Automatic Assessment of Electrical Load Impact due to Voltage Sags

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***Abstract*—A voltage sag is a short duration reduction in rms voltage caused by electrical faults and load start-up events. Voltage sags are often characterized by rms voltage magnitude and duration. This paper focuses on new techniques for automatic detection and quantification of electrical load impacted by a voltage sag. This paper will provide an overview of a load loss detection algorithm and will provide specific examples of voltage and current waveforms resulting in load change in LV and MV power systems**

Keywords—voltage sag, tolerance curve, power quality impact, load impact

I. Introduction

A voltage sag is a short duration reduction in rms voltage that can be caused by a short circuit or fault, the energizing of a transformer, or the start-up of electric motors. Voltage sags are frequently associated with voltage swells, particularly when the cause is a ground fault. Of the seven power quality categories defined by IEEE Std 1159-2019 [4], short-duration rms variations are the most disruptive and have the largest universal economic impact on energy consumers. One study by EPRI estimates an average of 56 voltage sags are experienced by power customers each year [6]. A study from 2008 concluded that industrial sectors lose upwards of €150 billion as a direct result of their electrical power installations not being sufficiently reliable and resilient for today's and future operating demands [1]. This would be an equivalent of €180 billion or $216 billion in US dollars today. As industries becoming increasingly dependent on equipment that is sensitive to voltage sags, the impact of these events has become more important.

Voltage sags are normally characterized by the minimum rms voltage detected during the event and the duration of time when the rms voltage is below voltage sag thresholds. Likewise, voltage swells are characterized by their maximum rms voltage. The impact of a voltage sag on end-use equipment is often estimated by evaluating where the voltage sag would be represented in tolerance curves defined by the Information Technology Industry Council (ITIC) or SEMI F-47. Tolerance curves are useful tools for summary reports, but they are general recommendations for specific applications at explicit voltage levels. They do not accurately predict how a specific system or piece of equipment will respond to a voltage sag event, what the event's impact will be to the electrical system, or how and where to economically mitigate the issue.

This paper introduces new techniques for automatic detection and quantification of electrical load impact due to voltage sags and swells. The characterization technique results in automatic detection of load loss, load gain, and load reversal. It also quantifies the amount of load impacted. This paper will provide an overview of the load loss detection algorithm and will provide specific examples of voltage and current waveforms resulting in load change from low voltage and medium voltage electric power systems.

II. IEEE Std 1564-2014

IEEE Std 1564-2014 presents a five-step procedure for computing voltage sag indices [5].

1. Obtain sampled voltages with a specified sampling rate and resolution.
2. Calculate event characteristics as a function of time from the sampled voltages.
3. Calculate single-event characteristics from the event characteristics.
4. Calculate site indices from the single-event indices of all events measured during a specific time period.
5. Calculate system indices from the site indices for all monitored sites within a certain power system.

IEEE 1564 provides equivalent methods for computing indices and characteristics concerning voltage swells. A voltage swell is a short-duration increase in voltage. On multiphase systems, a voltage swell on one phase can be associated with a voltage sag on another phase. Some of the methods discussed will classify such an event as both a voltage sag and a voltage swell.

The guidelines in IEEE 1564 advocate computing one or more characteristics from the sampled voltages. From the sampled waveforms in the three phases, such as in Fig. 1, one or three voltage magnitudes as a function of time can be obtained. For single-channel and multi-channel measurements, the rms voltage is computed over one cycle and is updated every half cycle. This quantity is defined in IEC 61000-4-30 [7] as Ums(1/2) but in IEEE 1564 is defined as Vrms(1/2). For three-phase measurements, either the minimum Vrms(1/2) is used to characterize the event, or the "characteristic voltage" is used.

These time functions are used to determine two basic single-event characteristics: retained voltage ("sag magnitude") and duration.

A. RMS Voltage as a Function of Time

From the sampled voltages one or more characteristics as a function of time are calculated for every recording. This function is used to determine the retained voltage and the duration of the event. To calculate the rms voltage, IEEE 1564 specifies sampled voltages should be squared and averaged over a window with a one-cycle duration, as described in the following equation:

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

where N is the number of samples per cycle, v_i is the sampled voltage waveform, and k=1,2,3, etc.

