# Automatic Analysis of Voltage Sag Waveforms for Origin, Probable Cause, and Impact

**Dan Sabin, P.E., IEEE Fellow**
Distinguished Technical Expert
Schneider Electric Digital Power
dan.sabin@se.com

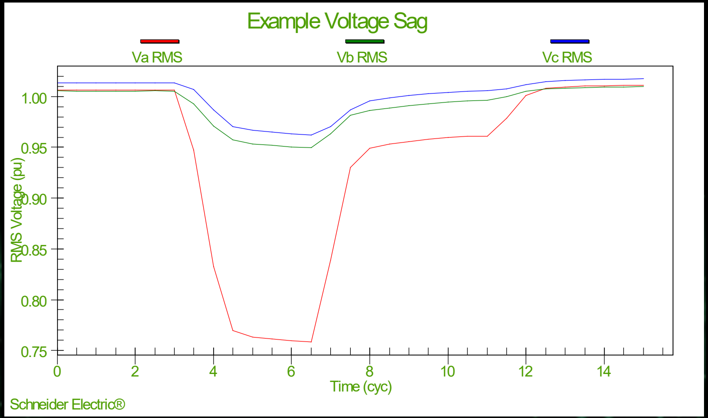
Life Is On | Schneider Electric

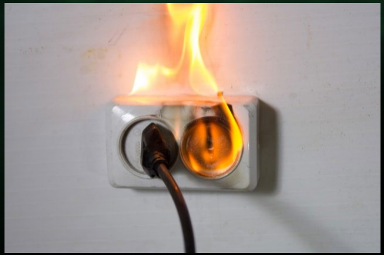
# Agenda

1. What are Voltage Sags
2. Review of IEEE Standards
3. Voltage Sag Analysis
4. Transient Analysis
5. Event Characterization Roadmap

# What are Voltage Sags and Their Impacts?

- Voltage sags are a brief reduction in rms voltage typically caused by electrical faults and load energization.
- IEEE Std 1409-2012 estimates that industrial and commercial customers experience an average of 56 voltage sags each year.
- In 2022, the Electric Power Research Institute (EPRI) published a technical brief that estimates that the total annual cost of PQ events to all U.S. business establishments in may be roughly US$145 to US$230 billion.



Life Is On | Schneider Electric

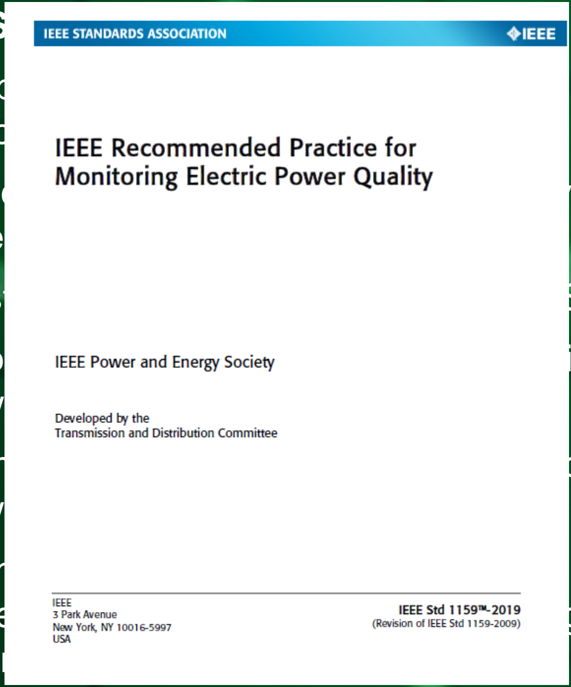
# IEEE Std 1159-2019

**IEEE Std 1159-2019 Overview**

- Recently completed a revision to IEEE Std 1159 Recommended Practice for Monitoring Electric Power Quality
- Describes nominal conditions and deviations from these nominal conditions that may originate within the source of supply or load equipment or that may originate from interactions between the source and the load
- Discusses power quality monitoring devices, application techniques, and the interpretation of monitoring results.
- This standard includes definitions and descriptions of commonly used disturbance categories.

**IEEE S… ories**

- Imp… Mic…
- Os… Me… ,
- Ins… Swell
- Mo… Sw… ion, Sag,
- Te… Sw… on, Sag,
- Lo… Inte… Cu… ined ge,


IEEE STANDARDS ASSOCIATION ◆IEEE

IEEE Recommended Practice for Monitoring Electric Power Quality

IEEE Power and Energy Society

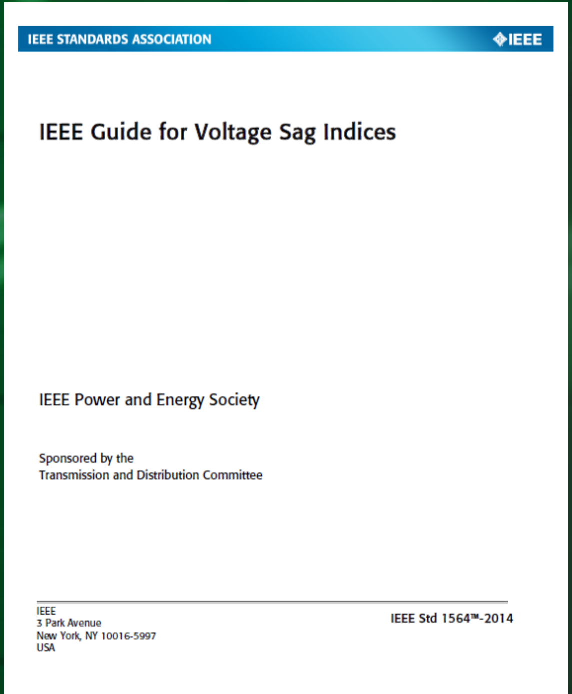
Developed by the
Transmission and Distribution Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 1159™-2019
(Revision of IEEE Std 1159-2009)

# IEEE Std 1564-2014

- IEEE 1564 identifies voltage sag indices and characteristics of electric power and supply systems as well as their calculation methods.
- IEEE 1564 specifies methods to quantify the severity of individual voltage sag events, to quantify the performance at a specific location via single-site indices, and to quantify power system performance via system indices.
- The methods are used in transmission, distribution, and utilization electric power systems.
- Single-site indices defined in IEEE 1564 include System Average RMS Variation Frequency Index (SARFI), voltage sag magnitude vs duration tables, voltage sag energy, and voltage sag severity.


