Workshop:
Applying the New IEEE Std. 1668

Event Sponsored by IEEE and the Electric Power Research Institute

April 23, 2018
10:00 AM to 5 PM

Welcome and Kickoff

Bill Howe, PE, CEM
IEEE PES SCC-22 Chair

Workshop Agenda

- Welcome and Kick-Off, Bill Howe, Chair PES SCC-22
- Scope, Purpose, and Normative References, Alden Wright, 1668 WG
- Laying the Groundwork, Jim Rossman, 1668 WG
- Primer on Voltage Sags, John Mentzer, 1668 WG
- Recommended Test Requirements, Mark Stephens, 1668 WG
- Test Procedures and Guidelines, Mark Stephens, 1668 WG
- Test Equipment Requirements, Scott Bunton
- Certification and Test Reports, Scott Bunton
- Closing Remarks, Bill Howe, Chair PES SCC-22

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Applying the New IEEE Std. 1668

"Scope, Purpose, and Normative References"

Presented by: Alden Wright, PE, CEM, CP EnMS
April 23, 2018

Summary of What is Inside….

- 90 Pages front to back.
- Contains a significant amount of newly created content from working group members.
- References existing work from ANSI, CIGRE, EPRI, IEC, IEEE, and SEMI.
- In-depth voltage sag primer included
- Voltage sag characteristics and descriptions built on findings from CIGRE C4.110 working group.
- Voltage sag test levels an extension of SEMI F47 (Type I and Type II) and includes 3-phase (Type III) sags.
- Test Procedures and Guidelines thoroughly document various test methodologies and approaches.
- Defines test equipment requirements.
- Defines certification and test report requirements.

Contents

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IEEE 1668: Scope

- IEEE Std 1668-2017 is ***a non-industry-specific*** recommended practice for voltage-sag ride-through performance and compliance testing for all electrical and electronic equipment connected to low-voltage power systems that can experience malfunction or shutdown as a result of reductions in supply voltage lasting less than one minute.
- The recommended practice includes defining minimum voltage-sag immunity requirements based on actual voltage-sag data.
- It includes a clause dedicated to the detailed analysis of voltage sags experienced by end users provides insight into real-world voltage sags.
- Testing procedures and test equipment requirements are clearly defined within this document to reflect this electrical environment, including single-phase, two-phase, and three-phase balanced and unbalanced voltage sags.
- This recommended practice also defines certification and test reporting requirements, including voltage-sag ride-through equipment characterization.

IEEE 1668: Purpose

- Clearly define test methods and ride-through performance for determining the sensitivity of electrical and electronic equipment to voltage sags.
- Provides the foundation for both test methods and performance criteria, aligning themselves as closely as possible to the end user's electrical environment.
- Defines the characteristics in terms of the depths/magnitudes, durations, phase angles, and vectors of voltage sags required to relate to real-world voltage sags.
- Shows how different voltage-sag testing methods can be used to simulate real-world sags.
- Allows end users to use the recommended practice in their purchase specifications to help ensure the required level of equipment performance.
- Evaluates voltage-sag criteria as a performance benchmark for existing equipment.
- Provides a benchmark that can be used to identify equipment that has enhanced ride-through characteristics.

IEEE 1668: Limitations

- Limited to the testing of equipment to voltage sags.
  - Other power disturbances— including swells and harmonic and high-frequency impulsive transient events—are not within the scope of this document.
- Assumes a baseline electrical environment in compliance with ANSI C84.1-2011 Range A for steady-state utilization voltage and IEEE Std 519™-2014 for harmonics.
- Proper application of this recommended practice does not require any filtering of the harmonics during the testing or analysis to achieve accurate quantification of ride-through performance.
- IEEE 1668 is a performance specification and does not address safety issues.
  - It should not supersede any safety requirements.
- Does not override applicable international, national, and local codes.
- Does not address product quality that may or may not result in the application of the required immunity test levels.

