SAND2022-7779C

Accurate Characterization of Voltage Sags and Swells

Identification of Point-on-Wave Inception and Recovery Instants

Alvaro Furlani Bastos, PhD

Energy Storage Technologies and Systems Dept., Sandia National Laboratories

Panel Session *Power Quality Assessment for Networks With High Penetration of Renewable Energy Sources*

17th International Conference on Probabilistic Methods Applied to Power Systems (PMAPS 2022)

June 15th 2022, Manchester, UK [Online]

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SAND XXXX-XXXX P

Agenda

Takeaway: characterizing voltage sags only through magnitude and duration is incomplete and possibly insufficient for evaluation of equipment sensitivity.

Contribution: simple, yet accurate and robust, algorithm for estimation of the point-on-wave of sag or swell inception and recovery instants.

Motivation

What are point-on-wave of sag inception and recovery instants and why they matter

The Basics of Voltage Sags

- Voltage sags are one of the most common power quality disturbances observed in distribution systems.
- Definition:
  - A temporary reduction of the rms* ac voltage at a point in the electrical system below a threshold† (usually 90% of the nominal voltage at the power frequency).
- Causes:
  - Short-circuit faults and the subsequent operations of overcurrent protective devices;
  - Sudden load changes, such as starting of industrial loads that require high starting currents;
  - Intermittent loose connections in power wiring.
- Impacts:
  - Uneventful as the blinking of light or resetting of microwave oven clocks;
  - Catastrophic as a complete disruption of industrial processes with major economic impacts.

*The term *rms* stands for *root-mean-square*.
†A decrease in the rms voltage to above this threshold is not regarded as a voltage sag since most equipment can ride through a shallow sag .

The Link Between DERs and Voltage Sags

- DERs can provide voltage regulation functionalities.
  - Power-electronics-based DERs can be designed to compensate for grid voltage variations and unbalance.
  - Particularly beneficial at the end of long feeders to manage grid voltage profiles.

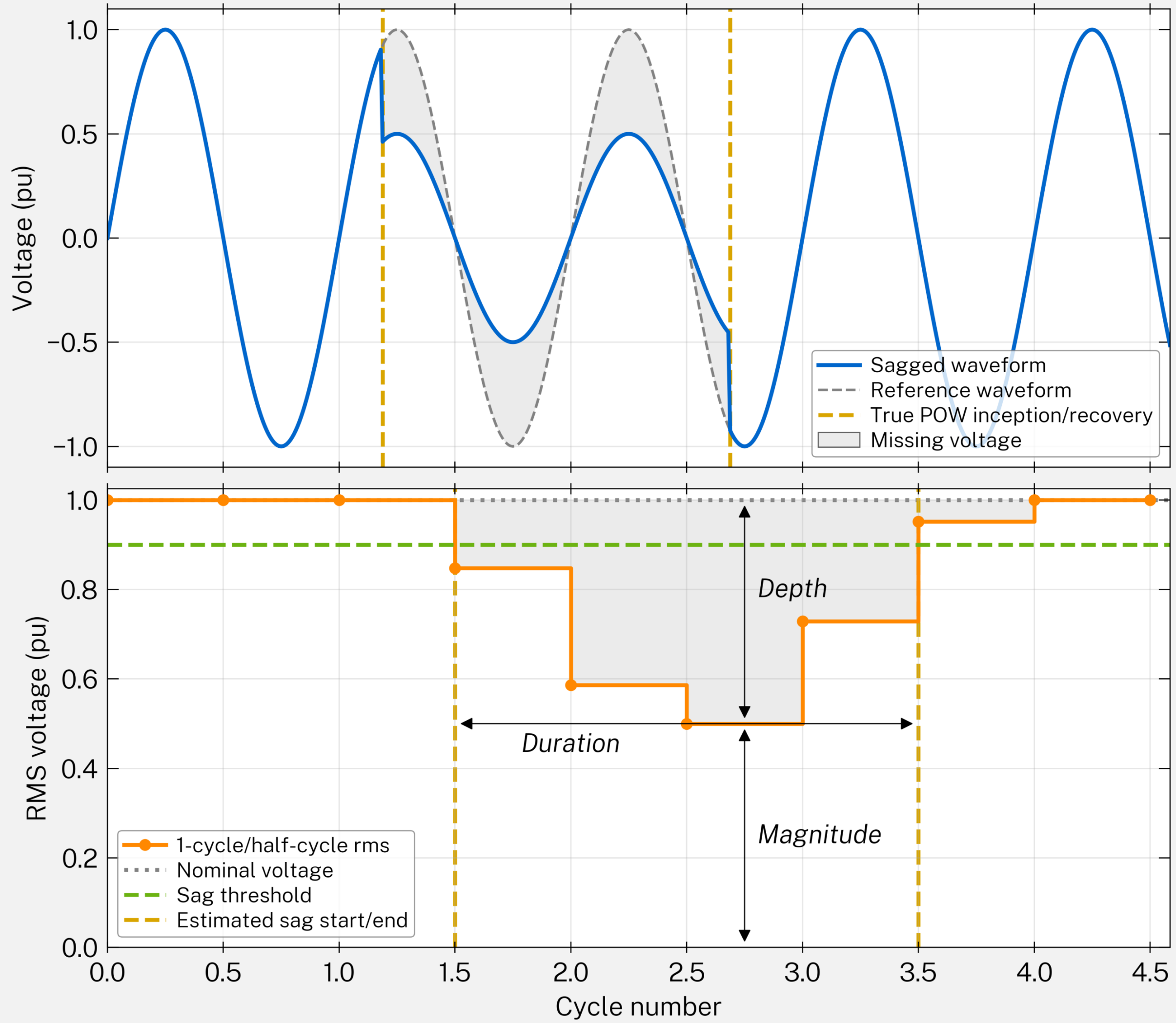
- DERs tripping and restart can cause voltage sags and swells in distribution systems with high DER penetration levels.
  - For a solar PV plant that has tripped off-line due to an undervoltage (IEEE Std. 1547):
    - ✓ At the tripping instant, the local grid voltage may be reduced even further due to a loss of generation (equivalent to an additional stage of the voltage sag);
    - ✓ Upon reconnection, the grid may experience a local voltage swell;
    - ✓ Cold load pickup issues increase if a PV plant is not automatically reconnected after tripping.

The term *DER* refers to *distributed energy resources*.

Characteristics of Voltage Sags (I)

Note: sliding-window rms voltage values used for voltage sags identification/characterization are measured over ***one cycle*** of the sampled voltage waveform and refreshed each ***half cycle*** ($V_{rms(1/2)}$).

- *Magnitude* (or *retained voltage*): the lowest rms voltage value during a sag.
  - *Depth*: the maximum reduction in the rms voltage with respect to a reference value.
- *Duration*: the amount of time that the rms voltage is below the sag threshold.
- Characterizing a voltage sag through its magnitude and duration alone is simple but rather incomplete.
  - Equipment sensitivity may depend on other sag characteristics.



The term *1-cycle/half-cycle rms* refers to rms values measured over *one cycle* of the sampled voltage waveform and refreshed each *half cycle*.

Characteristics of Voltage Sags (II)

- Other voltage sag characteristics of interest:
  - *Point-on-wave (POW) of inception and recovery*: voltage waveform's phase angle at the sag inception and recovery instants.
  - *Phase angle shift*: phase angle difference between the reference and sagged voltage waveforms.
  - *Missing voltage*: instantaneous difference between the reference and sagged voltage waveforms.
  - *Maximum unbalance ratio**: ratio of the maximum difference between the three rms voltages (*A*, *B*, *C*) to the average of these same three rms voltages.

**Maximum unbalance ratio* applies only to three-phase systems.

Importance of POW of Sag Inception/Recovery Instants

- POW of sag inception and recovery affect equipment sensitivity to voltage sags.
  - For some industrial equipment, POW of sag inception/recovery may have a greater influence than the sag magnitude and/or duration.

- Examples of devices that are sensitive to the POW of sag inception/recovery:
  - Electromagnetic relays and contactors*
  - Switch-mode power supplies (SMPS):
    - ✓ POW at inception determines the energy available in the dc-link capacitor for sag ride-through
    - ✓ POW at recovery determines the inrush current at the end of the event
  - Induction machines (such as DFIG-based wind turbines):
    - ✓ Current and torque peaks during asymmetrical faults depend on the POW at inception

- Transient currents during fault-related sags are affected by the POW at inception.
  - Large transient currents may disrupt sensitive equipment.

*IEEE Std. 1668-2017 (Section 4.3) examines how POW at inception affects the minimum voltage required to keep contactors operational.