IEEE STANDARDS ASSOCIATION IEEE

IEEE Guide for Voltage Sag Indices

IEEE Power and Energy Society

Sponsored by the
Transmission and Distribution Committee

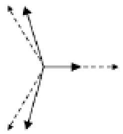
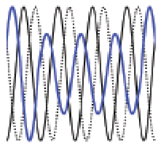
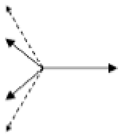
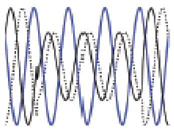
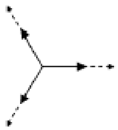
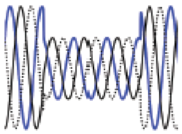
IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 1564™-2014

# IEEE Std 1668-2017

- *Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 V*.
- Developed by the Power Systems Engineering Committee of the IEEE Industry Applications Society (IAS)
- Specifies voltage sag ride-through performance recommendations and compliance testing procedures for low voltage electrical equipment.
- Defines testing procedures and test equipment requirements for single-phase, two-phase, and three-phase, balanced and imbalanced voltage sags.
- Being considered by the IEEE P1564 task force while revising IEEE Std 1564-2014.

Table 8—Recommended Type I, Type II, and Type III voltage-sag classifications [B1]

| Voltage-sag type | Description[a] | Vector diagram | Waveform |
|---|---|---|---|
| Type I | This is a voltage sag in which a drop in voltage takes place mainly in one of the phase-to-ground voltages. $\bar{U}_a = \bar{V}$ $\bar{U}_b = -\frac{1}{2}\bar{V} - \frac{1}{2}j\bar{E}\sqrt{3}$ $\bar{U}_c = -\frac{1}{2}\bar{V} + \frac{1}{2}j\bar{E}\sqrt{3}$ |  |  |
| Type II | This is a voltage sag in which a drop in voltage magnitude takes place mainly in one of the phase-to-phase voltages. $\bar{U}_a = \bar{E}$ $\bar{U}_b = -\frac{1}{2}\bar{E} - \frac{1}{2}j\bar{V}\sqrt{3}$ $\bar{U}_c = -\frac{1}{2}\bar{E} + \frac{1}{2}j\bar{V}\sqrt{3}$ |  |  |
| Type III | This is a voltage sag in which there is a drop in voltage magnitude that is equal for the three voltages. $\bar{U}_a = \bar{V}$ $\bar{U}_b = -\frac{1}{2}\bar{V} - \frac{1}{2}j\bar{V}\sqrt{3}$ $\bar{U}_c = -\frac{1}{2}\bar{V} + \frac{1}{2}j\bar{V}\sqrt{3}$ |  |  |

# IEEE 1564 SARFI: System Average RMS Variation Frequency Index

**SARFI-X**

- SARFI-90: Count or rate of voltage sags and interruptions with retained voltage
  below 90% of voltage reference
- SARFI-110: Count or rate of voltage swells with retained voltage above 110% of voltage reference

**SARFI-Curve**

- SARFI-ITIC: Count or rate of voltage sags and interruptions with retained voltage and duration below the lower portion of the ITI (CBEMA) Curve
- SARFI-SEMI: Count or rate of voltage sags and interruptions with retained voltage and duration below the lower portion of the SEMI F47 Curve

- Temporal Aggregation, Monitor Availability

| Time Stamp | Retained Voltage | Duration |
|---|---|---|
| 2000-07-01 09:48:52 | 73% | 9 c |
| 2000-07-01 09:50:16 | 73% | 9 c |
| 2000-07-07 14:20:12 | 0% | 82 c |
| 2000-07-10 15:55:23 | 13% | 100 c |
| 2000-07-21 09:48:52 | 0% | 2.6 s |
| 2000-08-08 07:35:02 | 49% | 34 c |
| 2000-09-02 08:30:28 | 0% | 41 s |
| 2000-09-08 10:30:40 | 59% | 40 c |

| Index | Count | Events per 30 Days |
|---|---|---|
| SARFI-90 | 8 | 2.61 |
| SARFI-70 | 6 | 1.96 |
| SARFI-50 | 5 | 1.63 |
| SARFI-10 | 3 | 0.98 |

# Improved PQ Applications

## Understand Voltage Variations with SARFI Index

A customer and a utility may agree upon a contract of how many voltage sags and what level of voltage sags is acceptable. SARFI Report helps both the customer and utility to understand the count of the voltage variations and fulfill the contract

**Supply**

Utility customers may run SARFI index at each of their customers to monitor and benchmark voltage variations, such as voltage sag, among their customers

**Demand**

In order to know the number of voltage variations, such as voltage sag, from their utility, demand customers may compute SARFI index at each of their plants at the service entrance

Schneider Electric

SARFI Report

1/1/2019 12:00:00 AM - 1/1/2020 12:00:00 AM (Server Local)

| Source | SARFI | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 10 | 50 | 70 | 80 | 90 | 110 | 120 | 140 | ITIC | SEMI |
| Keating.Main_7650 | 1 | 2 | 4 | 14 | 72 | 0 | 0 | 0 | 4 | 1 |
| Keating.Panel_B | 1 | 1 | 4 | 14 | 86 | 0 | 0 | 0 | 5 | 1 |
| Keating.Panel_E | 1 | 1 | 4 | 14 | 86 | 0 | 0 | 0 | [illegible] | [illegible] |
| Keating.Panel_M | 1 | 1 | [illegible] | [illegible] | [illegible] | 0 | 0 | 0 | [illegible] | [illegible] |
| Keating.Panel_M_Left | 0 | 1 | 3 | 28 | 63 | 0 | 0 | 0 | [illegible] | [illegible] |
| Keating.Panel_M_Right | 0 | 0 | 4 | 23 | 61 | 0 | 0 | 0 | [illegible] | [illegible] |
| Keating.Panel_R | 1 | 1 | 4 | 14 | 86 | 0 | 0 | 0 | 5 | 1 |
| Keating.RTU_5 | 1 | 1 | 4 | 14 | 86 | 0 | 0 | 0 | 5 | 1 |
| Keating.Server_Room_IT_Load | 1 | 1 | 1 | 10 | 38 | 0 | 0 | 0 | 2 | 2 |

