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Comparison of Methods for Determining Inception and Recovery Points of Voltage Variation Events

Alvaro Furlani Bastos¹, Surya Santoso, *The University of Texas at Austin*,
Grazia Todeschini, *Swansea University*

Abstract—Voltage sags and swells occur often in power systems; however determining the duration of these events is not straightforward. Seven methods for estimating the inception and recovery points (and consequently, the duration) of voltage sags and swells are surveyed: threshold rms voltage, waveform envelope, discrete wavelet transform, missing voltage, dq transformation, numerical matrix, and peak detector. Each method has its own strengths and weaknesses; however, no one method works on all conditions. An algorithmic approach to determining inception and recovery points is suggested. Such approach employs one method in combination with other methods based on the event characteristics.

Index Terms—fault, inception point, recovery point, voltage sag, voltage swell

I. INTRODUCTION

Voltage sags/swells are common events in power systems; however, their characterization may be inaccurate and incomplete [1]. For example, a voltage sag is defined in terms of its duration and retained voltage (i. e. the lowest rms voltage during the event) [2]–[4], while other characteristics such as point-on-wave inception and recovery, and phase angle shift are not always considered.

The event duration estimation is usually described on an rms basis, which introduces delays and inaccuracies. Only voltage variation events lasting more than 0.5 cycle are classified ‘short-duration variations’ [2]; a critical reader may be uncertain whether not considering events shorter than 0.5 cycle is due to the limitations of the processing techniques or if these events do not affect sensitive loads. Moreover, even the retained voltage magnitude may be improperly estimated for very short sag/swell events, as it is not possible to guarantee that any sliding window for rms computation contains exclusively event data.

This paper reviews methods for estimating the inception and recovery instants of a voltage sag or swell, based either on instantaneous or rms voltage values. Each method is briefly summarized, and its strengths and limitations are discussed through examples of balanced and unbalanced faults and transient events.

II. INCEPTION AND RECOVERY POINTS ESTIMATION

This section presents different methods for estimating the inception and recovery points of voltage sag/swell events. The application of each method is illustrated through simulated

and real-world voltage measurements of short-circuit faults and capacitor energizing.

A. Estimation Method using Threshold rms Voltage

The threshold rms voltage method identifies a voltage variation event if the measured rms voltage is below α_{inf} pu (sag) or above α_{sup} pu (swell); commonly adopted threshold values are $\alpha_{inf} = 0.9$ and $\alpha_{sup} = 1.1$. This is the method recommended by most standards [2], [3], which establish that rms values must be computed through a one-cycle sliding window and updated every half cycle.

The sag (swell) start instant is defined as the first point where the rms voltage drops below (rises above) the threshold setting. Similarly, the sag (swell) end corresponds to the instant at which the rms value recovers above (below) the threshold setting for at least $\frac{1}{2}$ cycle. The threshold settings for start and end instants estimation are not required to be equal. For example, it is appropriate to adopt a lower threshold setting to determine a sag end, as the voltage usually does not recover to the pre-sag value in case of a large motor starting.

This method is easily implementable and requires low computational effort. The synchronization of sampling to the power frequency is not necessary, as the difference between synchronized and non-synchronized rms measurements is small [2]. On the other hand, determination of the start and end instants is inaccurate, as the rms voltage may take up to one cycle to transition from the pre-event to the during-event values [5]. Reference [6] proposes to reduce the sliding window length to half-cycle to improve the accuracy; its main advantage is a faster transition between steady-state and sag/swell voltage values. However, the voltage transition time may still be as long as half-cycle.

Consider the voltage sag during a fault represented in Fig. 1a; visual inspection of the voltage waveform allows to accurately determine the start and end instants of the event, which lasts for 2.022 cycles. The rms voltage profiles are computed for both 1-cycle and half-cycle long sliding windows, and the update rate (i. e. the time interval between each 2 consecutive computed values) of rms values is either half-cycle or 1 sample, as shown in Fig. 1b and Fig. 1c, respectively.