B. Retained Voltage and Duration

A voltage sag or voltage swell can be characterized by its duration and its retained voltage. The duration is the time that the rms voltage stays below the threshold. The retained voltage is the lowest rms voltage during the event. Instead of retained voltage, the depth may be used, which is the difference between the retained voltage and a reference or declared voltage.

Voltage swells can be characterized in the same way as voltage sags. The rms voltage is again used as a characteristic versus time. The single-event indices are the "duration" and the "retained voltage" or "maximum swell voltage magnitude".

Fig. 2 presents the rms voltage samples for the voltage sag of Fig. 1. The dashed line indicates the voltage sag threshold, which is chosen as 90% of the phase-neutral base voltage of 7.2 kV. If we consider the three phases individually, two phases show a voltage sag of 9.5 cycles duration below the threshold. The retained voltage is 5.21 kV for Phase B.

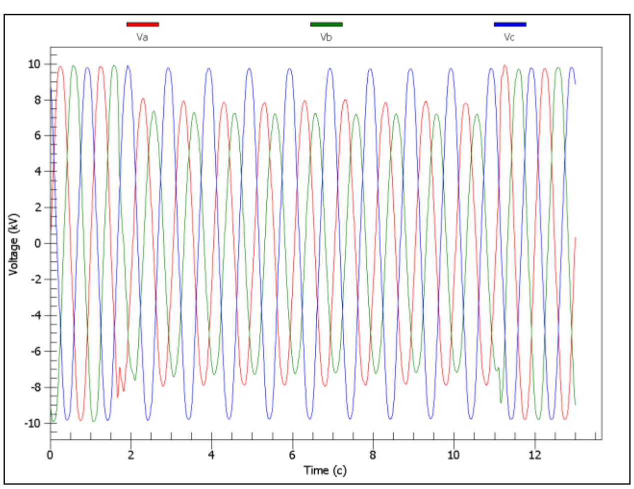

Fig. 1: Voltage Sag Example: Three-Phase Voltage Waveform Samples

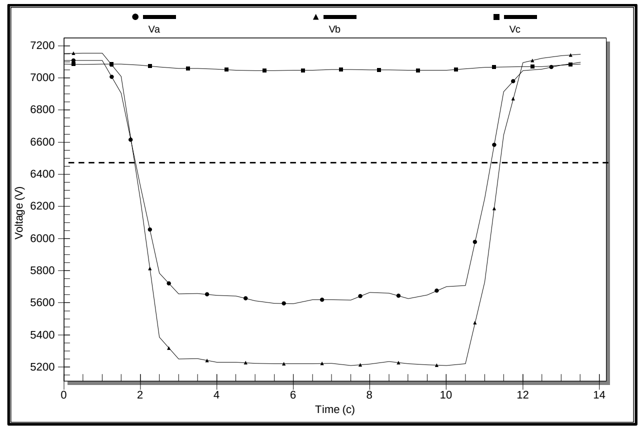

Fig. 2: Voltage Sag Example: Three-Phase Voltage RMS Samples with Sag Threshold

IEEE 1564 also describes additional event characteristics including voltage sag energy, voltage swell energy, and voltage sag severity. The event characteristics in IEEE 1564 focus on voltage only. That is, there are no event characteristics defined that focus on the impact of the voltage sag to an electric load, which is a key focus of this paper.

III. Voltage Sag Magnitude vs Duration Analysis

It is common for single-event characteristics derived using the guidelines in IEEE 1564 to be displayed together in a summary table or scatter plot. Fig. 3 illustrates a well-known magnitude-duration plot of voltage magnitude and duration: the ITI Curve (often referred to as the ITIC curve or CBEMA Curve) [8]. The ITIC Curve describes "an AC input voltage envelope which typically can be tolerated (no interruption in function) by most Information Technology Equipment (ITE)," and is "applicable to 120V nominal voltages obtained from 120V, 208Y/120V, and 120/240V 60 Hertz systems." The "Prohibited Region" in the graph "includes any surge or swell which exceeds the upper limit of the envelope." Events occurring in this region may result in damage to ITE. The "No Damage Region" includes sags or interruptions that are not expected to damage ITE.

