresent the waveform). In this paper, we elaborate on the use of the "Goodness of Fit" (GoF) metric as introduced in [6] as a quantitative indication of the usefulness of synchrophasor data from a PMU for fault location application. We demonstrate how providing the GoF together with synchrophasor data from a PMU can help improve the reliability and trustworthiness of a synchrophasor-based fault location application.

Goodness of Fit

A PMU estimates a number of parameters to describe a substantially-sinusoidal function described by the following equation:

$$x(t) = A\cos(\omega t + \varphi) \tag{1}$$

where A is the amplitude, ω is the angular frequency and φ is the phase. A PMU could also calculate various measurement quality indicators before discarding the waveform data that were used for calculating a phasor. One possible quantitative synchrophasor quality metric is the GoF as defined in [6], expressed in decibels as follows:

$$\mathrm{GoF} = 20\log\frac{A}{\sqrt{\frac{1}{(N-m)}\sum_{k=1}^{N}(u_k - v_k)^2}} \tag{2}$$

where N is the number of samples, m is the number of parameters being estimated in the equation (one more than the number of degrees of freedom), A is the signal amplitude, u_k is the signal sample value and v_k is the estimated sample value. The parameter ($N - m$) is the residual degrees of freedom [7], and m is 3 in this case (the number of parameters being estimated in equation (1)).

The GoF metric effectively evaluates the mismatch between the actual voltage or current waveform and the corresponding waveform reconstructed from their respective phasor measurements obtained from PMUs. More details on use of GoF to describe synchrophasor measurements are given in [6] including a number of examples showing impact of noise, phase offset, and distorted waveforms during real faults on a transmission line.

Extensions to GoF

Trying to use synchrophasor data in practical real-world applications, we have observed that the GoF can be low for various reasons including:

- Noise in the measured signal, especially at low currents (low signal-to-noise ratio)
- Distorted waveforms, particularly during the first or last cycle of faults
- DC offsets (decaying DC) during the early cycles of faults with long time constants
- Distortions due to CT saturation
- Distorted waveforms during high-impedance faults

We observe that the usefulness of synchrophasor data with lower GoF is different depending on the reason for GoF being low, and in particular, if the DC offset is the only reason for GoF being low, the synchrophasor data may still be quite useful (serve the function of interest). This is perhaps intrinsically obvious as the synchrophasor calculation algorithms (such as Fourier Transforms) are very effective at filtering out the DC component and identifying the magnitude and phase of the power frequency component of the signal even in the presence of significant DC. Nonetheless, the generic GoF metric given by equation (2) does not discriminate between the cases where GoF is low due to presence of a DC offset, as opposed to other possible sources stated above.

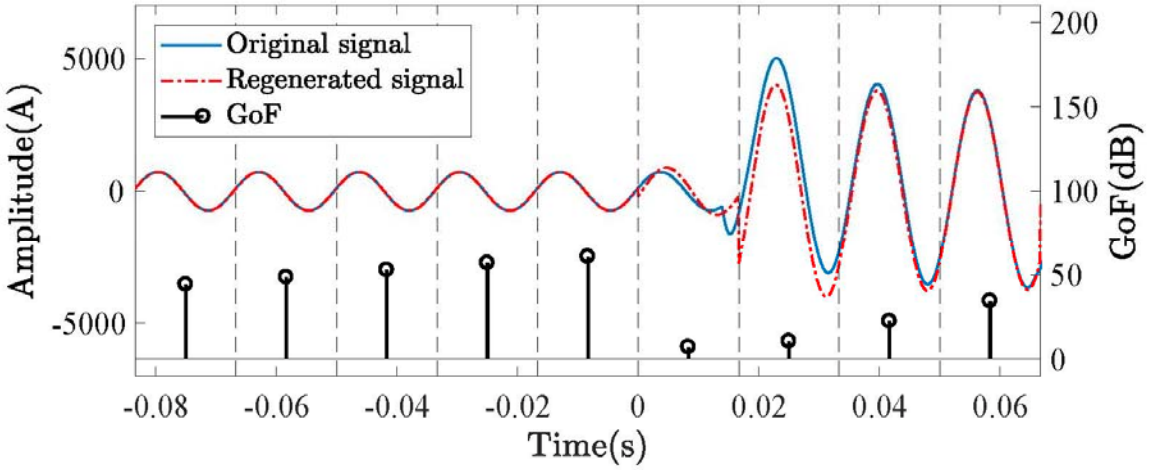
In a separate article [8], focusing on fault location, we provide more mathematical details on the use of synchrophasors for fault location calculation. We also introduce a variant of $\underline{\mathrm{GoF}}$, $\overline{\mathrm{GoF}}$, that may be particularly useful for voltage and current signals during faults with decaying DC components:

$$\overline{\mathrm{GoF}} = 20\log\frac{A}{\sqrt{\frac{1}{(N-m)}\sum_{k=1}^{N}(u_k - U_{DC} - v_k)^2}} \tag{3}$$

where U_{DC} is the DC value (average value over the measurement interval) of the signal being sampled.

To help illustrate the concept, Figure 1.a shows the actual current waveform and that regenerated from PMU synchrophasor measurements (one-cycle, P-class synchrophasors) together with the corresponding value of the GoF for a simulated fault initiated at time 13.3 ms (80% of the cycle from the beginning of a sampling window). Figure 1.b. shows the same with the difference that the reconstructed signal includes the DC offsets measured in each sampling window (GoF in Figure 1.b is effectively $\overline{\mathrm{GoF}}$.) As evident, in the first sampling window containing a full cycle of fault data after the fault initiation (between time 16.7 ms and 33.3 ms), the DC offset addition improves the fit and improves the GoF. Figure 1 also demonstrates, that when the reason for the low GoF is not DC offset, reconstructing the waveform from

synchrophasor information may be very difficult as shown in the sampling window 0 to 16.7 ms, and both GoF and $\overline{\mathrm{GoF}}$ will be similarly low.



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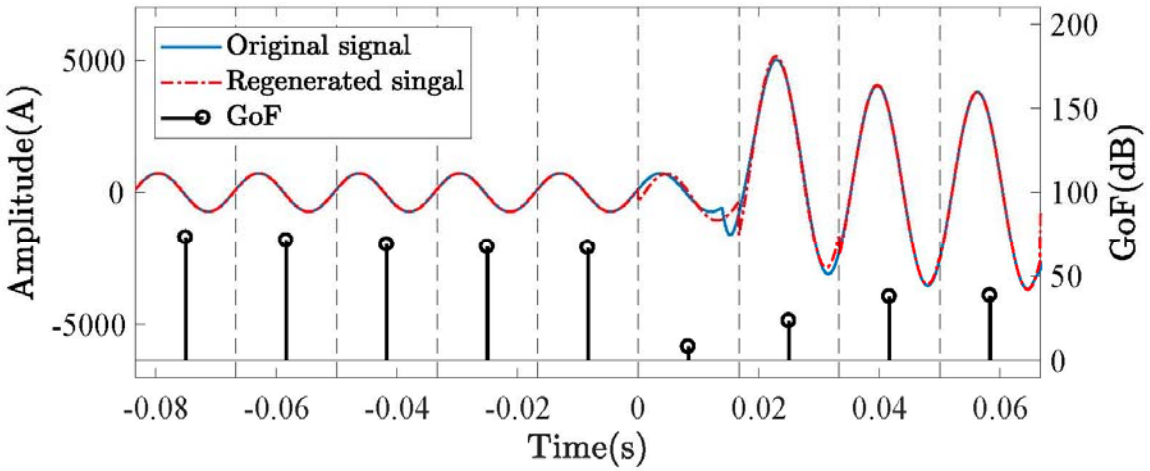


(b)

Figure 1. Actual current waveform and that regenerated from PMU phasor measurements (a) without and (b) with DC-offset modification. The corresponding GoF values are also shown. P-class measurements per 60 Hz cycle are used. Fault initiates at time 13.3 ms (80% of the cycle from the beginning of the sampling window).

Using GoF Metric to Improve Trustworthiness of PMU-Based Fault Location Results

We propose a PMU that not only provides the synchrophasor measurements, but it also provides GoF and $\overline{\mathrm{GoF}}$ for each measurement. Each synchrophasor measurement is transmitted together with the corresponding GoF metrics so that the end user of the synchrophasor data, depending on the application, can choose to use the synchrophasor or not (or may be able to apply an uncertainty margin to the end results). This may be considered a "smarter" PMU. Of course, the additional data requires additional communications bandwidth (translating to additional cost). To minimize the communications bandwidth requirement, one may configure a system that will not send GoF unless it is below certain level (say 30 dB), i.e., send GoF by exception only. Synchrophasor data with GoF above 30 dB (or some other value, to be determined for a particular system or environment) may be considered reliable enough for most

applications; those with lower GoF should probably be sent together with the GoF value so that the application can judge for itself whether to use the data or not.