Background

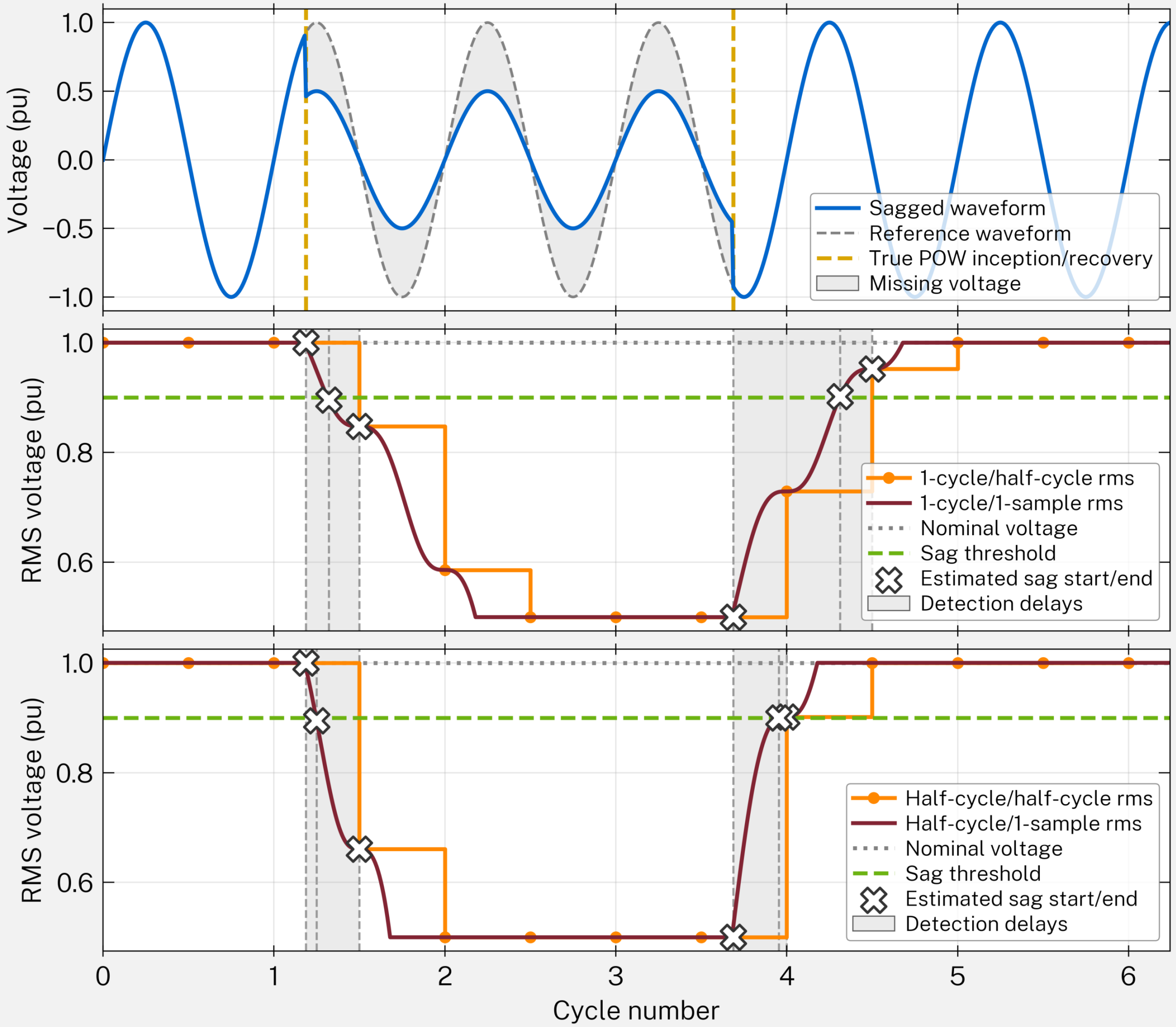
How identification of point-on-wave of sag inception and recovery instants is currently done

The Standard Method

Simulated sag:
- Start: cycle 1.1875
- Magnitude: 0.5 pu
- Duration: 2.5 cycles
- 128 samples/cycle

- IEEE and IEC standards definition:
  - Sag inception/recovery are based on the rms voltage profile crossing a threshold;
  - Low accuracy.
- Alternatives:
  - Reduce the length of sliding windows from 1 cycle to half-cycle;
  - Increase update rate from half-cycle to 1 sample.

Window length	Update rate	Inception latency (samples)	Recovery latency (samples)	Duration (cycles)	Duration error (%)
1 cycle	Half cycle	40	104	3.000	+20.0
1 cycle	1 sample	17	80	2.992	+19.7
Half cycle	Half cycle	40	40	2.500	+0.0
Half cycle	1 sample	8	34	2.703	+8.1



Comparison of Methods

- Review of seven methods for estimating POW of sag inception/recovery instants:
  - None of them yield high accuracy for all types of sags;
  - The discrete wavelet transform (DWT) method provides the best estimation performance for most of the cases.

Method	Voltage input data	Accuracy	Magnitude
Threshold rms voltage	1-phase, rms	Low	Yes
Peak detector	1-phase, instantaneous	Low to high*	Yes
Missing voltage	1-phase, instantaneous	Low to high*	No
Waveform envelope	1-phase, instantaneous	Low to medium*	No
Discrete wavelet transform	1-phase, instantaneous	Low to high*	No
Numerical matrix	1-phase, instantaneous	Low to medium*	No
dq transformation	3-phase, instantaneous	Low to medium*	No

*Higher detection accuracy is obtained for some specific scenarios.

For a more detailed comparison, see: A. F. Bastos, S. Santoso and G. Todeschini, *"Comparison of Methods for Determining Inception and Recovery Points of Voltage Variation Events,"* IEEE Power & Energy Society General Meeting (PESGM), 2018, doi: 10.1109/PESGM.2018.8585977.

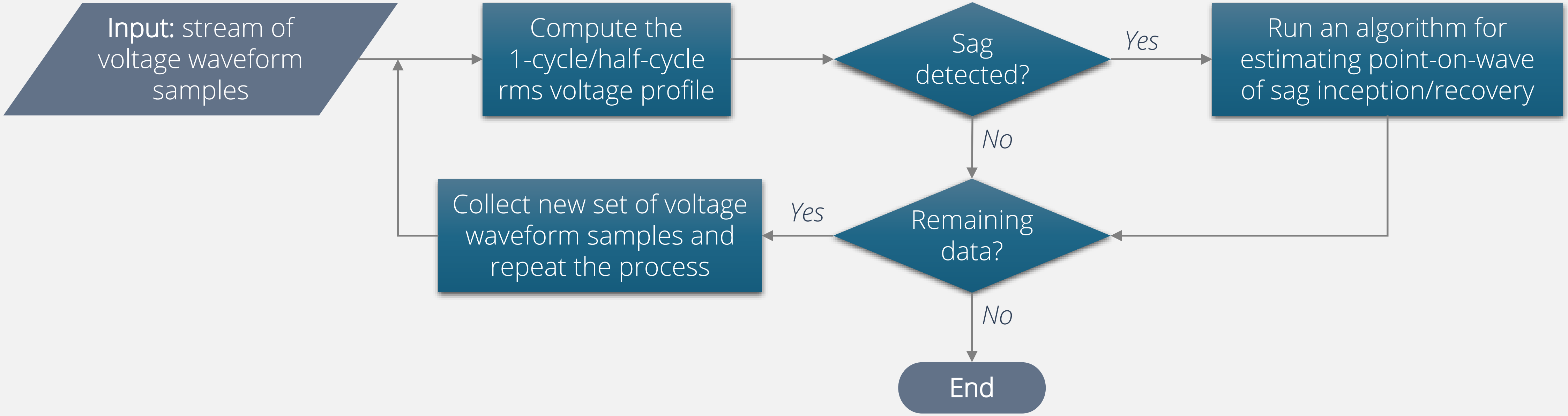
Proposed Method

How identification of point-on-wave of sag inception/recovery instants can be greatly improved

A. F. Bastos, K. Lao, G. Todeschini and S. Santoso, *"Accurate Identification of Point-on-Wave Inception and Recovery Instants of Voltage Sags and Swells,"* in IEEE Transactions on Power Delivery, vol. 34, no. 2, pp. 551-560, April 2019, doi: 10.1109/TPWRD.2018.2876682.

Algorithm Overview (I)

- The standard method is used for *detecting* voltage sags.
  - The first instant (k_{inc}) at which the rms voltage profile is below the sag-threshold is the initial approximation for the POW of sag inception.
- Use the proposed method for *estimating* the true POW of sag inception.