Tolerance curves (e.g., the ITIC curve) are useful; however, it is important to remember they are also generalized recommendations for specific applications, often at explicit voltage levels. They do not indicate how a specific system or piece of equipment will respond to a sag/swell event, what the event's impact will be on the electrical system, or how/where to economically mitigate an issue. Furthermore, various zones within the electrical system are regarded the same, even though each IED typically monitors a unique load or combination of loads. Because each facility is inherently distinctive, generalized magnitude-duration plots are imperfect for discrete applications.

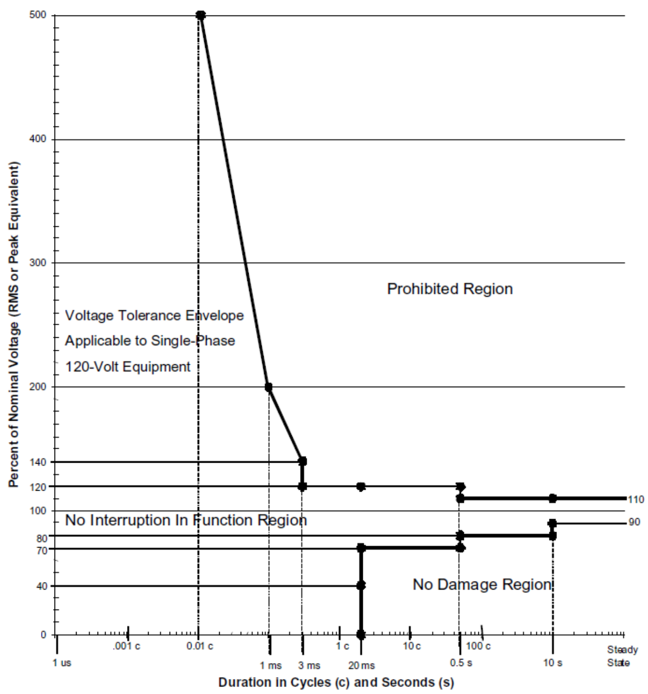

Fig. 3: Information Technology Industry Curve (ITIC Curve)

IV. Impact of Voltage Sags on Electrical Loads

The voltage sag in Fig. 1 was due to a downstream fault on a utility distribution feeder. The impact of this type of voltage sag event on an energy consumer's facility is primarily dependent on the four factors:

1. The nature and source of the voltage sag event
2. The susceptibility of the load(s) to the event
3. The event's influence on the process or activity
4. The cost of a process interruption due to this event

Consequently, each customer system and operation will respond differently to a voltage sag. For example, it is possible for a voltage sag event to significantly impact one customer's operation while the same voltage sag may have little or no noticeable impact on another customer's operation. It is also possible for a voltage sag to impact one part of a customer's electrical system differently than it does another part of the same electrical system.

A. Automatic Load Impact Assessment

The method for computing single-event characteristics for voltage sags presented in IEEE 1564 can be augmented to automatically assess whether a voltage sag was an impactful event following these steps:

1. Obtain sampled voltages and current waveforms with a specified sampling rate and resolution.
2. Calculate rms voltage and active power as a function of time from the sampled voltages and currents. The rms voltage and active power are computed over one cycle and are updated every half cycle.
3. Calculate single-event event characteristics: retained voltage, duration, voltage sag energy, voltage sag severity, and load change.

For "load change", active power is computed as the average of the instantaneous power over one cycle. To calculate the active power, the sampled voltage and current are multiplied together and averaged over a window with a one-cycle duration, as described in the following equation:

$$P_{(1/2)}(k) = \frac{1}{N}\sum_{j=1+k-N}^{k} v_j i_j$$

where N is the number of samples per cycle, v_j is the sampled voltage waveform, i_j is the sampled current waveform, and k=1,2,3, etc.

"Load change" can be computed by subtracting the initial value of active power $P_{(1/2)}(0)$ from the final value of active power $P_{(1/2)}(K)$. The load change value can be computed by phase, but more often it is a three-phase value computed by summing the single-phase phase values of load change. Load change be expressed in watts or percent of the pre-event load.