In [8], we provide a summary of a large number of simulations with various fault types, fault impedances, locations, etc., and we use the GoF and $\overline{\mathrm{GoF}}$ to qualify the results. We also point out that if $\overline{\mathrm{GoF}}$ is lower than 25 dB, the chance of larger error in fault location (larger than 1% of the transmission line length) is significantly higher. Based on those case studies, we proposed a synchrophasor-based fault location application that only uses synchrophasors with the associated $\overline{\mathrm{GoF}}$ or GoF values higher than 25 dB, resulting in 99% of the fault location results (about 530 cases) being within 0.7% (% of line length) from the actual location of the fault and the remaining 1% of the faults all being within 1.2% of the actual location of the fault.

Here, we show more specific results for various simulated situations. In the following discussions, we define the "fault location error" as the ratio of the distance difference between the actual location of the fault (known for the simulation) and the calculated location of the fault (from the synchrophasor data) divided by the total length of the line (220 km in all cases shown here). The fault location error is usually provided in percent (= 100 x the ratio described above). For example, if the fault was at 10 km from a terminal, but the fault location algorithm (using synchrophasors) determines that the fault was at 12.2 km from that terminal, we say that the "fault location error" is 1% (=100% x [12.2 – 10.0] / 220).

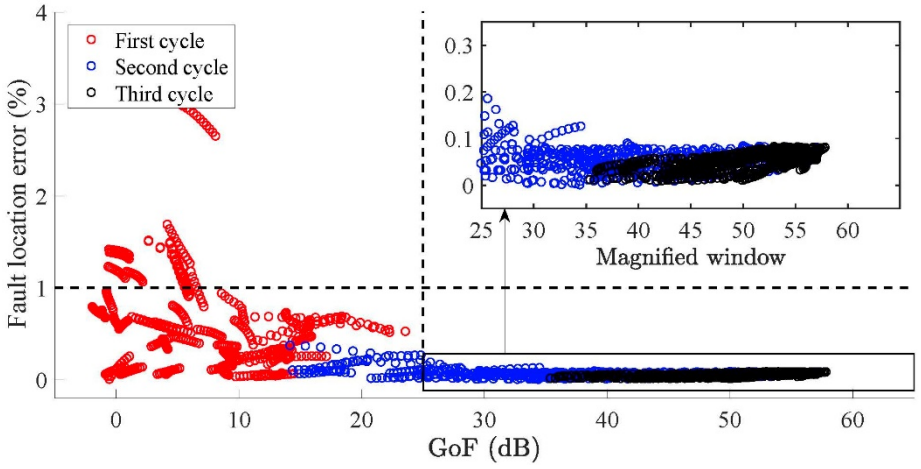
Figure 2 shows the results of simulations showing single phase to ground faults at various locations along the length of the transmission line. Simulation cases include fault locations at 10, 60, 110, 160, and 210 km from one end of a 220 km transmission line, with fault resistances of 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, 27.5, 30 Ω at 11 initiation times distributed at 30º angle from each other along the first cycle. P-class PMU data at 60 measurements per second (one synchrophasor measurement per cycle) are used for fault location calculations. Each fault is assumed to take 3 cycles to clear. Accordingly, Figure 2 covers 605 fault cases and 3 fault location attempts per case (using first cycle, second cycle, or third cycle synchrophasors); a total of 1815 cases.

One can observe in Figure 2 that the larger fault location errors are associated with the measurements taken from the first time window (red dots) during which the fault is initiated. These measurements also typically show lower GoF as compared to the measurements taken from the second or third time windows after the fault. This observation is somewhat expected, as the first time window includes the transition from the normal condition to the fault waveform, not a substantially sinusoidal waveform in this time window (e.g., see the blue waveform in Figure 1 between time 0 and 16.67 ms). One can also see that the GoF does not improve signficantly for them (red dots) as the DC offset is considered (Figure 2.b), most likely because DC offset is not the main reason for poor GoF, rather distorted (transitioned) waveform is. For the time window after the fault initiation (blue dots in Figure 2), removing DC offset substantially improves GoF (compare Figure 2.a with 2.b), since the main contribution to lower GoF is the DC offset (during the fault). The third cycle has mostly higher GoF and removing DC offset (Figure 2.b) doesn't push the black cloud of dots to a much higher GoF because they already have fairly high GoF (most of the DC offset is already decayed by the third cycle). The fourth time window results are not shown here and they are very similar to the first time window as they include the distorted waveforms as we transition from fault waveform to regular or no signal (interrupted fault current) during this time (we had fault duration of 3 cycles in all cases).