IEEE 1668: Normative References

- ANSI C84.1-2011, American National Standard for Electric Power Systems and Equipment—Voltage Ratings(60 Hertz).
- IEC 61000-4-34, Electromagnetic compatibility (EMC)—Part 4-34: Testing and measurement techniques— Voltage dips, short interruptions and voltage variations immunity tests for equipment with mains current more than 16 A per phase.
- IEEE Std 519™-2014, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.
- SEMI F47-0706, Specification for Semiconductor Processing Equipment Voltage-Sag Immunity.

Applying the New IEEE Std. 1668

"Laying the Groundwork"

Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 V

Presented by: Jim Rossman PE,
IEEE 1668 Working Group Member
April 23, 2018

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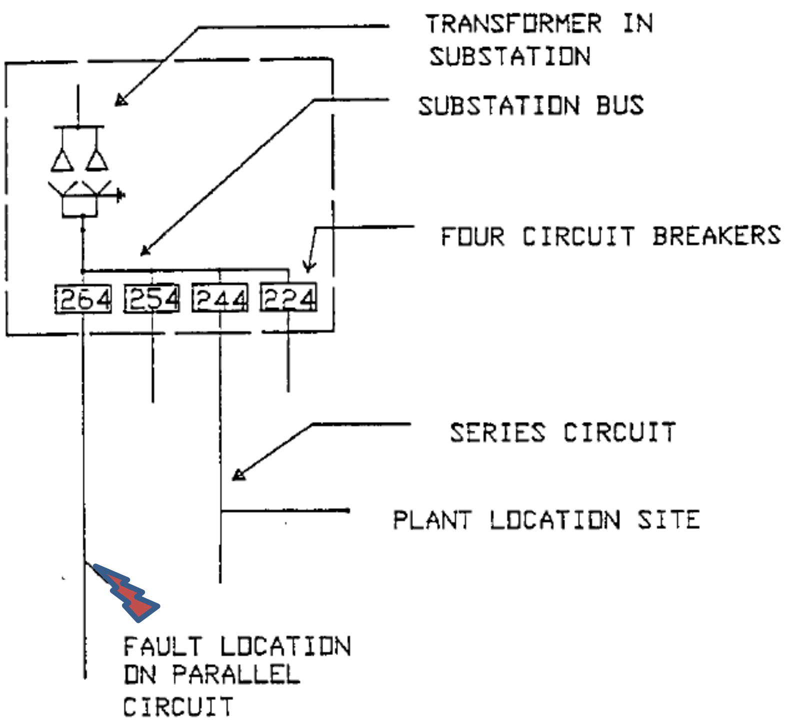
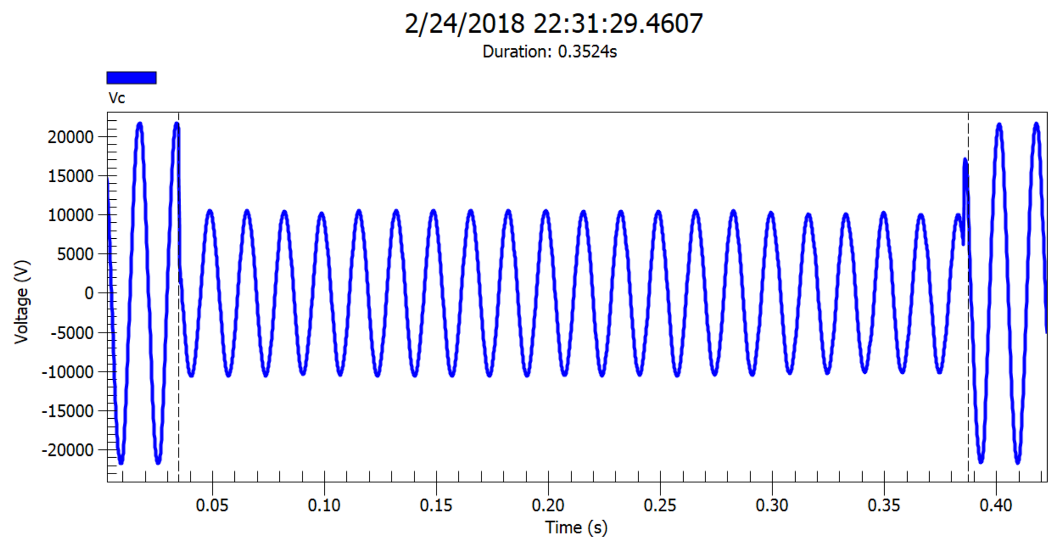
WHAT IS A VOLTAGE SAG?