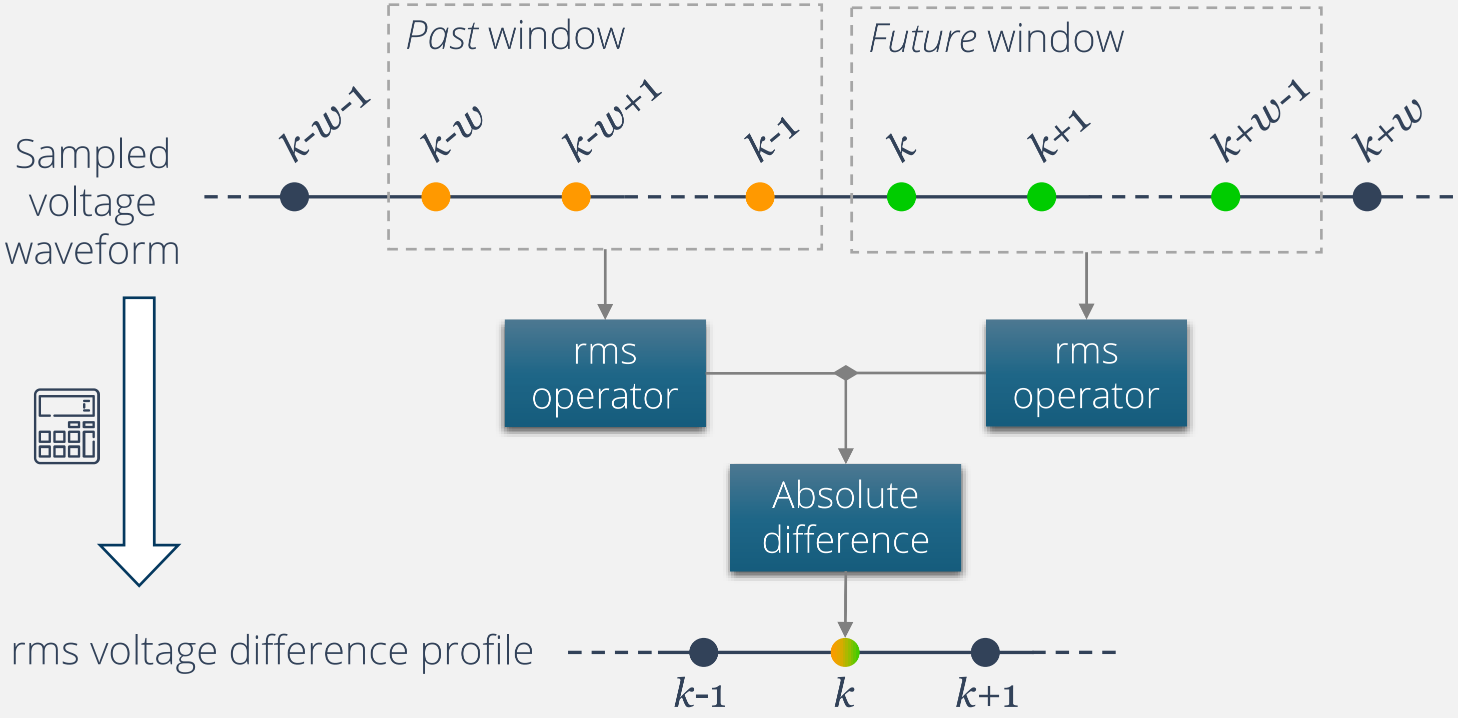
Note: although this discussion focuses on the sag inception instant, the same approach is also used for the sag recovery instant.

Algorithm Overview (II)

- Estimation of the true point-on-wave of sag inception is based on the absolute difference between the *past* and *future* rms voltage values.

- For a given voltage sag:
  - For k from $k_{inc} - 1.5N^*$ to k_{inc}:
    1. Apply the rms operator to the *past* and *future* windows of k;
    2. Obtain the absolute difference between them.

- The estimated point-on-wave of sag inception is the instant of the local maximum in the *rms voltage difference profile*.



Note: although this discussion focuses on the sag inception instant, the same approach is also used for the sag recovery instant.
*The symbol N represents the sampling rate (samples/cycle) of the voltage waveform.

Illustration of the Proposed Method (I)

Simulated sag:
- Start: cycle 2.25
- Magnitude: 0.5 pu
- Duration: 2.5 cycles

- *Full pre-sag inception instant* ($\boldsymbol{k_1}$): both *past* and *future* windows contain exclusively pre-sag voltage samples; the rms voltage difference is 0.
- *Partial pre-sag inception instant* ($\boldsymbol{k_2}$): the *past* window contains exclusively pre-sag voltage samples, whereas the *future* window contains a mixture of pre- and during-sag voltage samples; the rms voltage difference increases compared to $\boldsymbol{k_1}$.

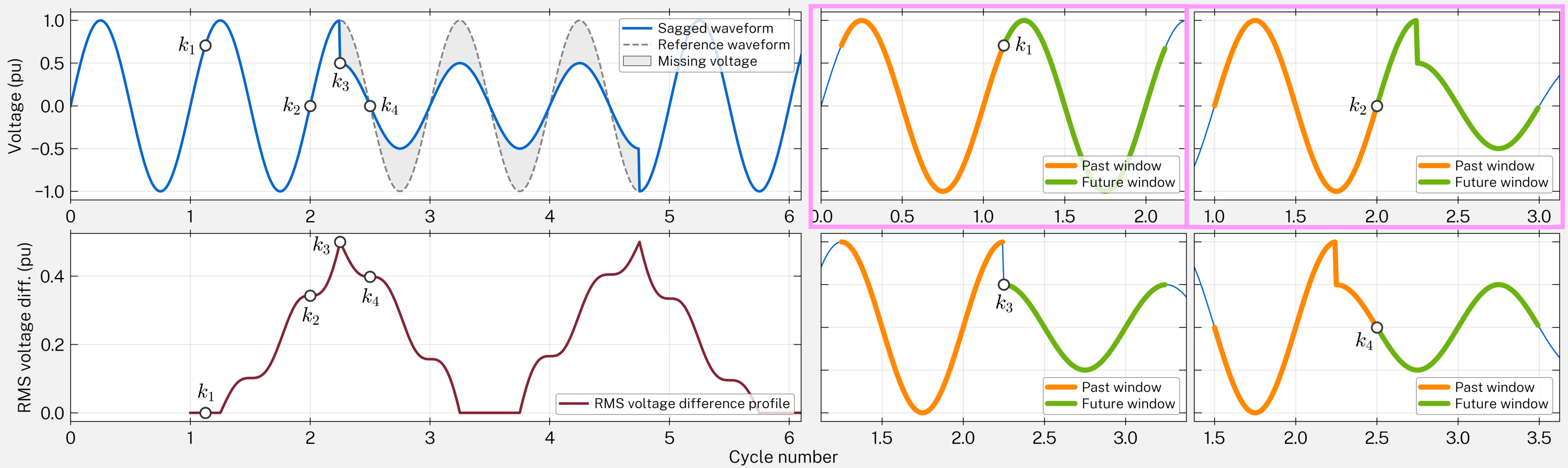
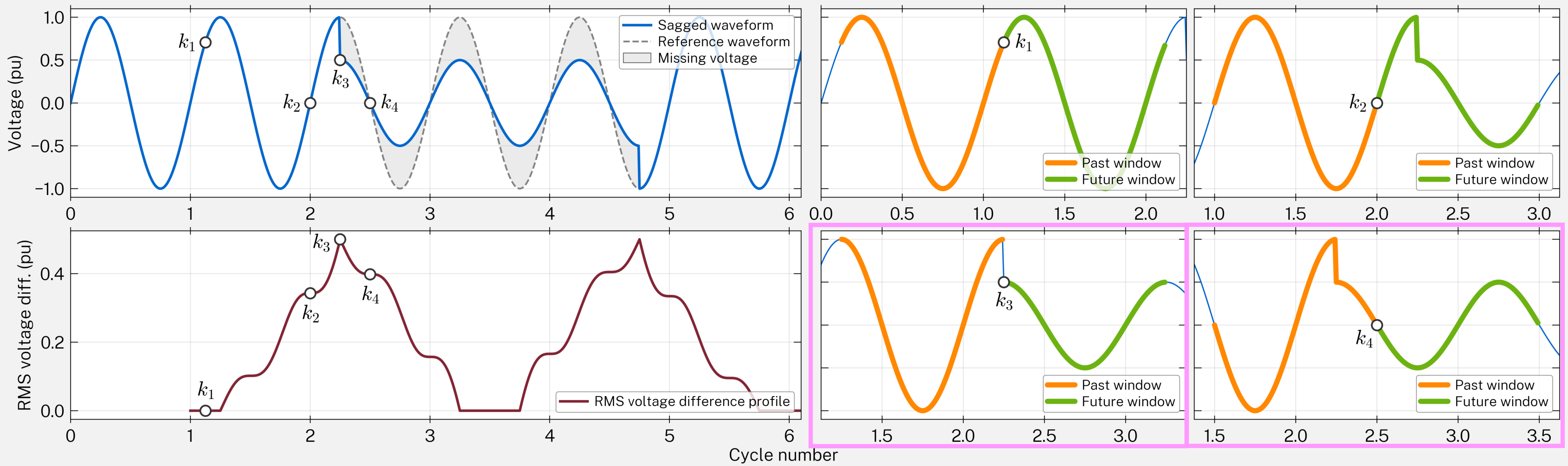


Illustration of the Proposed Method (II)

Simulated sag:
- Start: cycle 2.25
- Magnitude: 0.5 pu
- Duration: 2.5 cycles

- *Sag inception instant* (k_3): the *past* and *future* windows contain exclusively pre- and during-sag voltage samples, respectively; the rms voltage difference reaches its local maximum value.
- *Partial post-sag inception instant* (k_4): the *future* window contains exclusively during-sag voltage samples, whereas the *past* window contains a mixture of pre- and during-sag voltage samples; the rms voltage difference decreases compared to k_3.