SARFI-X

Curve

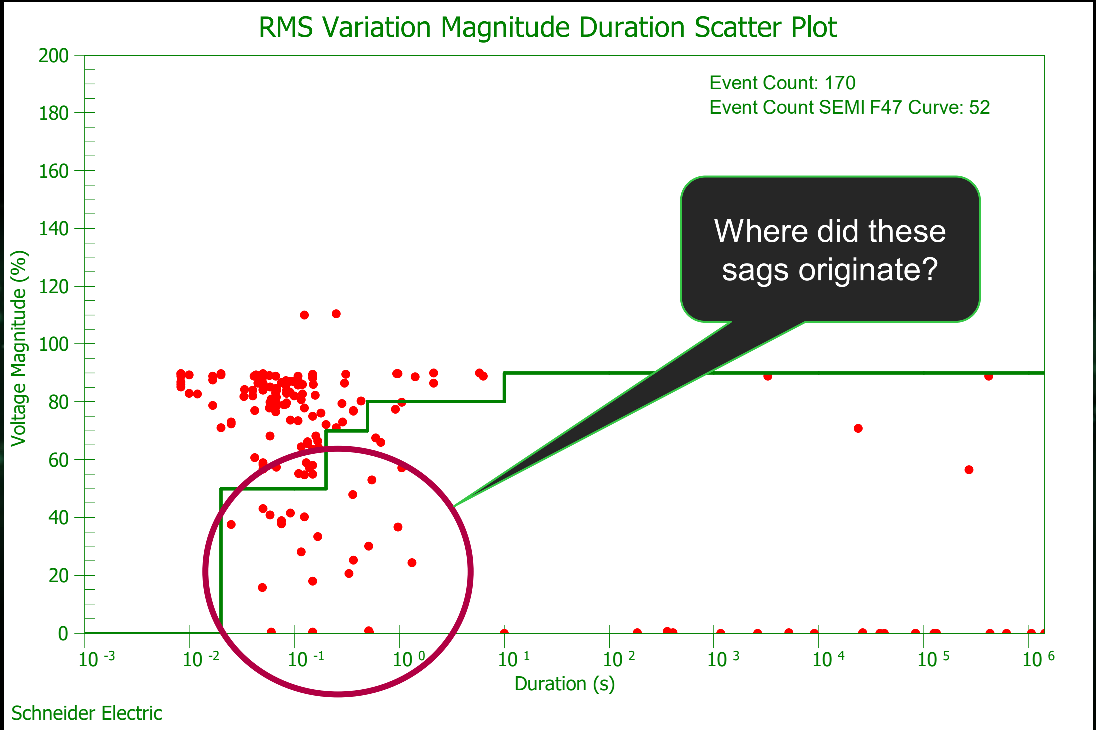
SARFI-

Generated on: 7/14/2020 2:46:17 PM

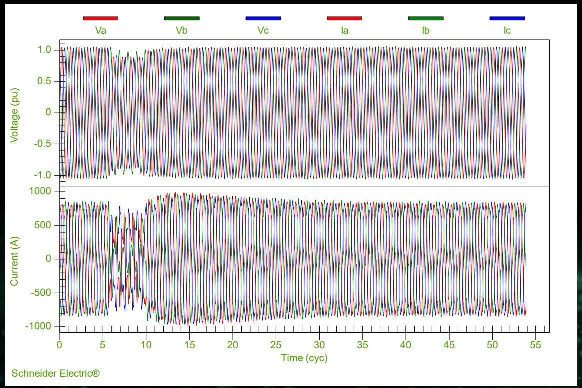
Page 1 of 1

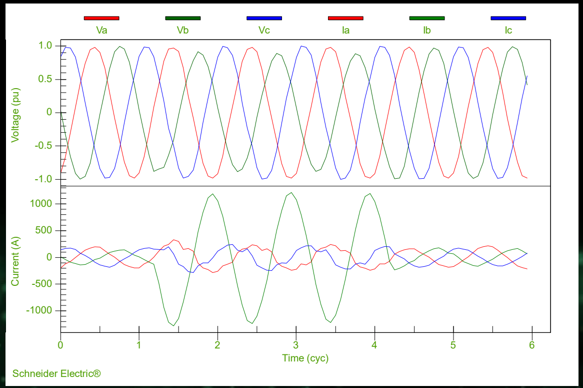
# Analysis of Voltage Sags using Voltage Only

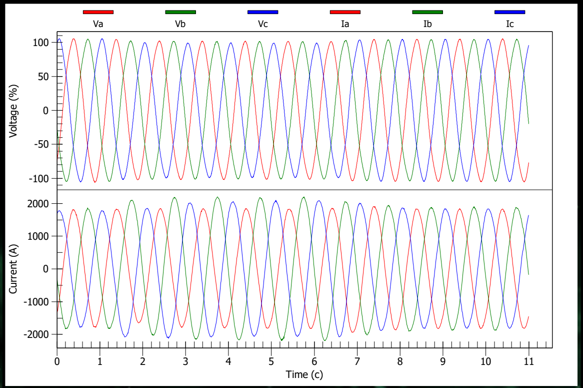
- Voltage Magnitude
- Event Duration
- IEEE Std 1159 Disturbance Category
- IEEE Std 1668 Sag Type
  - Type I: Single-Phase Sag
  - Type II: Line-Line Sag
  - Type III: Three-Phase Sag
- ITIC Charts/SEMI F47 Charts