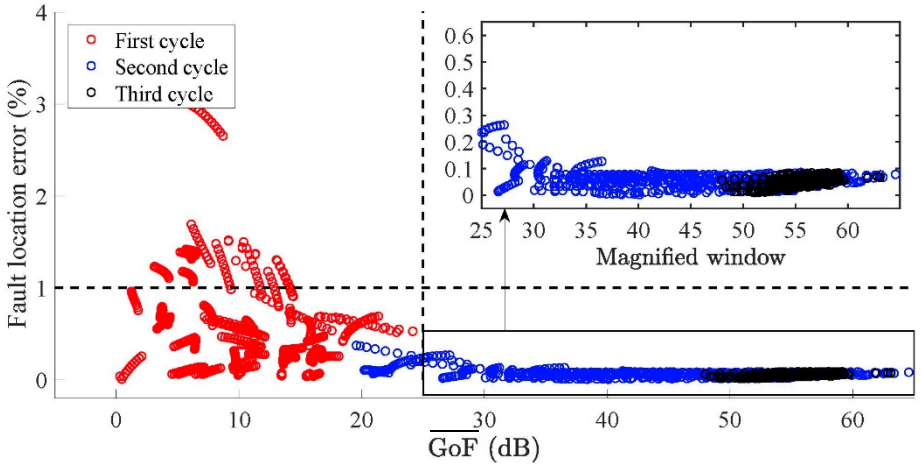
One approach to achieve fault location results with higher level of confidence is to use synchrophasor data with higher GoF or $\overline{\mathrm{GoF}}$ values only. If the GoF values were readily provided by the PMUs, together with the associated synchrophasor data, an application program that performs fault location using synchrophasor data could also estimate a confidence level associated with the calculated location.

Figure 3 shows a histogram of the number of cases versus GoF ranges for cases shown in Figure 2. A visual comparison of Figures 3.a and 3.b shows that using $\overline{\mathrm{GoF}}$ one can identify more cases (synchrophasor data during fault) that have higher goodness-of-fit and are suitable for fault location with a high level of accuracy and a high level of confidence. For example, Figure 2 shows that using synchrophasor data with GoF or $\overline{\mathrm{GoF}}$ larger than 35 dB will result in fault location accuracy better than 0.15% (within 330 m {about 1000 ft} along a 220 km (about 140 mile) transmission line), and Figure 3 shows that using $\overline{\mathrm{GoF}}$ (as opposed to the basic GoF) in a software application yields a larger number of

cases where goodness-of-fit values greater than 35 dB is available. Moreover, one can choose GoF or $\overline{\text{GoF}}$ larger than 40 dB to obtain even more accurate (<0.1% error) fault location with a very high level of confidence.



(a)



(b)

Figure 2. Fault location error as a function of (a) GoF and (b) $\overline{\text{GoF}}$ (Goodness-of-Fit after removing DC component) for 605 simulated cases of single phase to ground faults at various locations along the length of the transmission line. Colors red, blue, and black indicate results calculated from the synchrophasors obtained during the first, the second, and the third time window containing fault current waveforms, respectively (total of 1815 dots). The GoF or $\overline{\text{GoF}}$ value used for the plot is the lower of the GoF or $\overline{\text{GoF}}$ values of the current synchrophasors obtained from the two PMUs at the two ends of the line.

In these simulated cases, faults all last 3 cycles, and therefore the first (and the fourth) time windows typically have the transition/distorted waveforms (and hence low GoF and $\overline{\text{GoF}}$ synchrophasor estimations). One may suggest to simply drop the first and the fourth time windows' synchrophasor data to increase the accuracy and reliability of the fault location application. While this may seem plausible here, in a real power system, the fault duration is not always fixed or known and the fault waveform's nature is not always predictable. Accordingly, identifying which synchrophasor measurement is from a "good" waveform (high $\overline{\text{GoF}}$) is not as obvious unless indicated by the PMU itself. Also, even amongst the measurements in the second (and third) time windows, measurements with higher GoF or $\overline{\text{GoF}}$ typically give more accurate fault location with a higher confidence. That is especially important for repair crews going to the fault site under adverse weather conditions, such as a stormy winter night.