Results

Case studies illustrating the performance of the proposed method

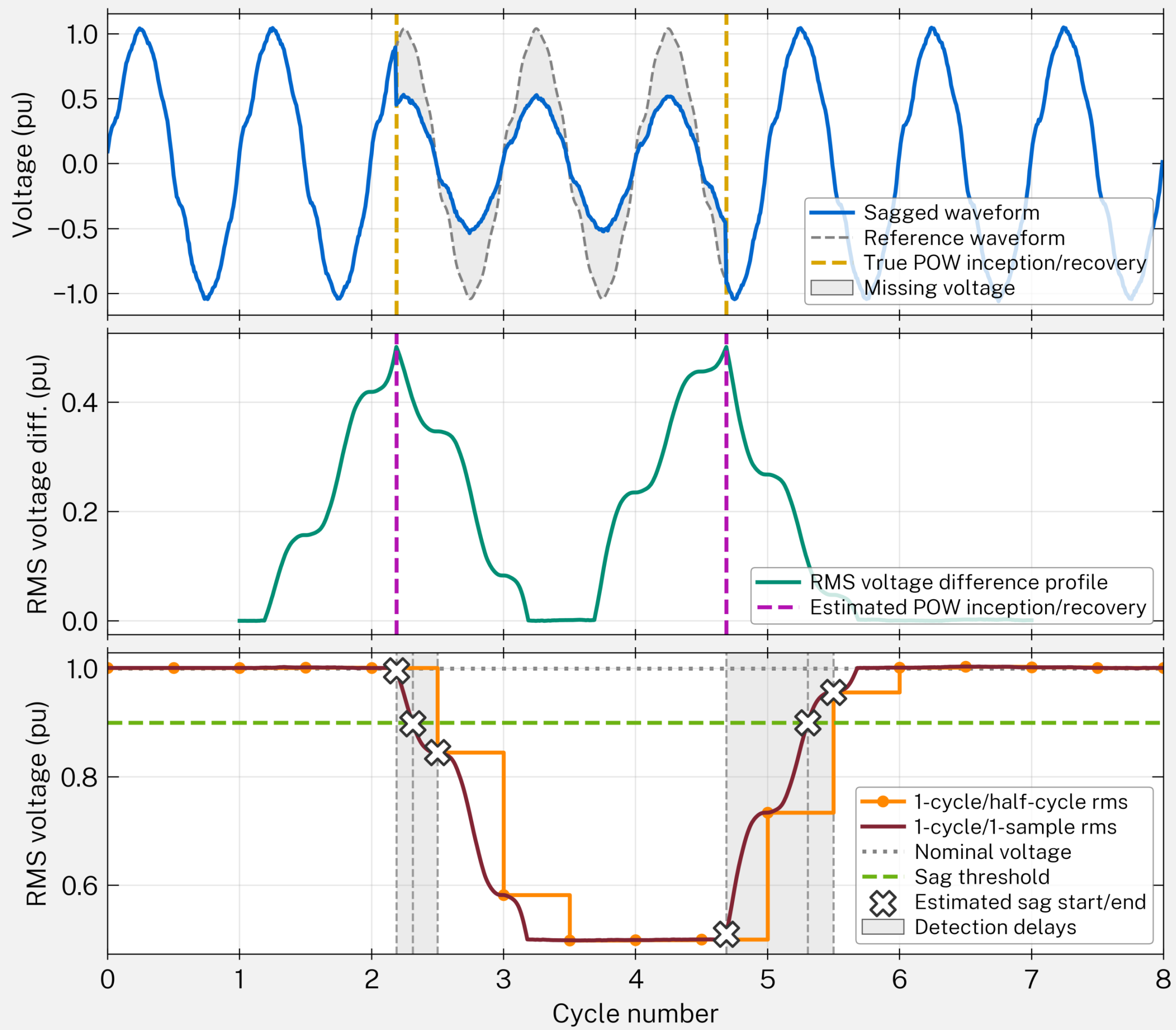
Notes:

1. All voltage waveforms are sampled at 128 samples/cycle for 60-Hz systems;
2. Field measurements are collected at the terminals of substation transformers;
3. The sag threshold is set to 0.9 pu;
4. Whenever possible, the true point-on-wave of sag inception and recovery instants are determined by visual inspection of the voltage waveforms for comparison purposes.

1: Synthetic Voltage Sag

- Waveform characteristics:
  - Fundamental (1 pu) and 3rd through 9th odd harmonics (0.03 pu)
  - Gaussian noise: 0 pu mean and 0.01 pu standard deviation
- Sag characteristics:
  - Start: cycle 2.1875 (equivalent to 67.5°)
  - Duration: 2.5 cycles
  - Magnitude: 0.5 pu

Method	Inception latency (samples)	Recovery latency (samples)	Duration (cycles)	Duration error (%)
1-cycle/half-cycle rms	40	104	3.000	+26.00
1-cycle/1-sample rms	16	79	2.992	+19.69
rms voltage difference	0	0	2.500	+0.00

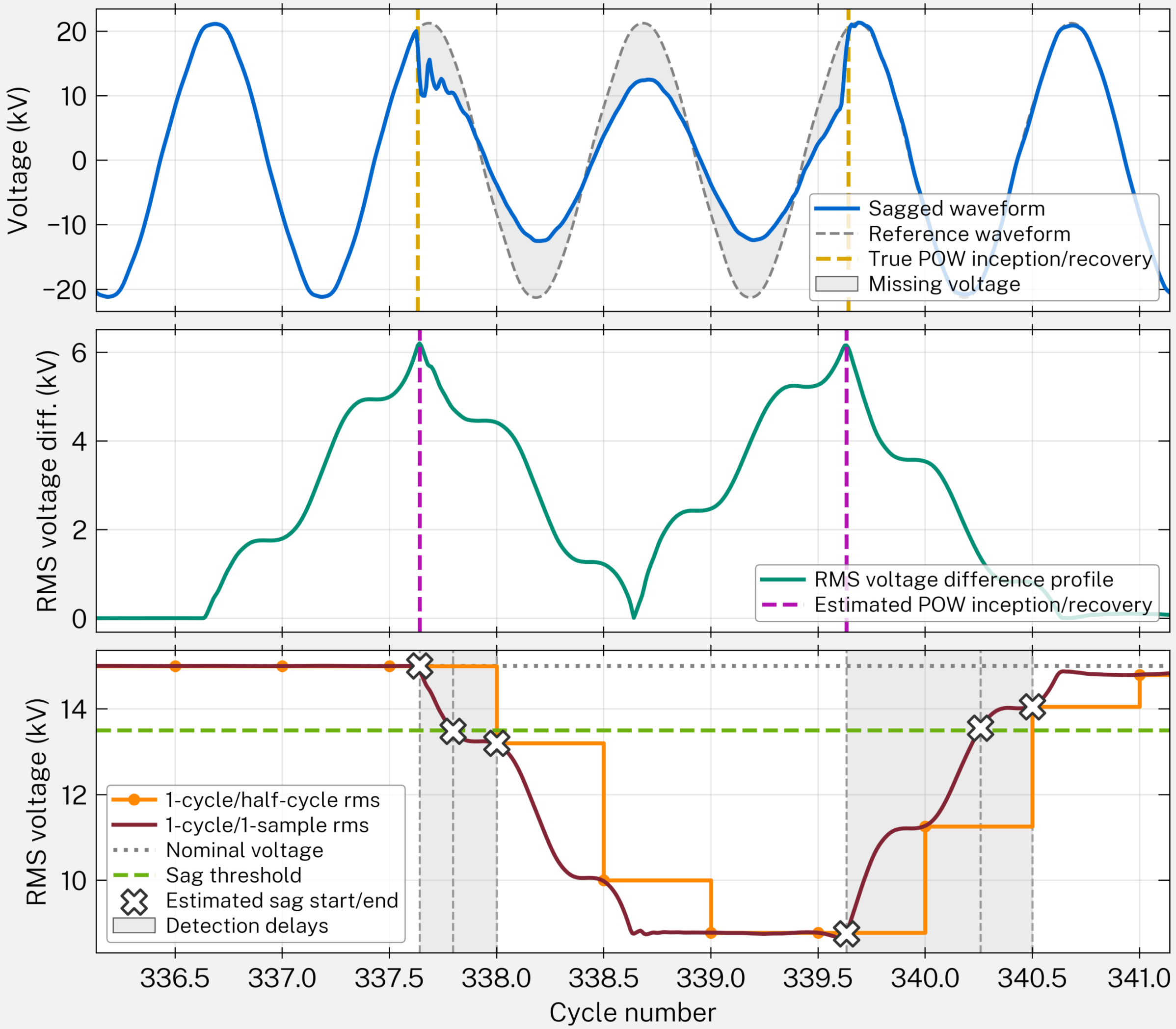


2: Field Data – Voltage Sag With Transients

- Most voltage sags exhibit transients around their inception and recovery instants, especially if those instants are not near a zero crossing.

- True sag duration: 2.008 cycles.