Typically, A Fault Occurs Somewhere (Besides Your Circuit)
You Don't See an Interruption
But You See a Voltage Sag Until The Fault Is Cleared





Summary of Voltage Sag Shown Above:

Voltage Sag – 49% of Nominal

Time – 0.35 sec. – 21 cycles

Definition of Voltage Sag – Shown in Voltage RMS Starts at 90% of Nominal and Ends at 90% of Nominal

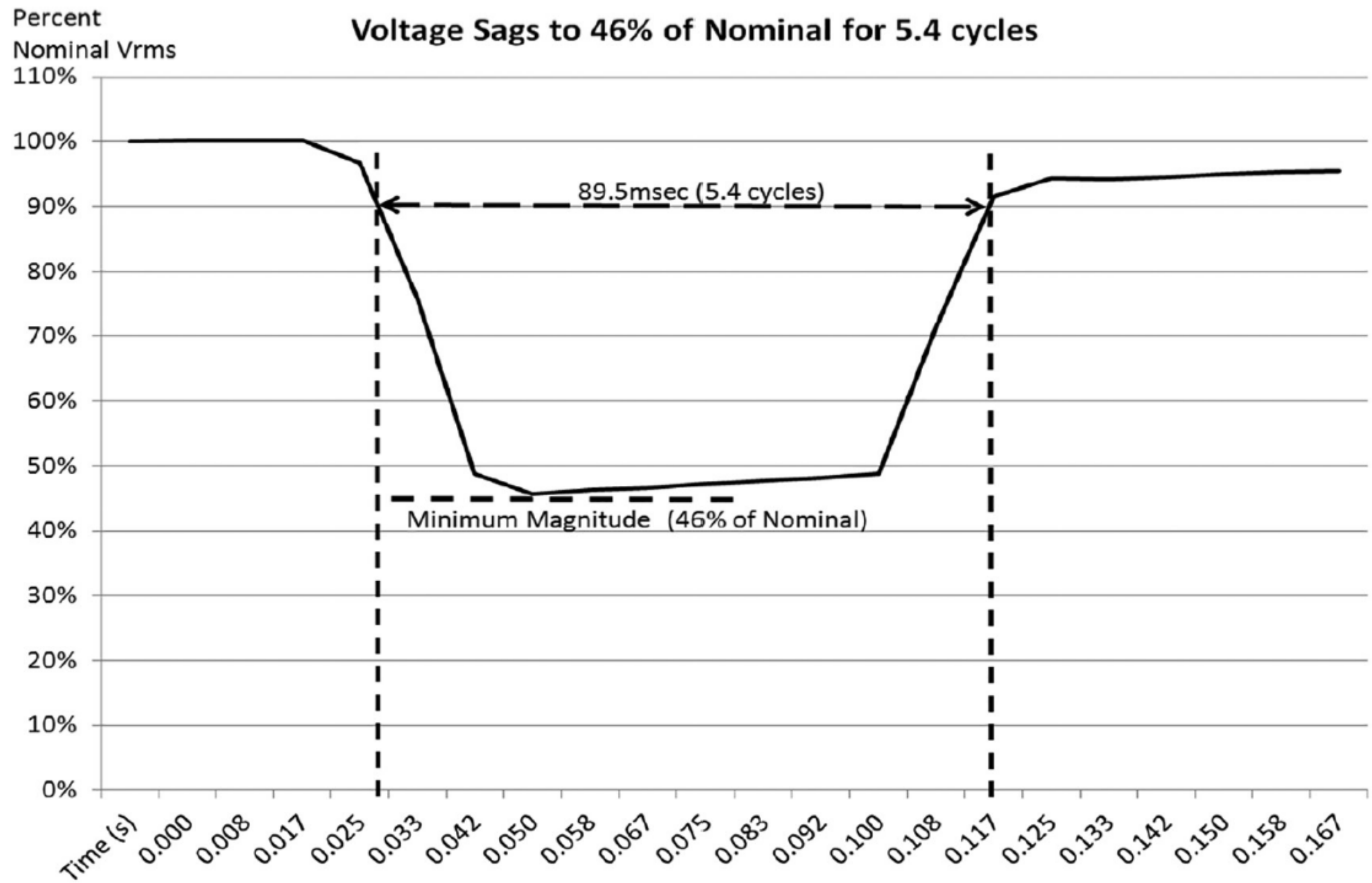


Figure 1—Single-phase voltage sag (instantaneous voltage rms plot)

WHY DO WE CARE ABOUT VOLTAGE SAGS?

Voltage Sag Downtime Issues Are Primarily Related to Industrial Production

- Severe Voltage Sags Stop Industrial Equipment
- The Equipment Stoppage Can Occur In a Manner
  - Where Equipment is Damaged
  - Production is interrupted
  - In-process product is damaged resulting in scrap
- In Automated Facilities Production Downtimes May be as Long as Production Shifts or Even Days
- A Voltage Sag Event May cause the facility to miss the Production Goal & Profitability for the Month!

COST OF INTERRUPTIONS AND VOLTAGE SAGS TO INDUSTRY

Presentation at EPRI PQA/ADA 2008 - Estimating Interruptions and Voltage Sag Cost for Industry - $11-$12 Billion/Year Cost Additional Cost Per Operating kWH -1.2 cents/kWH (2008 Estimate)

Utility Distribution-Fed Small-Load Industrial Cost Estimate	$8,347,001,789
Industrial Disturbance Cost/kWH - Small Industries in US	$0.012

Utility Distribution- Fed Large-Load Industrial Cost Estimate	$3,642,291,041
Industrial Disturbance Cost/kWH - Large Industries in US	$0.011

Total Industrial Downtime Estimate for 2008 $ 11-12 Billion/Year

$11 Billion Annual Downtime Cost Estimate for US Manufacturing Customers Due to Utility Short-Duration Power Interruptions and Voltage Sags