The time difference between the exact and estimated inception/recovery instant of the sag is called time latency and is shown in Table I. Note that the event duration is overestimated by up to 23.7%, and even half-cycle rms values are not accurate in determining the desired instants. It is worth noting

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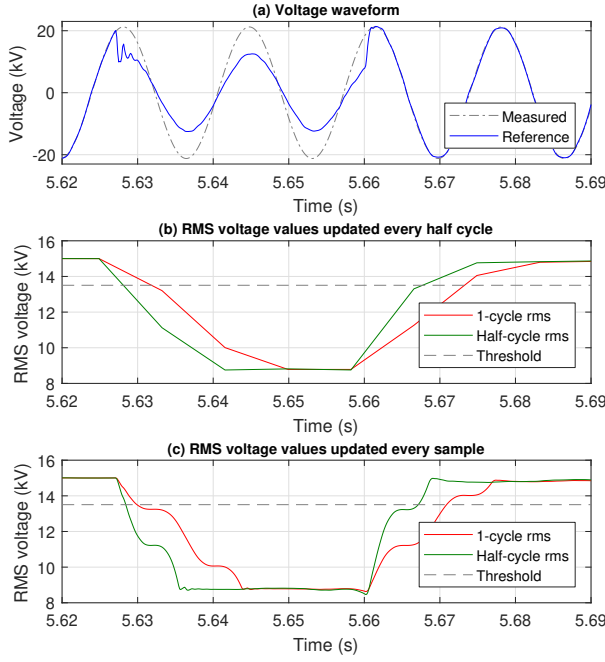


Fig. 1. RMS voltage profile during a voltage sag

TABLE I. TIME LATENCY OF THE RMS THRESHOLD METHOD

Window length	Update rate	Start delay (cycle)	End delay (cycle)	Duration* (cycle)
1 cycle	Half cycle	0.366	0.846	2.502
1 cycle	1 sample	0.174	0.612	2.460
Half cycle	Half cycle	0.366	0.846	2.502
Half cycle	1 sample	0.084	0.384	2.322

* The exact duration is 2.022 cycles.

that the time latency for an update rate of half-cycle does not depend on the sliding window length in this example, even though the half-cycle rms profile seems to give a more accurate estimate. This behavior is caused by the low update rate, as the event triggering occurs only after a new rms value is computed.

This method may be useful in obtaining rms voltage performance indices. However, it is inadequate to assess the performance of the transmission and distribution protection systems due to its limitations in determining the point-on-wave of the sag/swell inception and recovery [7].

B. Estimation Method using Waveform Envelope

The waveform envelope method utilizes the instantaneous phase voltage to determine the start and end instants of the event. Two sets of waveforms are created at $\pm 5\%$ and $\pm 10\%$ of the reference voltage, which is chosen as the pre-event steady-state voltage waveform [8], [9].

This detection method is triggered when the instantaneous voltage value falls outside the $\pm 10\%$ envelope. The inception point is defined as the last time prior to the triggering instant when the measured voltage fell outside the $\pm 5\%$ envelope. Similarly, the recovery point is determined as the instant at which the voltage waveform has returned to the $\pm 10\%$ envelope for at least $\frac{1}{2}$ cycle [7]. It is not required that the voltage waveform recovers to the $\pm 5\%$ envelope, likewise the higher threshold setting for recovery instant in the threshold

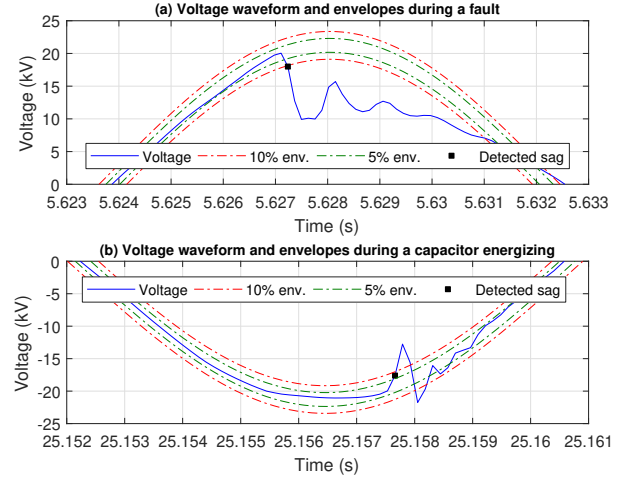


Fig. 2. Waveform envelope for fault and capacitor energizing events

rms method. Unlike the threshold rms voltage method, the waveform envelope approach determines the event duration based on the instantaneous voltage waveforms rather than on the rms voltage profile; therefore, it does not follow the typical definition of sag/swell duration given in the standards. Moreover, it provides no information about the retained voltage.