Method	Inception latency (samples)	Recovery latency (samples)	Duration (cycles)	Duration error (%)
1-cycle/half-cycle rms	47	110	2.500	+24.51
1-cycle/1-sample rms	21	79	2.461	+22.57
rms voltage difference	1	-1	1.992	-0.78

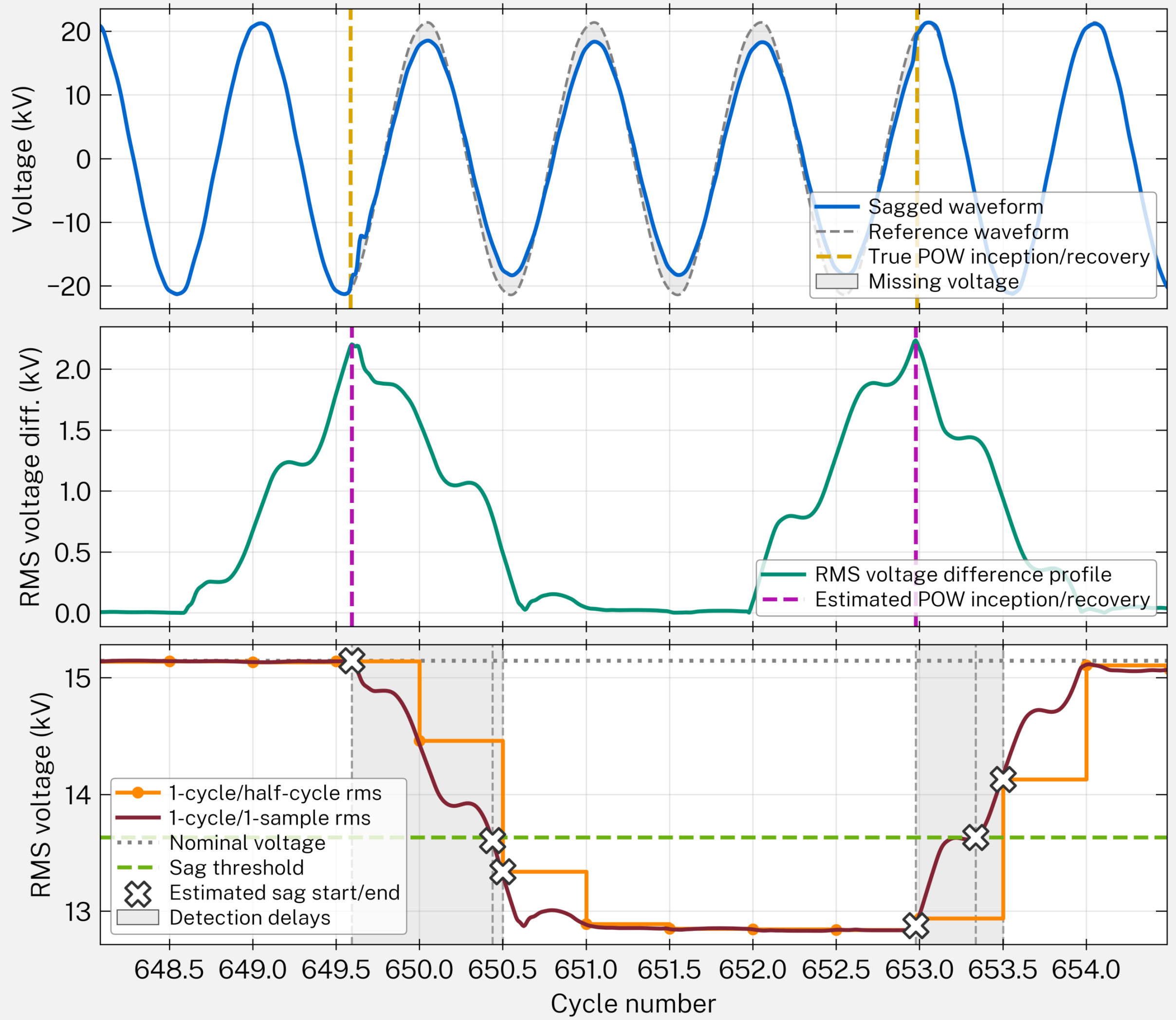


3: Field Data – Voltage Sag Without Transients

- Some sags have a seamless transition between sag and non-sag segments.
  - Waveform transients are non-existent or very subtle.

- True sag duration: 3.398 cycles.

Method	Inception latency (samples)	Recovery latency (samples)	Duration (cycles)	Duration error (%)
1-cycle/half-cycle rms	117	66	3.000	-11.72
1-cycle/1-sample rms	109	45	2.894	-14.71
rms voltage difference	1	-1	3.383	-0.46

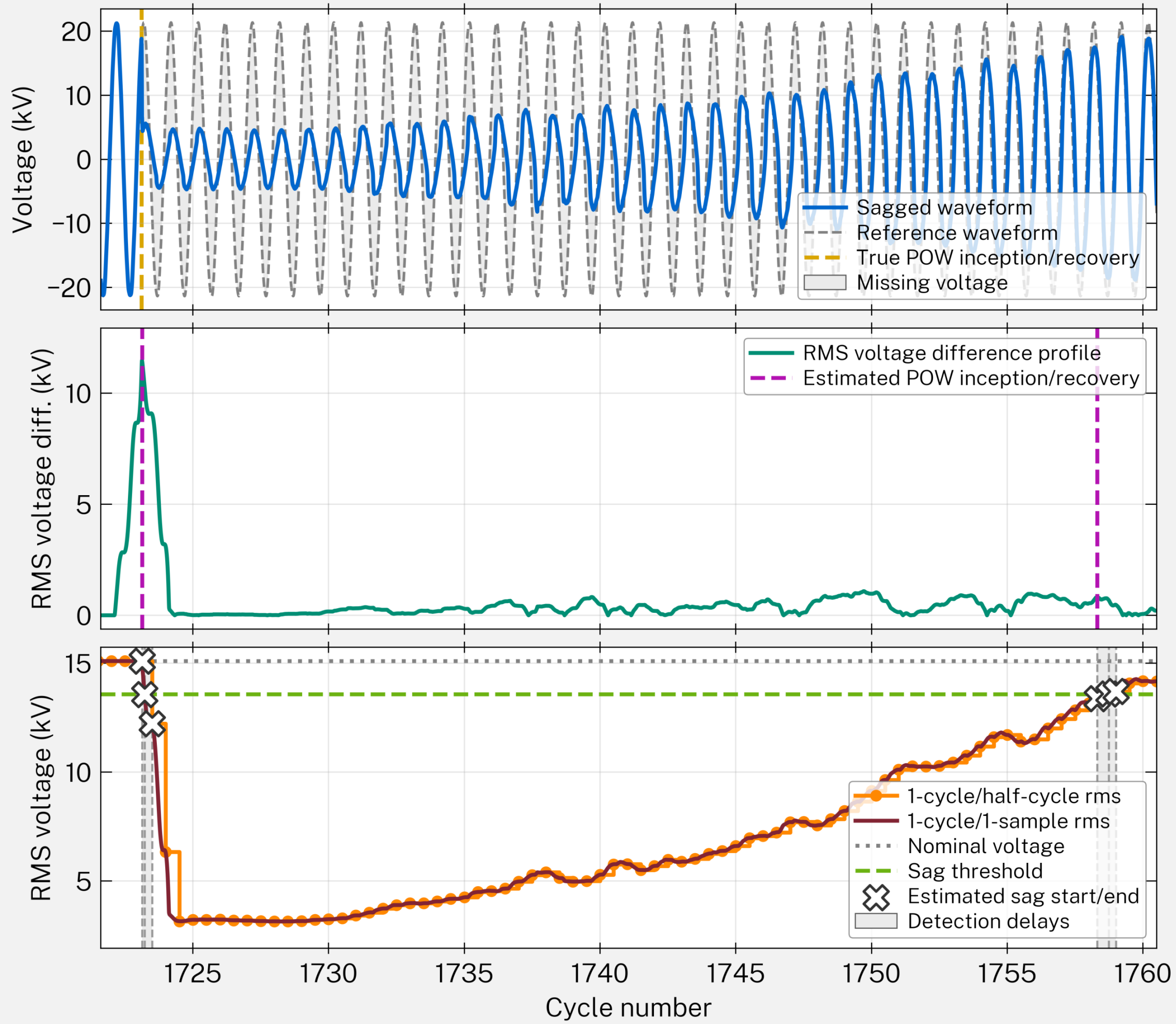


4: Field Data – Voltage Sag With Slow Recovery

- Not all voltage sags have well-defined time boundaries.
  - E.g.: the starting of large motors causes a substantial voltage drop initially, which gradually recovers to its pre-sag value.