James B. Rossman, P.E., **EPRI Power Quality Applications (PQA) and Advanced Distribution Automation (ADA) 2008 Joint Conference and Exhibition**

Presentation at EPRI PQA/ADA 2008 - Estimating Interruptions and Below 50% of Nominal Voltage Sag Cost for Industry – $7,000 Cost Per MW Impacted (2008 Estimate)

Small Industry – Estimated at 66.6% of Overall Industry Usage

	Interruption ≤10%	Severe Vsag >10≤50%	Moderate Vsag >50≤70%	Mild Vsag >70≤85%
Weighted Estimate	$6,683/MW	$5,183/MW 75% Interruption	$2,271/MW	$1,135/MW 50% Mod. Vsag

Industry
Food
Beverage/Breweries/Wine/Tobacco
Textile Product Mills
Apparel Mfg
Leather and Allied Products
Wood Products
Priniting
Plastics/Rubber
Clay/Glass/Cement/Concrete
Fabricated Metal Products
Computer/Electonic Products
Electric Equipment, Appliance
Furniture
Misc Manufacturing

Large Industry – Estimated at 33.3% of Overall Industry Usage

	Interruption ≤10%	Severe Vsag >10≤50%	Moderate Vsag >50≤70%	Mild Vsag >70≤85%
Weighted Estimate	$10,503/MW	$8,402/MW 80% Interruption	$3,562/MW	$1,781/MW 50% Mod. Vsag

Industry
Machinery
Textile
Paper Manufacturing
Petroleum/Coal
Chemical
Primary Metals/Steel/Iron/Aluminum
Transportation Equipment/Vehicles

From 2008 presentation summary *… its shows the need to keep working on the controls-level solutions and support of* ***IEEE 1668 compatibility efforts*** *to allow industries to ride-though mild Vsags.*

IEEE 1668 APPROACH TARGETING BOTH UTILITIES AND INDUSTRY

IEEE 1668 Draws "Line in Sand" With Targeted Responsibilities for Industries, Electrical Product Manufacturers and Utility Suppliers