This method is considered highly sensitive for finding the exact point of the event inception with low false-positive detections [8]; Fig. 2a illustrates that the exact and estimated points of inception are almost the same. Note that the first fault sample voltage falls outside both envelopes, and the time latency (0.0078 cycle) corresponds to one sampling period (the sampling frequency is 7.68 kHz). Therefore, this method tends to be more accurate for high sampling frequencies. On the other hand, the estimated recovery instant is less accurate, especially if the fault is accompanied by a phase-angle shift. Another problem with this method is the possibility of over-detection during transient events. For example, Fig. 2b represents the transient voltage caused by a capacitor energizing, which is triggered by the waveform envelope method as a voltage sag. Even though this switching operation increases the rms voltage, this variation (0.29%) is significantly lower than the threshold adopted for detection of voltage sag/swell events.

C. Estimation Method using Discrete Wavelet Transform

Discrete wavelet transform (DWT) has been widely used for electrical power quality analysis, being an effective tool in transient detection [10]. This method is based on the principle that the DWT coefficients are relatively small and constant during a steady-state operation, but they significantly increase during transient events due to the presence of high-frequency components [7]. DWT is applied to each phase voltage, and the inception and recovery instants of the voltage variation event are determined by searching for peaks in the DWT coefficients data. A DWT coefficient is considered to represent the start or end of a transient event if it differs by more than 3 standard deviations from its mean value [11], [12].

A critical aspect of the performance of this method is the proper choice of the mother wavelet. While short wavelets give better time localization of disturbances, their reported event

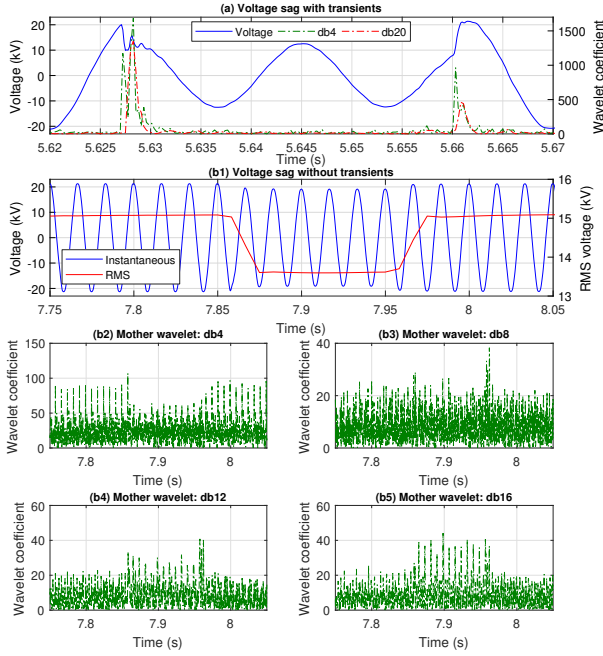


Fig. 3. DWT coefficients during a voltage sag (a) with and (b1-b5) without transients

detection accuracy is low (high false-negative rate). On the other hand, longer mother wavelets have a lower false-negative rate, but they are less accurate in determining its inception and recovery times. The approaches proposed include a hybrid detection using short (db2) and long (db8) wavelets [13], or an intermediate wavelet (db6) [7].

Fig. 3a shows the DWT coefficients during a voltage sag with transients for both short and long wavelets; Table II represents the delay between the exact and estimated start/end instants of the sag. Note that both short and long wavelets are very accurate in determining these instants.

TABLE II. TIME LATENCY OF THE DWT METHOD FOR THE VOLTAGE SAG ACCOMPANIED BY TRANSIENTS

Mother wavelet	Start delay (cycle)	End delay (cycle)	Duration* (cycle)
db2, db4, db6, db8, db10	0.006	0.000	2.016
db12, db14	0.024	0.048	2.046
db16, db18	0.024	0.000	1.998
db20	0.054	0.030	1.998

* The exact duration is 2.022 cycles.

However, this detection method fails to detect the voltage sag/swell when the event does not contain transient components, i. e., the sag is smooth. For example, Fig. 3(b1) corresponds to a 10% voltage sag, but neither short nor long wavelets were able to detect it, as the slight increase in Fig. 3(b2) through 3(b5) does not trigger the detector. Similarly, it would be unable to detect the recovery instant during a large motor starting, as the voltage gradually increases to the pre-sag value. Additionally, this method will detect other types of disturbances as well, even if they do not correspond to a sag or swell (such as capacitor energizing operations [14]).