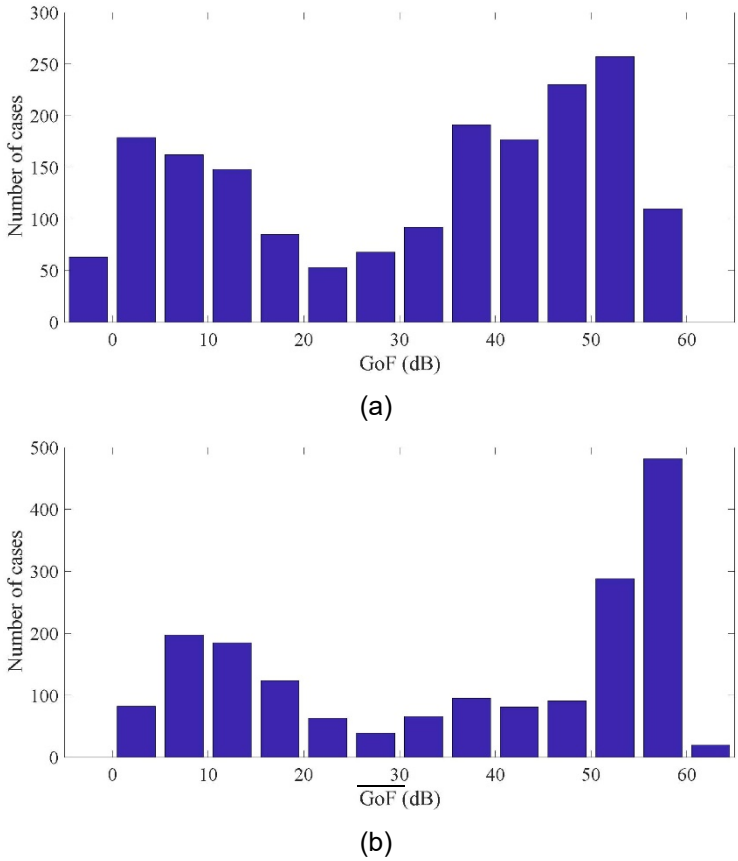


Figure 3. A histogram showing the distribution of the cases versus (a) GoF and (b) $\overline{\mathrm{GoF}}$ for the 1815 synchrophasor data shown in Figure 2.

Figures 4 and 5 show the results for simulations of phase-to-phase (A to B) and three-phase faults at various locations along the length of the same 220 km transmission line, respectively. Similar to the simulations shown in Figure 2, in each figure, 605 fault cases, with fault location calculation using synchrophasor data from the first, the second, and the third time window is shown for each fault case (1815 fault location estimations in each figure).

In short, similar to those in Figure 2, the data in Figures 4 and 5 support the conclusion that synchrophasors with higher goodness-of-fit generally yield more accurate fault locations with a higher level of confidence.