# Disturbance Direction



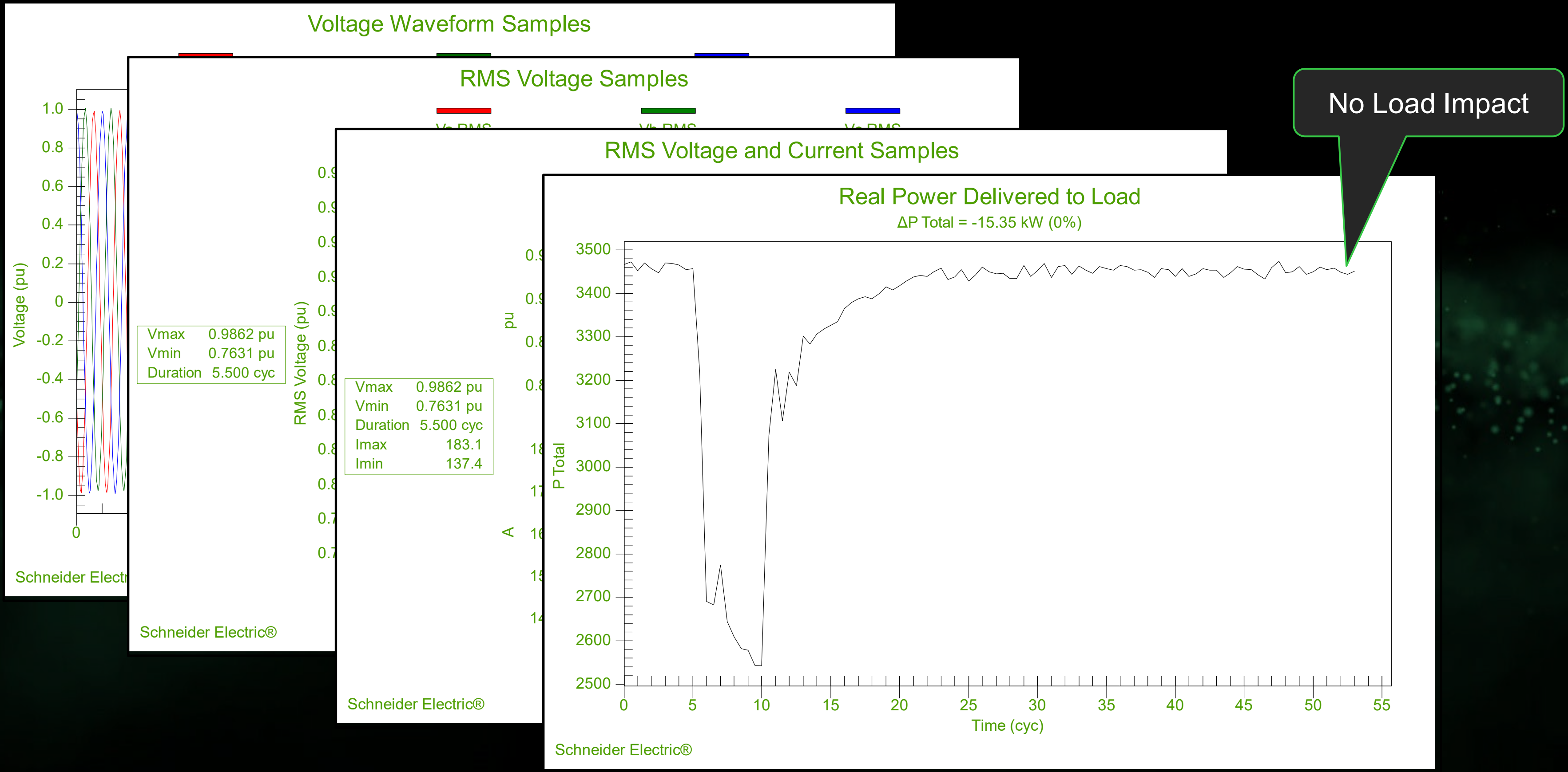




Upstream

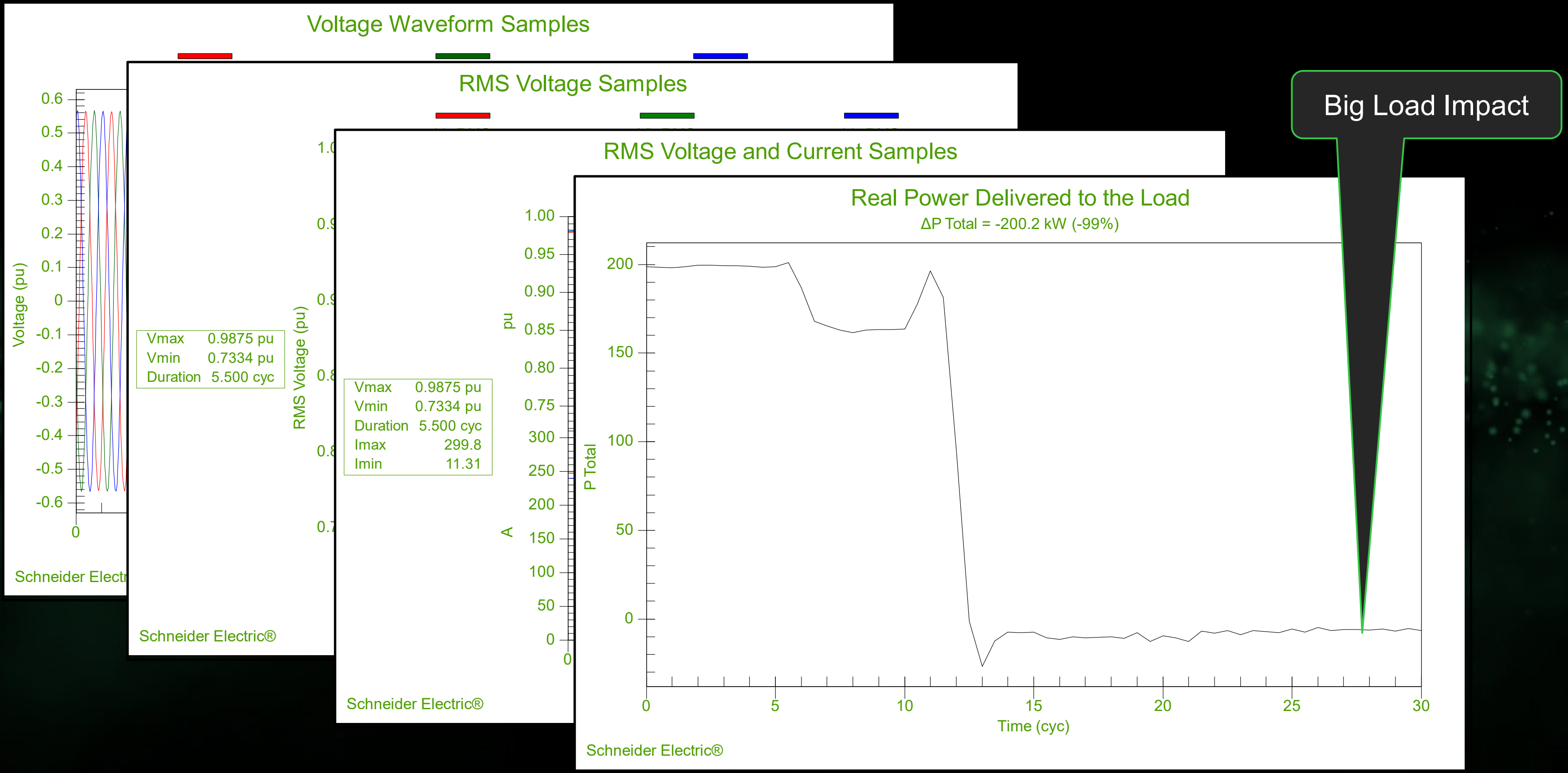
Downstream

Downstream

# Voltage Sag Example #1



# Voltage Sag Example #2



# Automatic Voltage Sag Analysis

## Voltage Only

- Voltage Magnitude
- Event Duration
- IEEE Std 1159 Disturbance Category
- IEEE Std 1668 Sag Type

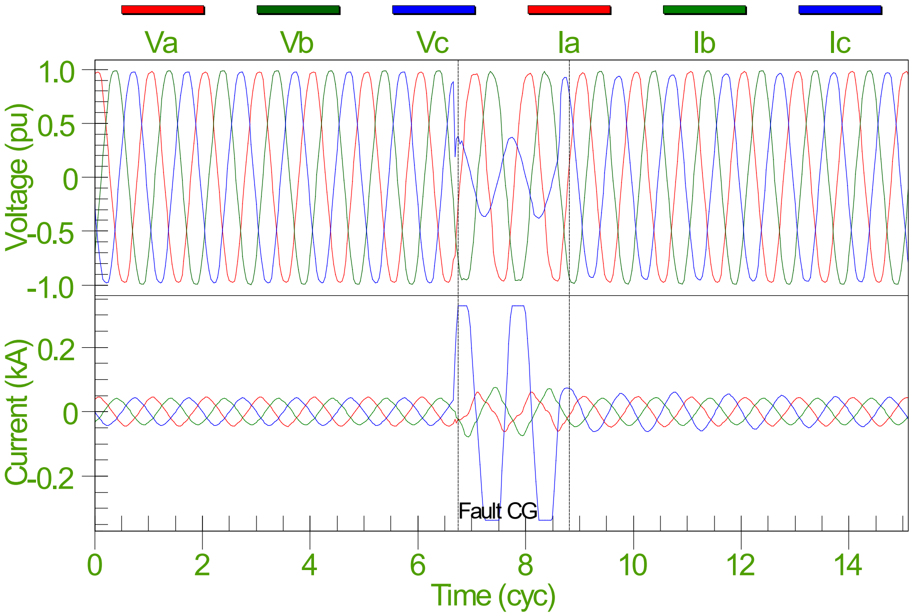
## Voltage with Current

- Disturbance Direction