The end of a voltage sag (that is, when the rms voltage returns to a range proximate to the nominal value) does not always correspond with the end of the changes in active power delivered to a load. For example, an electrical load may trip offline several cycles after a voltage sag has finished. Alternatively, a load can restart automatically within seconds of the end of a voltage sag. Care must be taken during measurement capture to ensure that a steady-state value of load current has been reached by the end of a measurement to allow complete load impact evaluation due to a voltage sag.

A negative value of load change would indicate that the voltage sag resulted in a loss or reduction of load. A positive value of load change would indicate that the voltage sag was due to the start-up of a load or perhaps the energizing of a transformer.

B. Load Loss Example

Fig. 4, Fig. 5, and Fig. 6 illustrate a voltage sag event on a three-phase, 60 Hertz, 277/480-volt wye-configured system. Examination of the event indicates the origin was upstream and was possibly a fault. Fig. 5 and Fig. 6 are derived from the event waveform data captured in Fig. 4. The voltage sag had a duration of about 3 cycles, and the minimum rms voltage was about 73.8% of the nominal on Phase C as shown in Fig. 5.

Fig. 6 illustrates the single-phase active power and three-phase total active power, computed over one cycle intervals, once every ½ cycle. This chart is the most relevant for determining the event's impact. Before the event, the total active power consumed by downstream load was about 64.5 kW. At the completion of the voltage sag event, the total active power consumed by the downline loads was about 11.2 kW. Coincident with the voltage sag, the change (pre-event vs. post-event) in the total active power flow to the load was a decrease of about 53.3 kW (or 83%).

One inference is that the voltage sag event caused 83% of the load to be deenergized or removed from the circuit, likely resulting in a significant impact to the facility's operation. A negative load change between 0 and -100% coincident with a voltage sag event generally indicates the voltage sag event was responsible for the load loss.

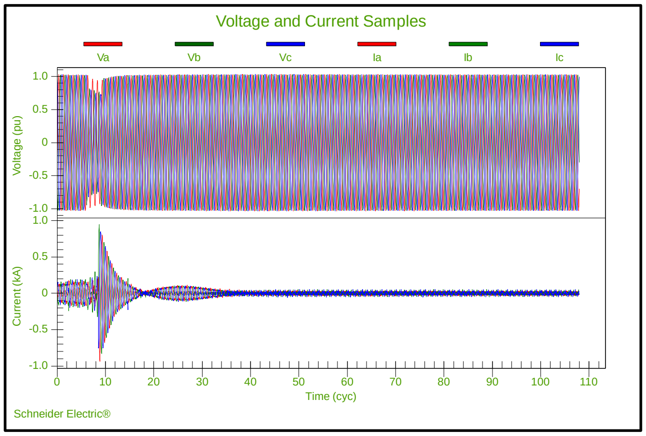

Fig. 4: Instantaneous Waveform Capture of Voltage Sag

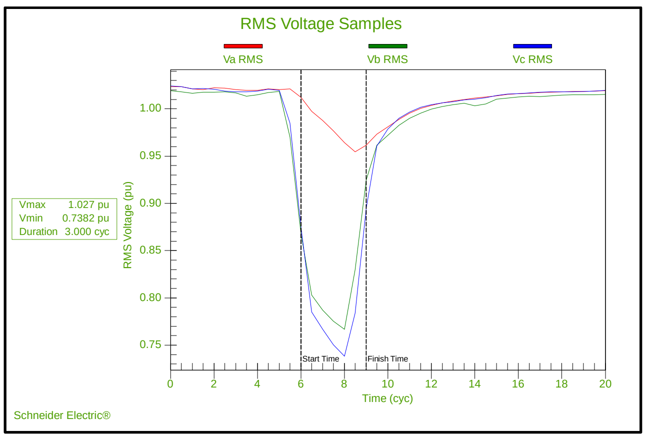

Fig. 5: First 20 Cycles of RMS Voltage from Voltage Sag for Waveforms Samples in Fig. 4