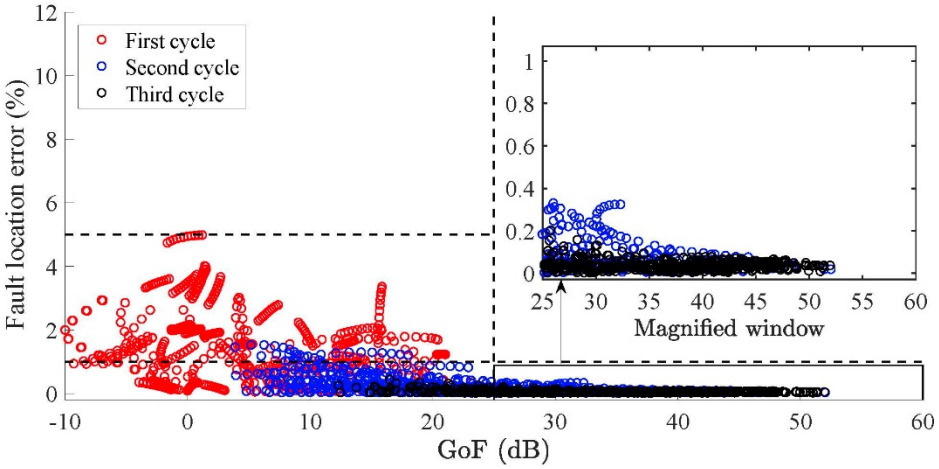
Summary and Conclusion

Synchrophasor systems and applications are maturing and evolving in the electric power industry. As they transition from early-stage trial applications into hardened production-grade applications, they need measurable and quantifiable performance and quality metrics. The goodness-of-fit metric introduced in [6] and its variant introduced in this paper ($\overline{\mathrm{GoF}}$) are two potential metrics for synchrophasor data that can help synchrophasor applications provide performance and confidence indications for their end results. In this paper, we demonstrated the use of the goodness-of-fit metrics to qualify a synchrophasor-based fault location application's results. The technique proposed can be used for a practical fault location application at a power utility, for example, with specific GoF thresholds and limits set based on the accuracy and confidence level desired for the fault location results for that specific power system.

The same approach can be extended to a number of other synchrophasor applications. For example, GoF can be used to qualify the synchrophasor data that may be used in an enhanced state estimation (or a linear state estimation) application to weed out the occasional low accuracy synchrophasor data (e.g.,

when an undetected high-impedance fault is resulting in distorted waveforms and inaccurate synchrophasor measurements).

In most power utilities, having synchrophasor measurements is still somewhat of a bonus. We are generally content to just have the synchrophasor data (and the associated application software), and we do not seem to worry much about the accuracy (beyond the basic 1% TVE defined in the standards for specific operating conditions). It is not too early to look into a future where lots of synchrophasor data may be available and to wonder how we can identify which synchrophasor data can serve the application better. Ultimately, we would like to find a way to improve the performance of the applications based on the measurable quality of the input data.



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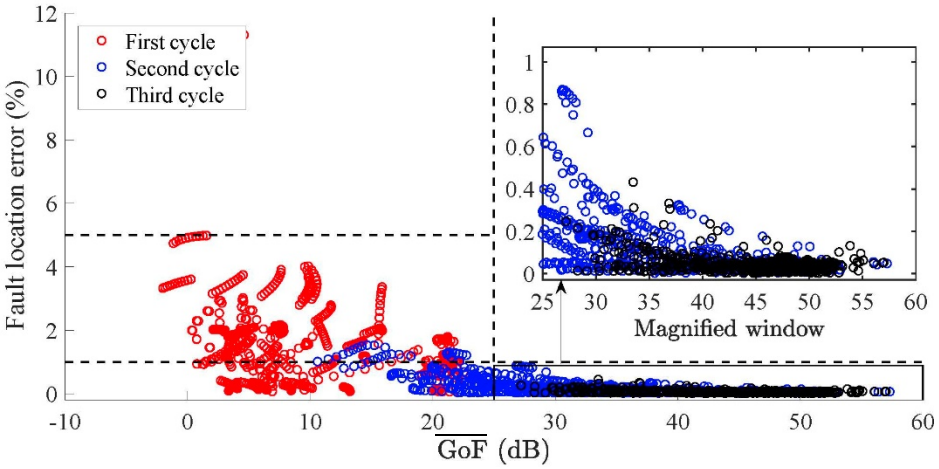
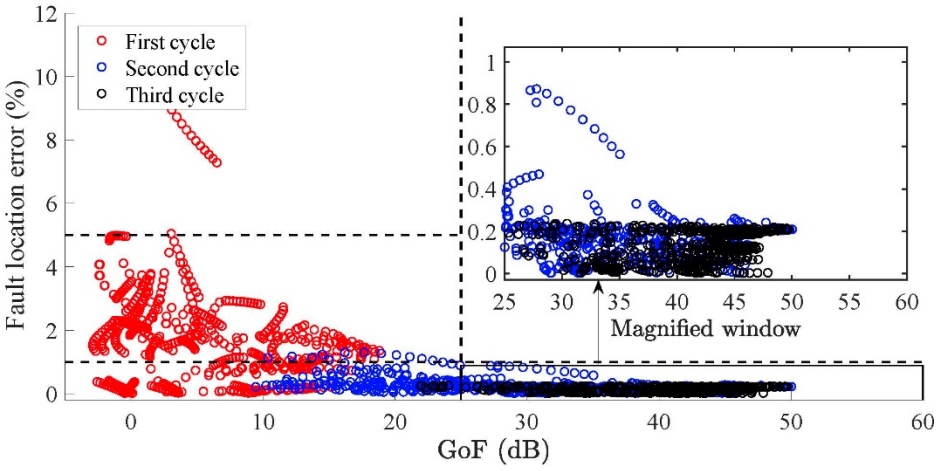