- Load Impact

# Downstream Single-Phase Fault

## Type I Instantaneous Voltage Sag - Downstream Single-Phase Fault

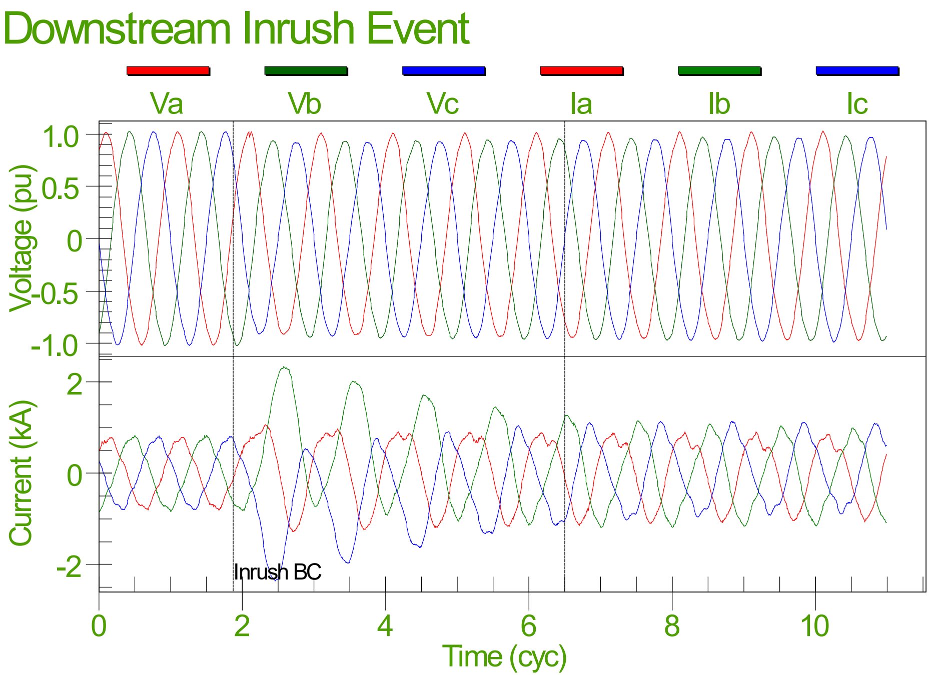
| | |
|---|---|
| Max Voltage | 1.027 pu |
| Min Voltage | 0.3522 pu |
| Max Current | 0.2808 kA |
| Min Current | 0.02693 kA |
| Load Change | -10.43 kW |
| Load Change | -2.67% |
| RMS Duration | 2.813 cyc |
| Positive-Sequence Rotation | True |