D. Estimation Method using Missing Voltage

The missing voltage technique computes the difference between the desired and measured instantaneous voltage values.

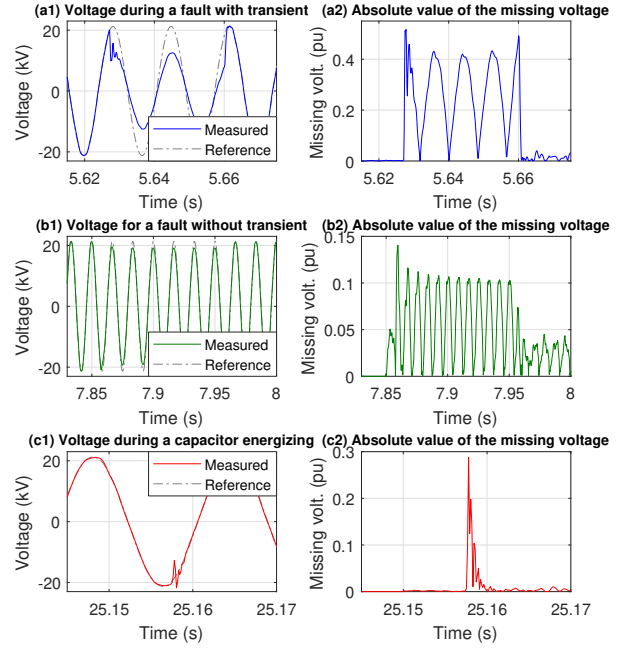


Fig. 4. Missing voltage during fault (a) with and (b) without transients and (c) during capacitor energizing events

The desired voltage value is obtained by extrapolating the pre-event steady-state voltage waveforms [15]. This process takes into account the frequency and phase angle variations over time, similar to the operation of a phase-locked loop [16].

A voltage sag/swell is identified if the absolute value of the computed difference is larger than the threshold setting (usually 10%) [17]. The inception instant is usually estimated with a low time response. On the other hand, this method is not accurate in detecting the point of recovery if the voltage sag/swell is accompanied by a phase-angle shift.

Fig. 4a shows the missing voltage values during a voltage sag with transients at the inception and recovery instants; indeed, the inception instant is accurately determined. However, estimation of the recovery point is more challenging. Note that the missing voltage decreases after the fault is cleared, but it is still as high as 0.04 pu, even though this example does not contain a phase-angle shift. This method also performs fairly well in the example represented in Fig. 4b, which corresponds to a fault not accompanied by transients. Note that the missing voltage is small around zero-crossing instants, even during a fault. Therefore, this method performs better for events that start near the voltage peak, regardless of the presence of transients. This method is also prone to false-positive detections during transient events, similarly to the waveform envelope method. For example, in Fig. 4c, which represents the voltage waveform during a capacitor energizing, the missing voltage reaches almost 0.3 pu, value large enough to trigger this event as a voltage sag or swell.

E. Estimation Method using dq Transformation

The dq transformation is a space vector control method that converts a stationary three-phase voltage set into a rotational orthogonal d - q frame [18]. The transformed components are computed as (1).

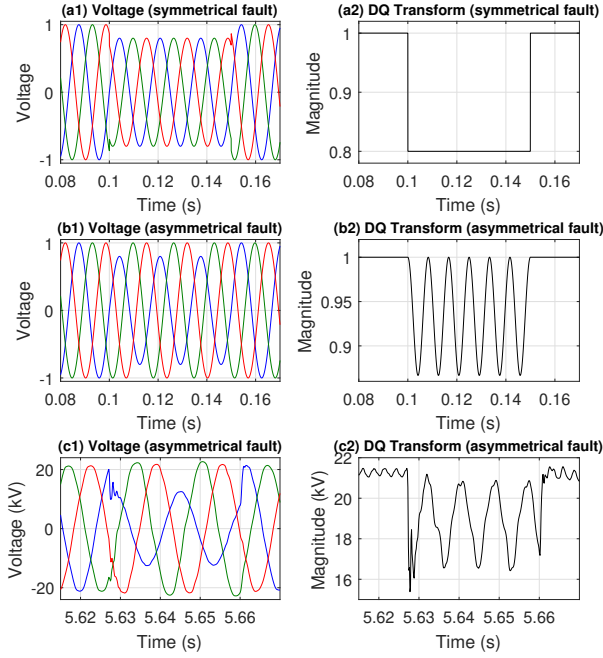


Fig. 5. Three-phase voltages and voltage v_d for symmetrical and asymmetrical faults, without and with harmonics

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(\omega t) & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

The voltage sag/swell is identified when v_d is below/above the specified threshold. This transformation can detect 3-phase symmetrical voltage sag/swell in real time, and it is very accurate in determining inception and recovery instants. However, v_d contains a sine wave component for asymmetrical voltage sag/swell, which hinders the estimation of inception and recovery instants [19].