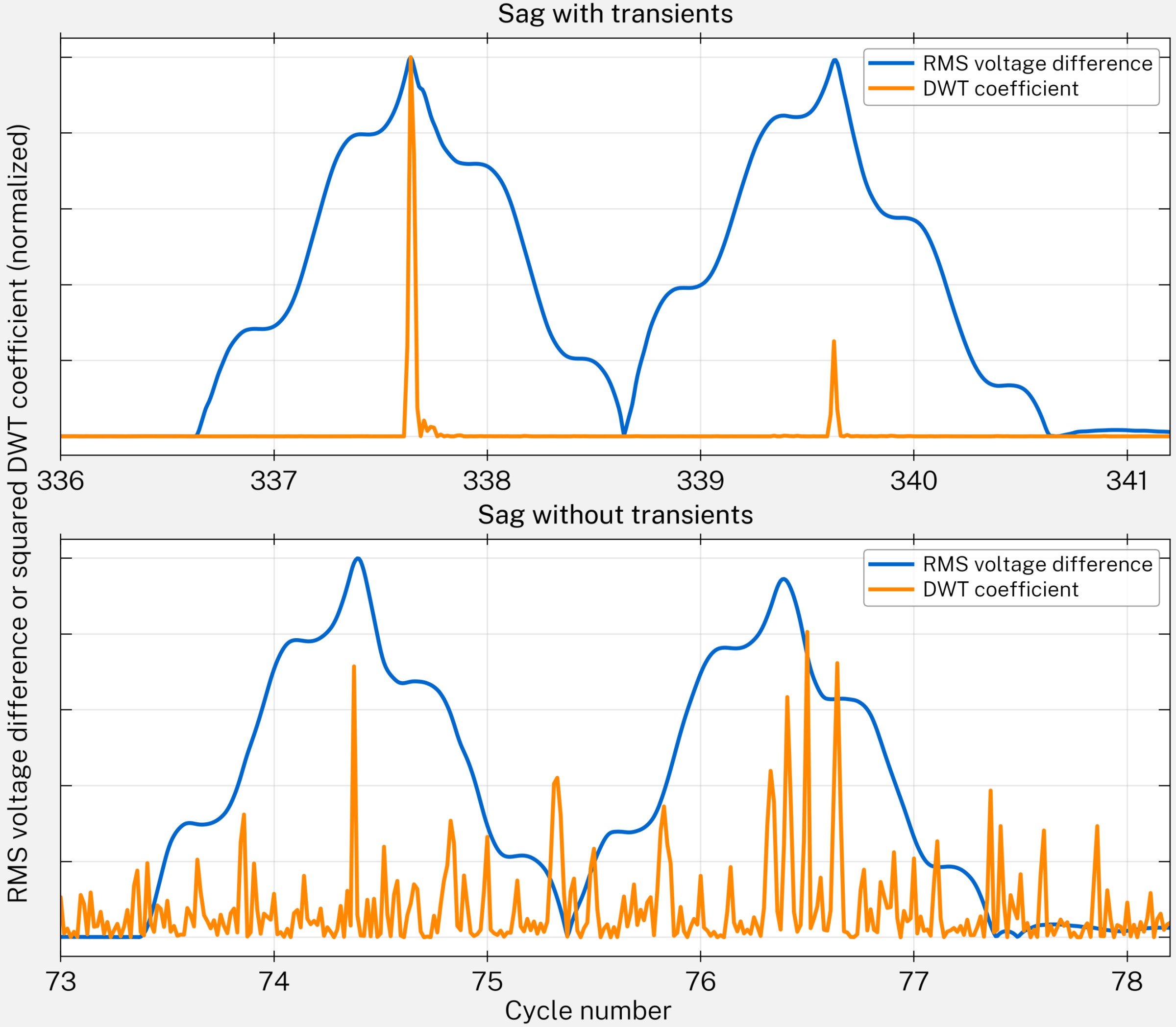
- True point-on-wave recovery instant cannot be determined.

Method	Inception latency (samples)	Recovery latency (samples)	Duration (cycles)	Duration error (%)
1-cycle/half-cycle rms	99	N/A	35.500	N/A
1-cycle/1-sample rms	29	N/A	35.508	N/A
rms voltage difference	4	N/A	35.484	N/A



5: Comparison to the DWT* Method

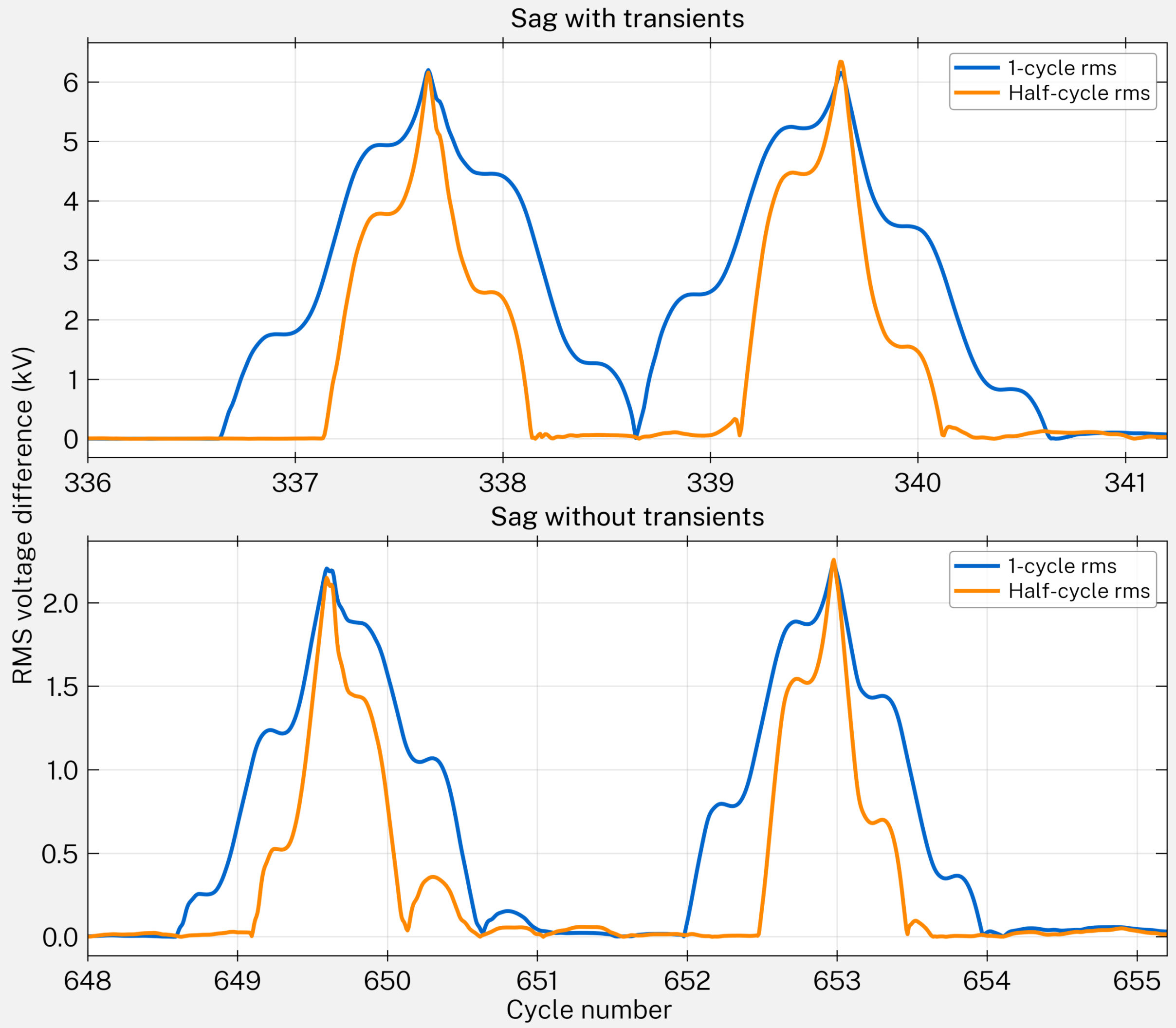
- DWT is the most accurate estimation method in the existing literature.
- Comparison for sags with/without transients:
  - DWT uses *Daubechies 4* as mother wavelet;
  - Sag with transients (top plot):
    - ✓ Both methods are equally accurate.
  - Sag without transients (bottom plot):
    - ✓ *RMS voltage difference method* is still very accurate;
    - ✓ DWT cannot detect the sag inception and recovery.
- General comments about the DWT method:
  - Its accuracy depends on the mother wavelet;
  - It is susceptible to false-positives due to noise or any other transients in the waveforms.



*The term *DWT* refers to *discrete wavelet transform*.

6: Effects of the Sliding Window Length

- Half-cycle-long sliding windows also can be adopted for rms computation.
- Both rms voltage difference profiles reach a local maximum at the same instant.
- Advantages:
  - Faster transition between sag and non-sag rms voltage values;
  - More appropriate for very-short sags.
- Disadvantages:
  - Half-cycle rms computation is sensitive to even-harmonic distortion.