Schneider Electric®

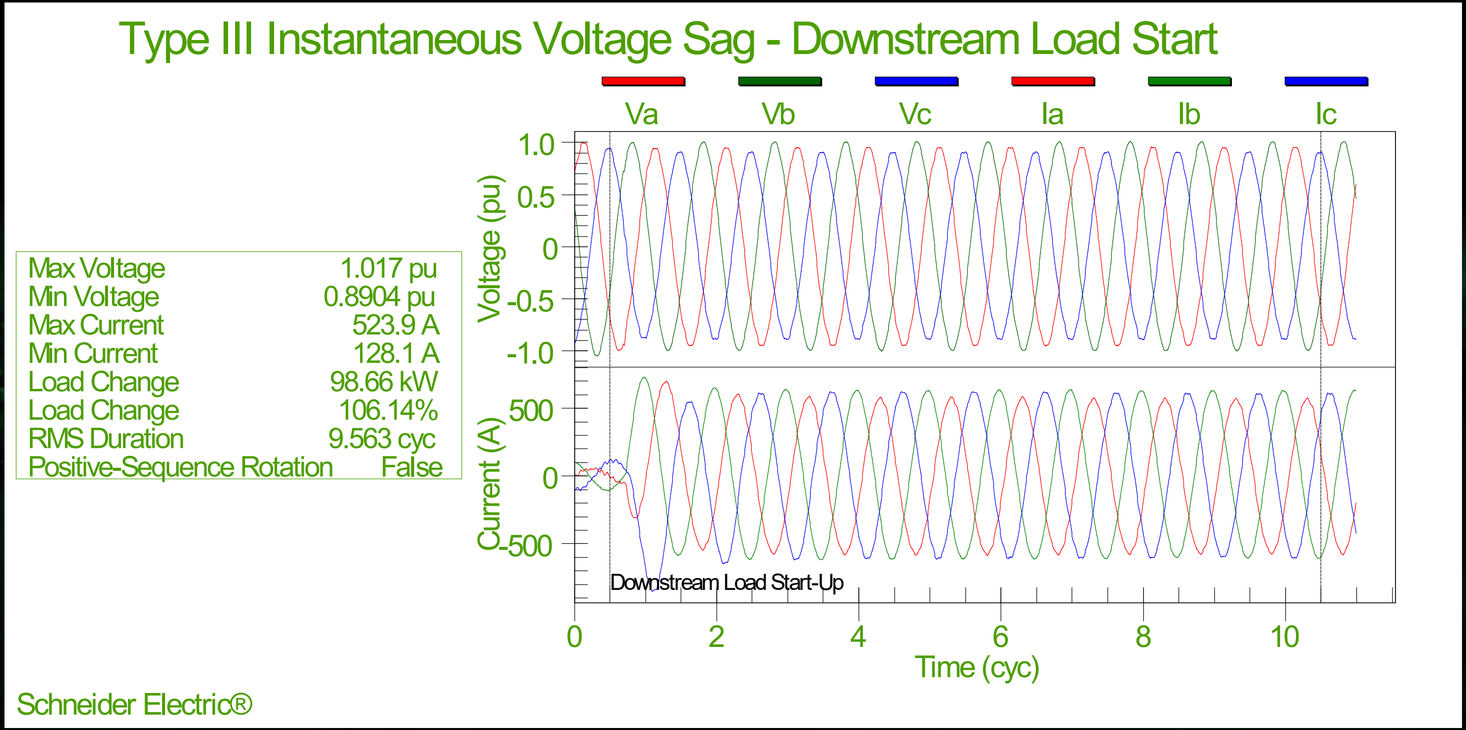
# Downstream Transformer Energizing Inrush

| | |
|---|---|
| Max Voltage | 1.018 pu |
| Min Voltage | 0.9100 pu |
| Max Current | 1.353 kA |
| Min Current | 0.5312 kA |
| Load Change | 41.66 kW |
| Load Change | 0.18% |
| RMS Duration | 0 cyc |
| Positive-Sequence Rotation | True |