Fig. 5a and Fig. 5b represent harmonic-free voltage waveforms for symmetrical and asymmetrical voltage sags between 0.1 and 0.15 s, respectively; Fig. 5c corresponds to real data measurements of an asymmetrical fault. Note that the dq transformation is very accurate in determining inception and recovery instants of symmetrical faults, but it performs poorly for asymmetrical faults. Moreover, the presence of harmonics and varying power frequency hinders the automatic estimation of those instants, as seen in Fig. 5c.

F. Estimation Method using Numerical Matrix

This method consists in determining the state of the system supply by decoupling each individual frequency components. The voltage values are sampled and stored in matrix format, $x_{2h \times 1} = A_{2h \times 2h}^{-1} b_{2h \times 1}$, where h is the number of harmonic components (including the fundamental). Each matrix is defined as follows (for $j, k = 1, 2, \dots, 2h$) [19]:

$$\begin{aligned} x(j, 1) &= |V_{[j/2]}| \sin\left(\phi_{[j/2]} + \frac{\pi}{2} \times (j \bmod 2)\right) \\ A(j, k) &= \sin\left((j-1)\omega_{[k/2]}T + \frac{\pi}{2} \times (k \bmod 2)\right) \end{aligned} \quad (2)$$

where $|V_r|$, ω_r , and ϕ_r are the magnitude, angular frequency, and phase of the r^{th} harmonic, respectively; $[\cdot]$ and \bmod

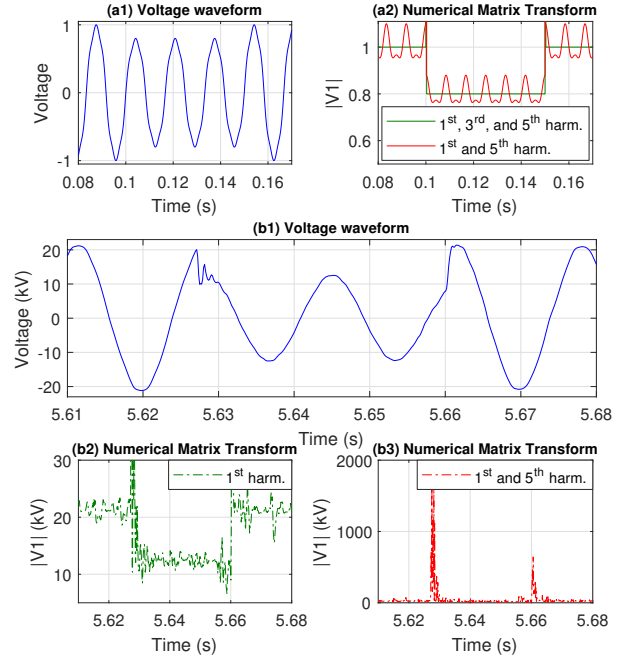


Fig. 6. Numerical matrix transform during voltage sags

represent the ceil and modulo operations, respectively. The column-vector b is formed by the sampled voltage values, starting with the most recent one. Note that $|V_1| = \sqrt{x(1, 1)^2 + x(2, 1)^2}$.

The number of simultaneous equations to be solved is twice the total number of harmonics detected in the voltage waveform. The voltage sag/swell is detected when the fundamental magnitude, $|V_1|$, is below/above the specified threshold. This method is believed to have small time latency in determining the sag/swell inception and recovery instants [19], specially for harmonic-free voltage waveforms.

Fig. 6a corresponds to a phase voltage waveform with 3rd and 5th harmonics, and a 20% voltage sag between 0.1 and 0.15 s. The numerical matrix can accurately determine the inception and recovery instants of the sag (as well as its magnitude) if all harmonics present in the voltage waveform are considered. However, its performance is negatively affected if only the fundamental and 5th harmonic are used. Similarly, Fig. 6b shows the poor performance of this method in the presence of multiple harmonic components. In this case, the use of only 2 harmonics was already sufficient to create an almost singular matrix A , and the computed voltage magnitudes increase significantly.