Residual voltage in percent nominal	Duration at 60 Hz
50%	3 cycles
70%	6 cycles
80%	120 cycles

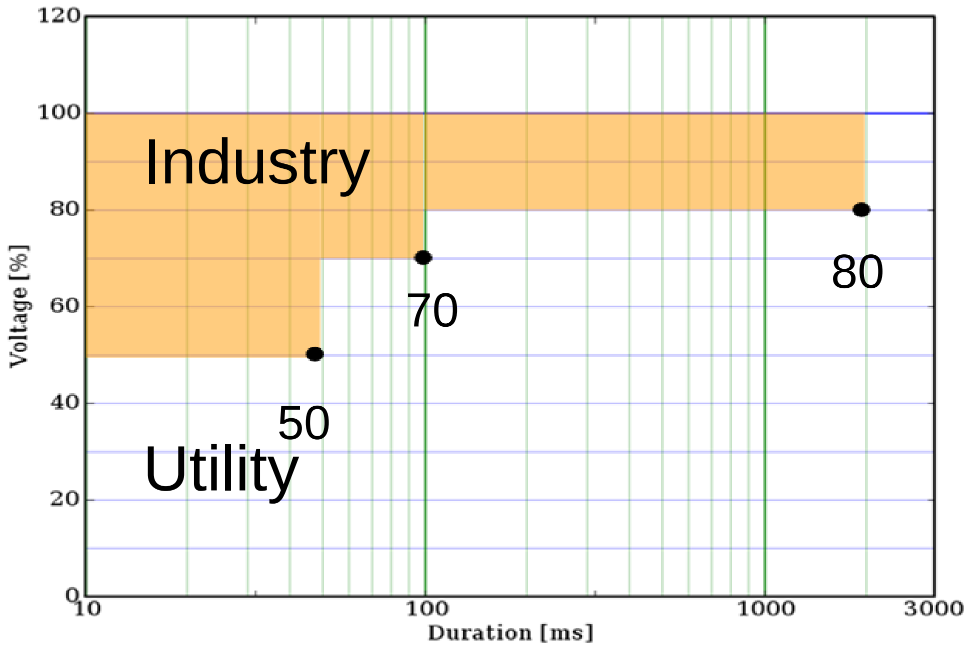


Figure 23—Recommended Type III test levels

Focus:

Industry:

Work on industrial systems to get them to ride-through voltage sags in brown area

Electric Manufacturers:

Provide a benchmark for design of electrical product to support the Industry Focus ride through target.

Utility:

Try to minimize depth & duration of voltage sag events (below brown area)

INDUSTRIAL COMMITMENT EXAMPLES

Example for Industry: Hardening Controls

Getting Under the Brown Area

By adding hardening components the paint oven controls trip-off levels were reduced from 77% of nominal to 50%