Schneider Electric®

# Downstream Three-Phase Load Start

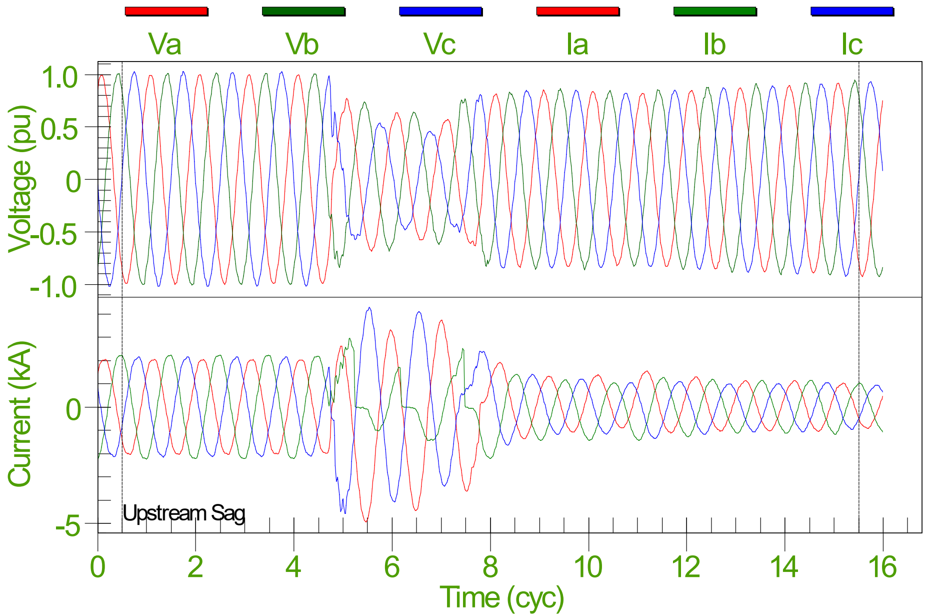


# Upstream Voltage Sag

## Causes Downtime to Downstream Load

### Type III Instantaneous Voltage Sag - Upstream Voltage Sag

| | |
|---|---|
| Max Voltage | 1.009 pu |
| Min Voltage | 0.4698 pu |
| Max Current | 3.083 kA |
| Min Current | 0.6630 kA |
| Load Change | -914.8 kW |
| Load Change | -62.73% |
| RMS Duration | 10.44 cyc |
| Positive-Sequence Rotation | True |

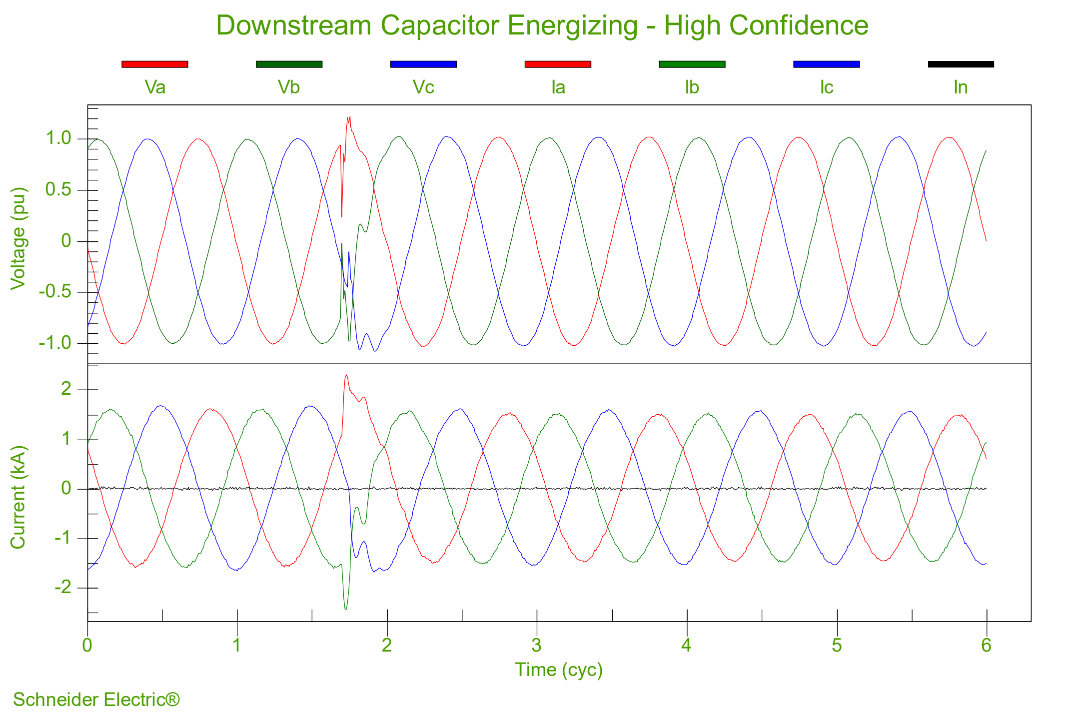



Schneider Electric®

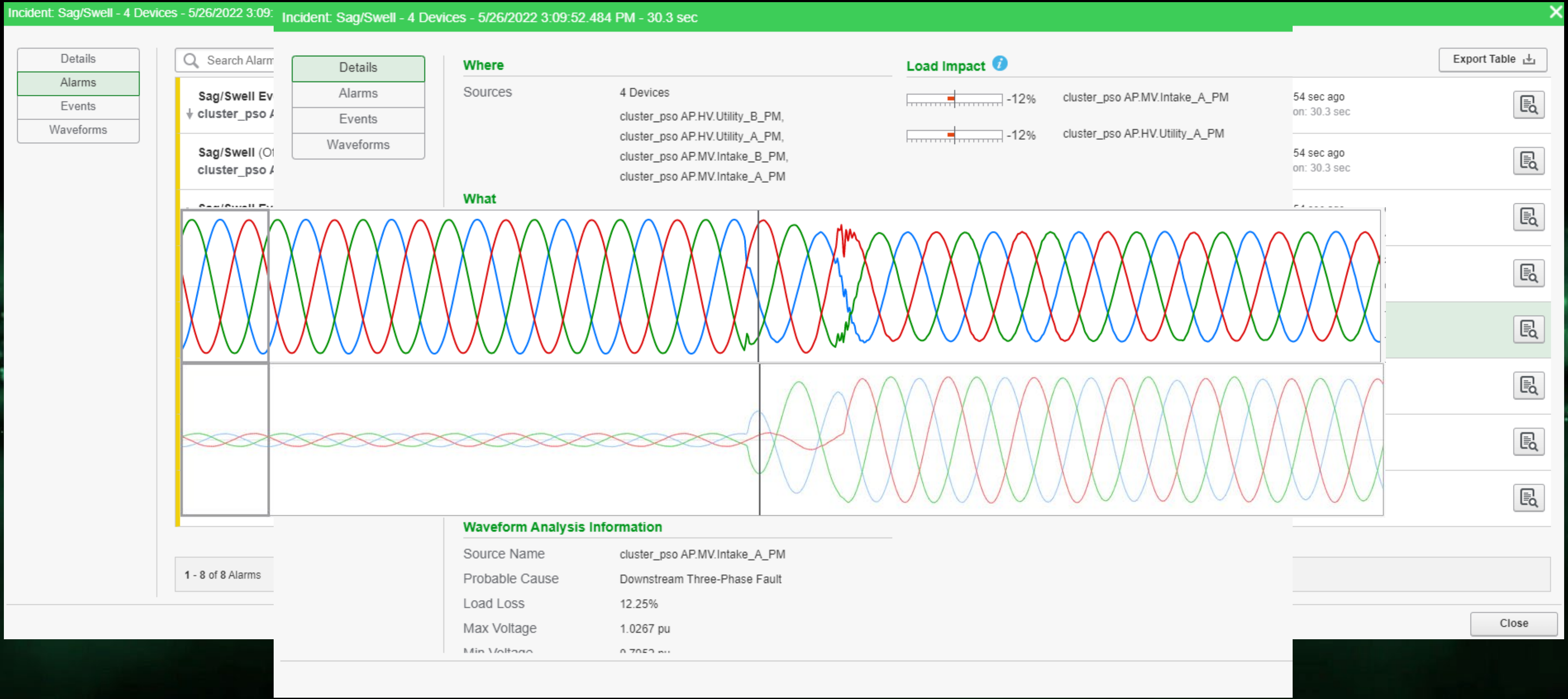
# What about transients?