G. Estimation Method using Peak Detector

The peak detector, also called orthogonal detector, is another method to determine the state of the power supply [20]. The harmonic-free phase voltage, v , and its 90°-shifted version, v_{shift} , are given as

$$\begin{aligned} v(t) &= V_p \sin(\omega t) \\ v_{shift}(t) &= V_p \sin(\omega t + 90^\circ) = V_p \cos(\omega t) \\ V_p(t) &= \sqrt{v(t)^2 + v_{shift}(t)^2} \end{aligned} \quad (3)$$

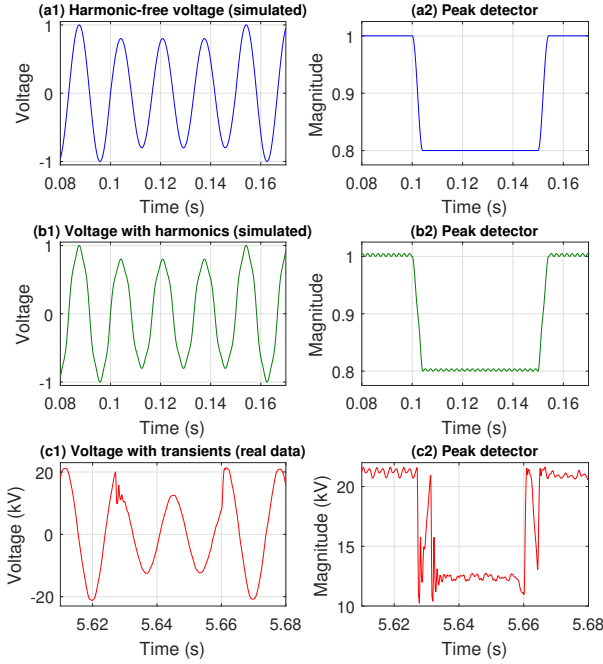


Fig. 7. Peak voltage during voltage sags

where V_p and ω represent the voltage peak value and angular frequency, respectively [21], [22].

Its implementation is very straightforward. The peak value, V_p , at the instant t^* is computed using the measured voltage values at t^* and $(t^* - T/4)$, where $T = 2\pi/\omega$ is the period of the voltage waveform. The voltage sag/swell is detected when V_p is above/below the specified threshold.

Fig. 7 represents the estimated instantaneous peak voltage during a voltage sag for three different cases. Note that this method is not very accurate in determining the event inception and recovery instants, as it may take up to a quarter cycle to detect a voltage variation. Moreover, the presence of harmonics and varying power system frequency weakens its detection performance, as seen in Fig. 7c.

III. CONCLUSION

This paper reviewed seven methods to estimate the inception and recovery instants of a voltage sag or swell, and the event duration, presenting their strengths and limitations. Table III summarizes the performance of each method; it is clear that the parameters of interest cannot be estimated accurately using either only instantaneous or rms voltage values. Given the limitations of each method, we recommend an algorithmic approach to estimating the inception and recovery instants. One such approach is as follows: use the threshold rms voltage method (preferably with short sliding windows and high update rate) to detect a voltage variation event and determine its magnitude, and the DWT method to estimate its inception and recovery instants, as well as its duration. This approach would fail if the event is not accompanied by transients. In this case, a second approach should be employed, substituting the DWT with the missing voltage method to estimate inception and recovery instants. The authors would like to emphasize that events with gradual voltage recovery, such as motor starting,

TABLE III. COMPARISON OF METHODS PERFORMANCE

Method	Voltage input data	Accuracy	Magnitude
Thresh. rms	1-phase, rms	low	yes
Wave. env.	1-phase, instantaneous	medium	no
DWT	1-phase, instantaneous	high	no
Miss. voltage	1-phase, instantaneous	medium	no
dq transform.	3-phase, instantaneous	low	no*
Num. matrix	1-phase, instantaneous	low	no*
Peak det.	1-phase, instantaneous	low	no*

* The retained magnitude can be computed in few specific scenarios.

remain a challenge. Although their inception instant can be determined, no method is superior in accurately determining the recovery instant under all conditions.

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