(b)

Figure 4. Fault location error as a function of (a) GoF and (b) $\overline{\text{GoF}}$ for 605 simulated cases of phase-to-phase faults (A to B) at 10, 60, 110, 160, and 210 km from one end of a 220 km transmission line, with fault resistances of 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, 27.5, 30 Ω at 11 fault initiation times distributed at 30° angle from each other along the first time window. Colors red, blue, and black indicate results calculated from the synchrophasors obtained during the first, the second, and the third time window containing fault current waveforms, respectively (total of 1815 dots).



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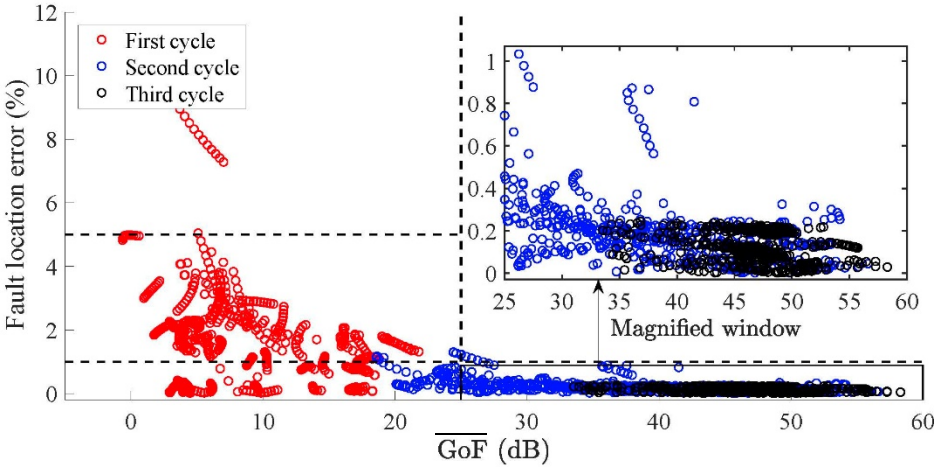

(b)

Figure 5. Fault location error as a function of (a) GoF and (b) $\overline{\text{GoF}}$ for 605 simulated cases of three-phase faults at 10, 60, 110, 160, and 210 km from one end of a 220 km transmission line, with fault resistances of 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, 27.5, 30 Ω at 11 fault initiation times distributed at 30º angle from each other along the first time window. Colors red, blue, and black indicate results calculated from the synchrophasors obtained during the first, the second, and the third time window containing fault current waveforms, respectively (total of 1815 dots).

References

[1] "IEEE standard for synchrophasors for power systems" *IEEE Std C37.118-2005*.

[2] "IEEE standard for synchrophasor measurements for power systems," *IEEE Std C37.118.1-2011 (Revision of IEEE Std C37.118-2005)*.

[3] "IEEE standard for synchrophasor measurements for power systems – amendment 1: Modification of selected performance requirements," *IEEE Std C37.118.1a-2014 (Amendment to IEEE Std C37.118.1-2011)*.

[4] A. S. Dobakhshari, "Noniterative parameter-free fault location on un-transposed single-circuit transmission lines," *IEEE Transactions on Power Delivery*, vol. 32, no. 3, pp. 1636–1644, June 2017.

[5] M. Kezunovic, "Smart fault location for smart grids," *IEEE Transactions on Smart Grid*, vol. 2, no. 1, pp. 11–22, March 2011.

[6] A. Riepnieks and H. Kirkham, "An introduction to goodness of fit for PMU parameter estimation," *IEEE Transactions on Power Delivery*, vol. PP, no. 99, pp. 1–1, 2016.

[7] D. Cuthbert, F.S. Wood, *Fitting Equations to Data*, New York: John Wiley & Sons, Inc., 1971.

[8] M. Rahmatian, Y. C. Chen, W. G. Dunford, and F. Rahmatian, "Incorporating Goodness-of-fit Metrics to Improve Synchrophasor-based Fault Location," submitted to *IEEE Transactions on Power Delivery.*