## Oscillatory Transient:

- A sudden, nonpower frequency change in the steady-state condition of voltage, current, or both, that includes both positive and negative polarity values.
- An oscillatory transient consists of a voltage or current whose instantaneous value changes polarity rapidly multiple times and normally decaying within a fundamental-frequency cycle.



# Example Application with Advanced Waveform Analysis



# Summary of Waveform Analysis Information

- Probable Cause: Downstream Single-Phase Fault, Downstream Two-Phase Fault, Downstream Three-Phase Fault, Downstream Inrush Event, Upstream Voltage Sag, Downstream Capacitor Charging Event, Upstream Charging Event
- Real Power: First Cycle and Last Cycle
- Load Change: Difference between kW of Last Cycle from kW from First Cycle (negative for events with a load impact)
- Load Loss or Load Gain in Percent
- Min/Max Voltage in per unit
- Min/Max Current in amps
- RMS Duration: Duration of Voltage Sag, Swell, or Interruption in Cycles

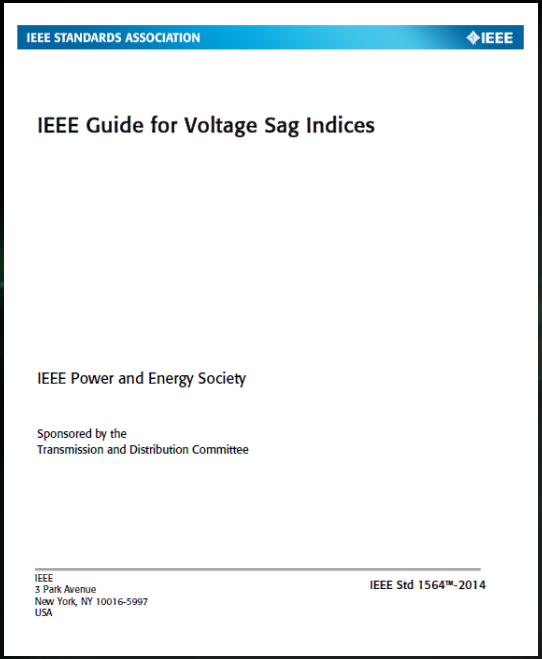
**Waveform Analysis Information**

| | |
|---|---|
| Probable Cause | Upstream Voltage Sag |
| Load Loss | 0.87 % |
| Load Change | -749.93 kW |
| Max Voltage | 1.063 pu |
| Min Voltage | 0.01917 pu |
| Max Current | 174.2 A |
| Min Current | 26.17 A |
| RMS Duration (Cycles) | 342.2 c |
| Real Power - First Cycle | 865.21 kW |
| Real Power - Last Cycle | 115.27 kW |

# Recommendation: Enhance IEEE Std 1564

- The IEEE PES Transmission & Distribution Committee just received approval from IEEE Standards Association to revise IEEE Std 1564. The revision work kicked off in July 2021.
- Indices based on:

| Today | | Tomorrow |
|---|---|---|
| Voltage Magnitude & Duration | → | Voltage Magnitude & Duration + Sag Type + Disturbance Direction + Load Impact |


IEEE STANDARDS ASSOCIATION
IEEE

IEEE Guide for Voltage Sag Indices

IEEE Power and Energy Society

Sponsored by the
Transmission and Distribution Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 1564™-2014

# Recommendation: Use Natural Language PQ Event Descriptions in Software using Voltage and Current Waveform Analysis

Upstream Voltage Sag — **98% Load Loss**

Downstream Inrush Event — **25% Load Loss**

Downstream Load Start — **Load Gain**

# Waveform Event Characterization Roadmap

**Electrical Faults**

- Permanent Faults
- High-Impedance Faults
- Fuse Operations

**Incipient Equipment Failure**

- Subcycle Cable Faults, Load Tap Changers, Fuses, Hinged Relays, PT/VT, Breakers

**Capacitor Bank Energizing**

- Identification of Normal Energizing, Back-to-Back Energizing
- Abnormal Energizing: Magnification, Restrike, Blown Fuses
- Characteristics for Analytics: Power Factor, Imbalance, Harmonic Resonance

**Load Startup**

- Generic Load-Startup
- Transformer Energizing Inrush
- Motor Starting

**Line Energizing**

- Aerial/overhead line energizing
- Cable line energizing

**Upstream Events**

- Upstream Voltage Sags
- Backfed Faults

**Converter Operation**

- 6-Pulse, 12-Pulse, 18-Pulse, Notching

**DER Interaction**

- Load Rejection Overvoltage

**Other Characterization**

- IEEE 1159.3 Disturbance Categorization
- IEEE 1668 Sag Type and Impacted Loads
- Characteristics Needed for Voltage Sag Mitigation (DVR)

# Questions ?

Life Is On | Schneider Electric