Conclusion

Final Thoughts

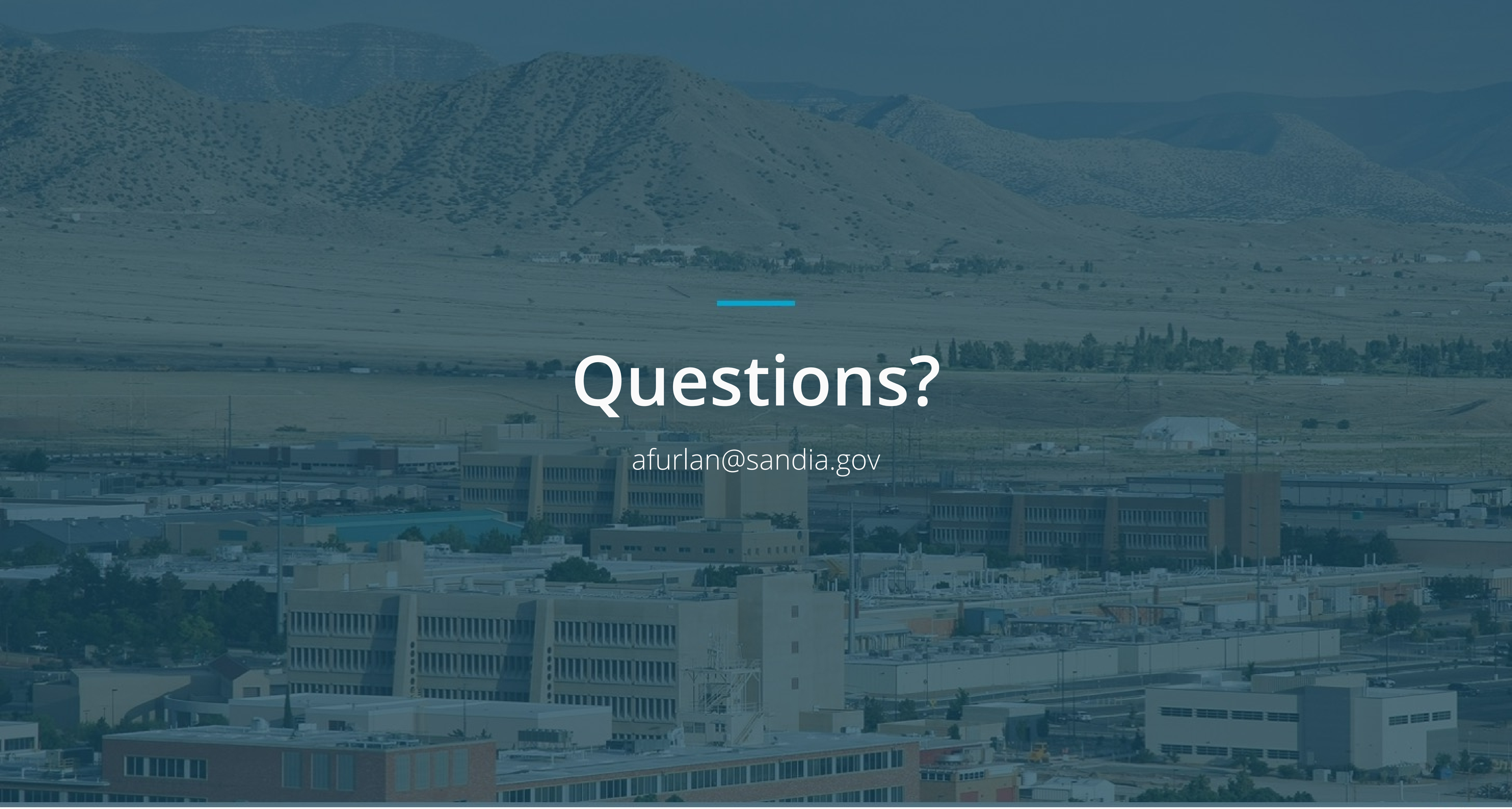
- The *rms voltage difference method* accurately determines the point-on-wave of sag inception/recovery instants, unlike the other methods found in the literature.
  - The estimation error is at most a few samples.
  - The estimation process requires both *past* and *future* voltage samples; i.e., the analysis for any given instant have a delay equal to the sliding window length (usually one or half cycle).

- The finite sampling rate of voltage waveforms entails a limit on the precision of the estimated phase angle at the estimated sag inception/recovery instants.
  - For a sampling rate of 128 samples/cycle, each sampling interval corresponds to 2.8125°.

- The *IEEE Voltage Sag Indices Task Force* is considering to add new parameters and methods for voltage sag characterization in the next update of the *IEEE Std. 1564*.
  - The *rms voltage difference method* is under consideration for being included in the standard.

References and Further Reading

- IEEE Std. 1564-2019, *"IEEE Guide for Voltage Sag Indices,"* doi: 10.1109/IEEESTD.2014.6842577.
- IEEE Std. 1159-2019: *"IEEE Recommended Practice for Monitoring Electric Power Quality,"* doi: 10.1109/IEEESTD.2019.8796486.
- IEEE Std. 1668-2017: *"IEEE Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 V,"* doi: 10.1109/IEEESTD.2017.8120227.
- IEEE Std. 493-2007: *"IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems,"* doi: 10.1109/IEEESTD.2007.380668.
- IEC Std. 61000-2-8, *"Electromagnetic Compatibility (EMC) – Part 2.8: Environment Voltage Dips and Short Interruptions on Public Electric Power Supply Systems With Statistical Measurement Results."*
- IEC Std. 61000-4-30, *"Electromagnetic Compatibility (EMC) – Part 4.30: Testing and Measurement Techniques – Power Quality Measurement Methods."*
- M. Bollen and I. Gu, *Signal Processing of Power Quality Disturbances*, Wiley-IEEE Press, 2006, doi: 10.1002/9780471931317.
- A. F. Bastos, K. Lao, G. Todeschini and S. Santoso, *"Accurate Identification of Point-on-Wave Inception and Recovery Instants of Voltage Sags and Swells,"* in IEEE Transactions on Power Delivery, vol. 34, no. 2, pp. 551-560, April 2019, doi: 10.1109/TPWRD.2018.2876682.
- A. F. Bastos, S. Santoso and G. Todeschini, *"Comparison of Methods for Determining Inception and Recovery Points of Voltage Variation Events,"* IEEE Power & Energy Society General Meeting (PESGM), 2018, pp. 1-5, doi: 10.1109/PESGM.2018.8585977.
- Electric Power Research Institute (EPRI), *"Waveform Characteristics of Voltage Sags: Statistical Analysis,"* Palo Alto, CA, May 1999, Technical Report TR-112692.



Questions?

afurlan@sandia.gov

Appendix: Mathematical Formulation

Proof: RMS Voltage Difference Profiles Have Local Maximums at the Sag Inception/Recovery Instants

- The claim that V_{rms}^{diff}, an rms voltage difference profile, reaches its local maximum value at the inception and recovery instants of sag is demonstrated through the simple case of an ideal sinusoidal voltage waveform.
- Let:
  - $v[k]$ is the sampled voltage waveform with a sag starting at instant k^*;
  - V_1 and V_2 are the rms voltages before and during the sag, respectively;
  - f and ϕ are the frequency and phase angle, respectively;
  - w is the sliding window length.
- Then:

$$v[k] = \begin{cases} v_1[k] \coloneqq V_1 \sin(2\pi f k + \phi), k < k^* \\ v_2[k] \coloneqq V_2 \sin(2\pi f k + \phi), k \geq k^* \end{cases}$$

- RMS voltage difference profile:

$$V_{rms}^{diff}[k] = \begin{cases} 0, & k \leq k^* - w \\ \frac{V_1}{\sqrt{2}} - V_{bf}[k], & k^* - w < k < k^* \\ \frac{V_1 - V_2}{\sqrt{2}}, & k = k^* \\ V_{af}[k] - \frac{V_2}{\sqrt{2}}, & k^* < k < k^* + w \\ 0, & k^* + w \end{cases}$$

where:

- $V_{bf}[k] = \left(\frac{1}{w}\left(\sum_{p=k}^{k^*-1} v_{1,p}^2 + \sum_{p=k^*}^{k+w-1} v_{2,p}^2\right)\right)^{1/2} > \frac{V_2}{\sqrt{2}}$
- $V_{af}[k] = \left(\frac{1}{w}\left(\sum_{p=k-w}^{k^*-1} v_{1,p}^2 + \sum_{p=k^*}^{k-1} v_{2,p}^2\right)\right)^{1/2} < \frac{V_1}{\sqrt{2}}$

- Therefore, $V_{rms}^{diff}[k^*]$ is a local maximum, as initially assumed.

Note: for simplicity, only the sag inception instant is analyzed here; discussion for the sag recovery instant is analogous. See the referenced paper for more details and discussion on the mathematical formulation of the proposed method.

Appendix: Miscellaneous

Sliding-Window RMS Voltage Profile (I)

The rms voltage profile as a function of time is computed through sliding windows as follows:

- From the sampled voltage waveform, rms voltage values are computed over a 1-cycle interval and updated every half cycle:

$$V_{rms}[k] = \left(\frac{1}{N} \sum_{i=k-N+1}^{k} v_i^2 \right)^{1/2}$$

where N is the number of samples per cycle, v_i is the sampled waveform, and $k = h\frac{N}{2}$ for $h = 2, 3, \ldots$.