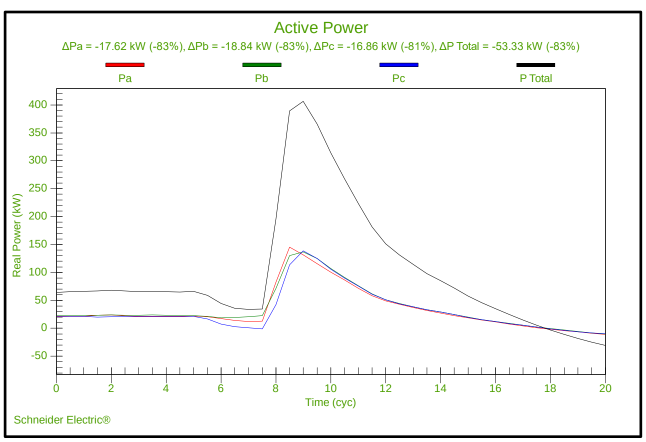

Fig. 6: Active Power from Voltage Sag in Fig. 4

C. *Updating ITIC Chart with Load Impact*

The familiar ITIC Chart of Fig. 3 can be updated to include voltage sag impact. An example of how to accomplish this is to plot the data points in the scatter chart that represent voltage sags with load loss with a different color. More than one color can be used to specify the different amounts of load loss. See Fig. 7.

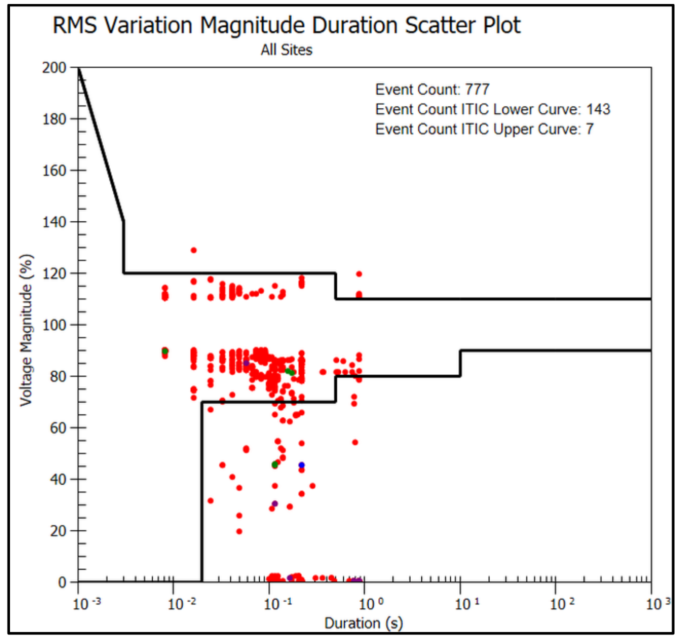

Fig. 7: RMS Variation Magnitude-Duration Scatter Plot Displaying Voltage Sags with Load Loss

V. CONCLUSIONS

Globally, voltage events such as voltage sags and momentary interruptions are the biggest contributor to losses related to power quality issues. Voltage sag events can be external (e.g., originate on the utility) or internal (e.g., originate inside the end-user's facility), anticipated (e.g., starting a large load) or unpredictable (e.g., a system fault), impactful (e.g., loads de-energies) or inconsequential (e.g., system continues to operate with no issues). Recognizing the existence of voltage sags and characterizing their properties (e.g., worst magnitude, duration, etc.) is insufficient; it is important to understand the operational impact to differentiate nuisance events from disruptive events. Ascertaining the level of impact from voltage sag events (regardless of their origin) facilitates easier prioritizing and filtering of alarms, creating and trending historical effects from disruptive perturbations, and determining locations and sizes of mitigation equipment.

VI. AUTHOR BIOGRAPHIES

Daniel Sabin is a Senior Principal Architect and Edison Technical Expert with Schneider Electric in Andover, Massachusetts, USA. Previously, Dan was a Principal Engineer and Software Architect with Electrotek Concepts, where he led the development of the PQView software team for power quality database management & analysis and automatic fault analysis and fault location. He also developed PQDiffractor, which is a widely used viewer for IEEE Std 1159.3 PQDIF and IEEE Std C37.111 COMTRADE files. Dan has a Master of Engineering Degree in Electric Power from Rensselaer Polytechnic Institute in New York. He is a registered professional engineer in Tennessee, an IEEE Fellow, the Vice Chair for Standards for the IEEE PES Transmission & Distribution Committee and a Past Chair of the IEEE PES Power Quality. He chairs the IEEE P1409 Working Group on Power Quality Solutions.

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