- For multichannel measurements, the rms voltage profiles are calculated for each channel separately.
- Ideally, the voltage waveform sampling should be synchronized to the power frequency (i.e., a fixed number of samples per cycle rather than a fixed number of samples per second). However, the difference between rms voltage profiles obtained from synchronized and non-synchronized sampling is usually small, as long as the power frequency is relatively close to its nominal value.

Sliding-Window RMS Voltage Profile (II)

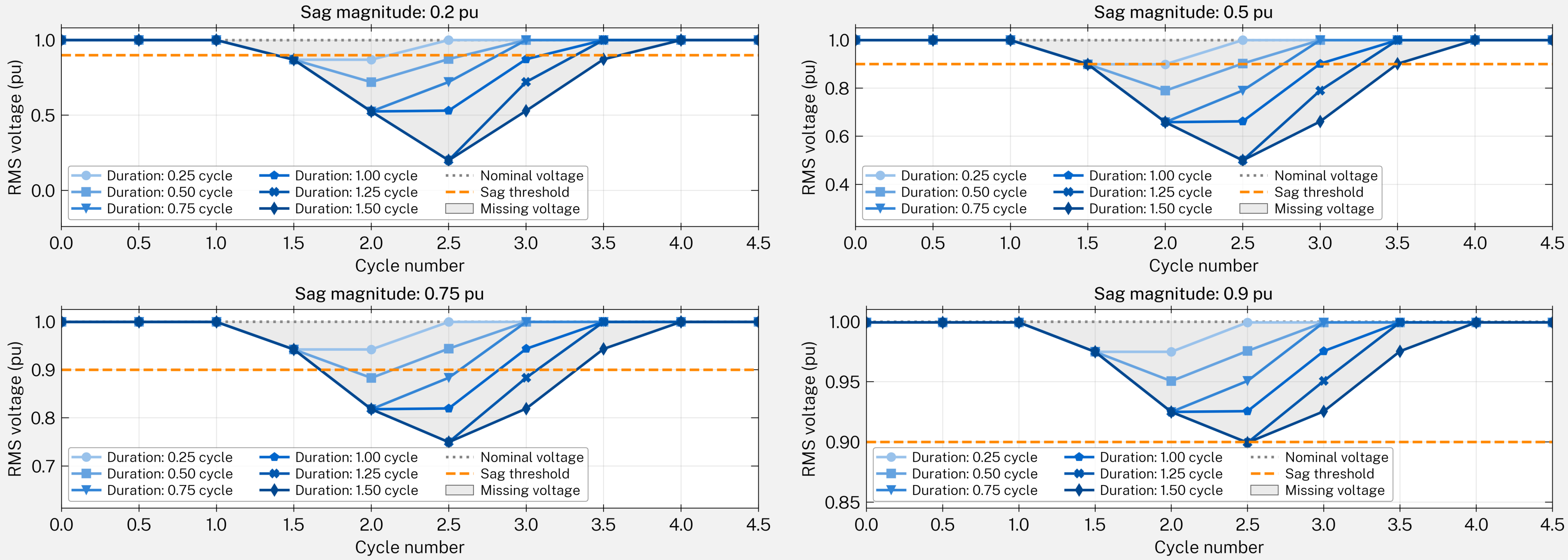
Rapidly updated rms voltage profile:

- During a voltage sag, it may be useful to calculate 1-cycle rms values at an update rate higher than half cycle, such as updating the rms voltage values for each new voltage waveform sample.
- Advantages:
  - More precise (but not exact) identification of the inception and recovery instants of the voltage sag using simple sag thresholds.
- Drawbacks:
  - Increased processing requirements, although there are techniques for optimizing the computation of rms voltage profiles with high update rates*;
  - Increased amount of derived data;
  - Introduction of a possibly misleading sliding filter.

*A. F. Bastos and S. Santoso, *"Root-Mean-Square Profiles under Varying Power Frequency: Computation and Applications,"* IEEE Power & Energy Society General Meeting (PESGM), 2019, pp. 1-5, doi: 10.1109/PESGM40551.2019.8973762.

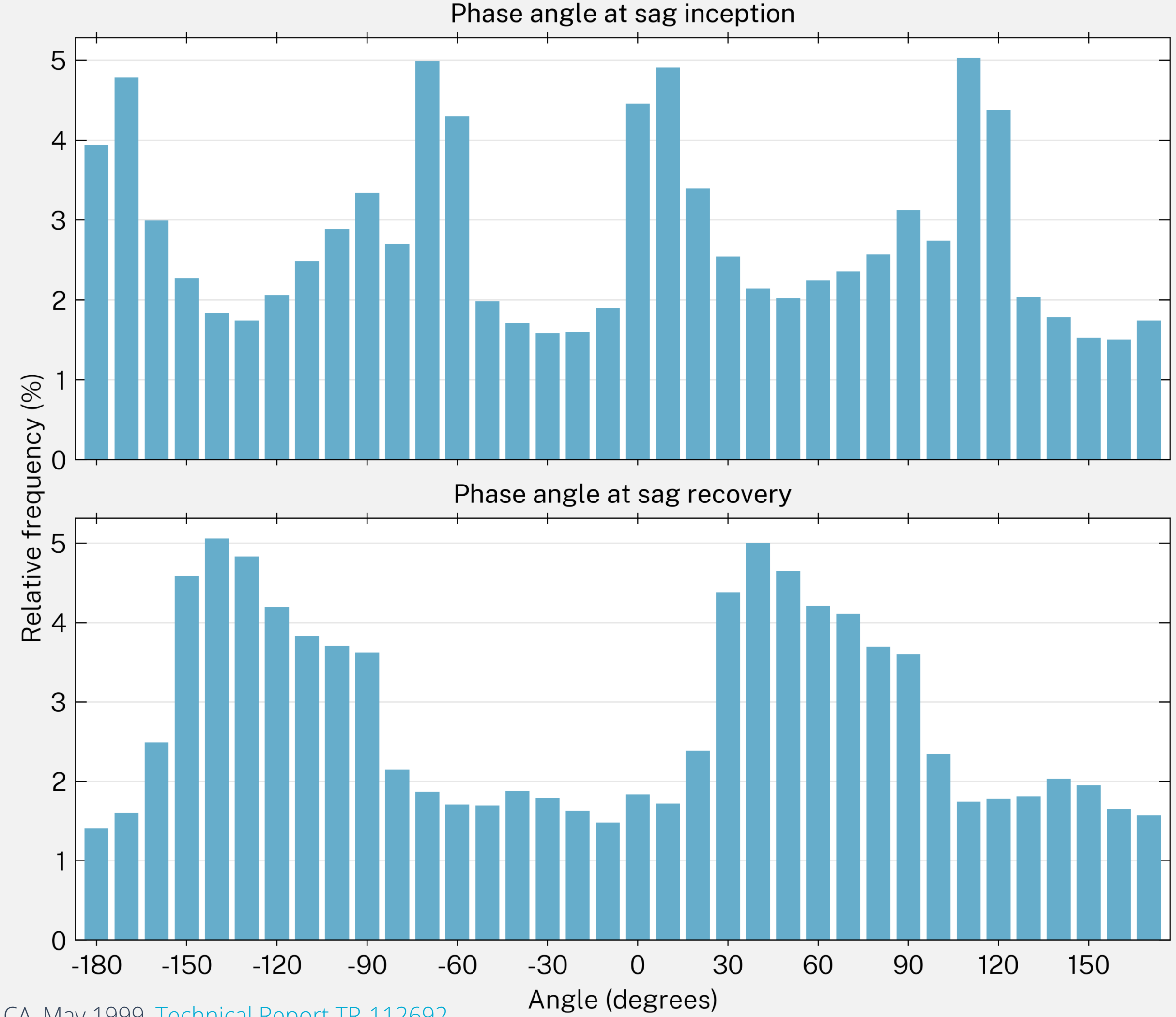
Detection/Characterization of Very-Short Sags

- Very-short sags (0.25-1.5 cycles) starting at cycle 1.25 with varying magnitudes:
  - Very-short sags may be undetected based on rms voltage values only, specially shallow sags.



Statistics on Sags POW Inception and Recovery Instants – Primary Distribution Data

- Statistics on the point-on-wave of sags inception and recovery instants with respect to a reference sinewave with a 0° phase angle.
- Data collected by the *EPRI Distribution System Power Quality Monitoring Project*:
  - June 1, 1993 through June 1, 1995;
  - 24 electric utilities across the United States , with geographical and operating-practice diversity;
  - 100 primary distribution feeders in the 4-33 kV voltage range;
  - 277 measurement locations;
  - Over 6.7 million measurements.
- Sag inception is not biased to the voltage peaks; rather, it is fairly random.
- Sag recovery seems to occur more often as the voltage waveform approaches a positive or negative peak.



Source: Electric Power Research Institute (EPRI), *"Waveform Characteristics of Voltage Sags: Statistical Analysis,"* Palo Alto, CA, May 1999, Technical Report TR-112692.

Note: the relative frequency values in these histograms were manually extracted from figures in the EPRI TR112692-1999 technical report; thus, they might be slightly different from the actual values.