More Discussion On This Later

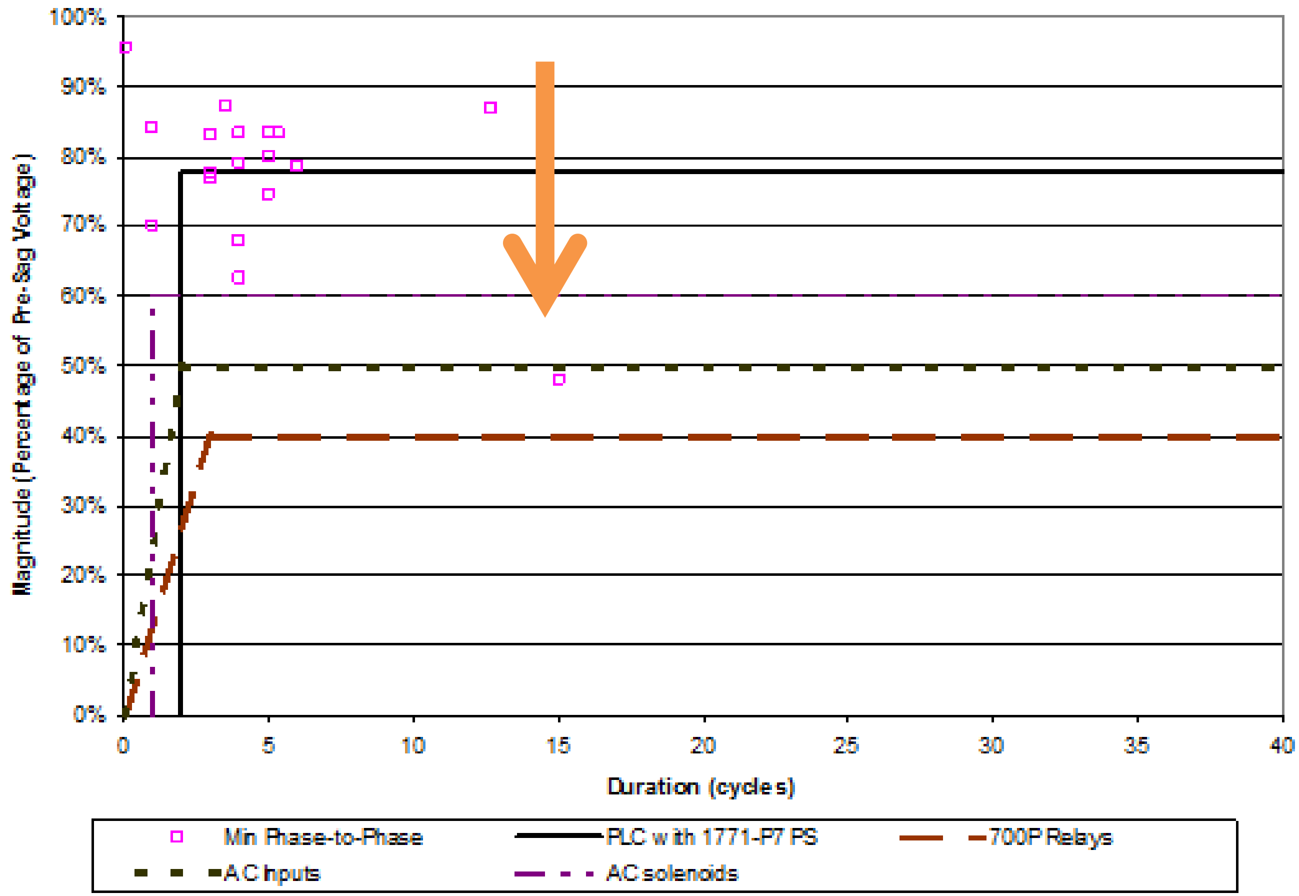


Figure 9
Composite Voltage Sag Ride-Through Curve for the Paint Oven System

Example for Industry: Custom - Modified Adjustable Speed AC Drives – 1990 Specification - 50% Of Nominal

Getting Under the Brown Area

IEEE 1668 Push-- to Make the Custom-Level a Standard-Level

	Phase Voltage Relative to 100% of Nominal Voltage		
	Phase A	Phase B	Phase C
Balanced 3-phase, 30-cycle voltage sag	50%	50%	50%
Unbalanced 3-phase, 30-cycle voltage sag (Condition 1)	88%	88%	33%
Unbalanced 3-phase, 30-cycle voltage sag (Condition 2)	80%	70%	50%

Source: Plant Engineering Consultants, Incorporated

NEW PLANT SITE DESIGN CONSIDERATIONS

UTILITY SYSTEM VOLTAGE SAG FUNDAMENTALS

System Faults and Voltage Sags

- Some faults are internal to an industrial facility
- But, the majority of voltage sags are the result of faults on the power supply system
- Protective relaying plays a critical role in the duration of the resulting voltage sags.
  - Breakers - require approximately 3 to 6 cycles to clear a fault
  - Protective relays detect faults and they signals breakers to operate:
    - Transmission Systems – 1/2 to 10 cycles (sometimes as long as 20 cycles)
    - Distribution Systems – 1/2 to 120 cycles
- The overall sag duration time is a combination of relay detection time and breaker operation time.

Fault Clearing (Voltage Sag Duration) Times May Be Limited By Speed of Breaker Operation Clearing The System Fault

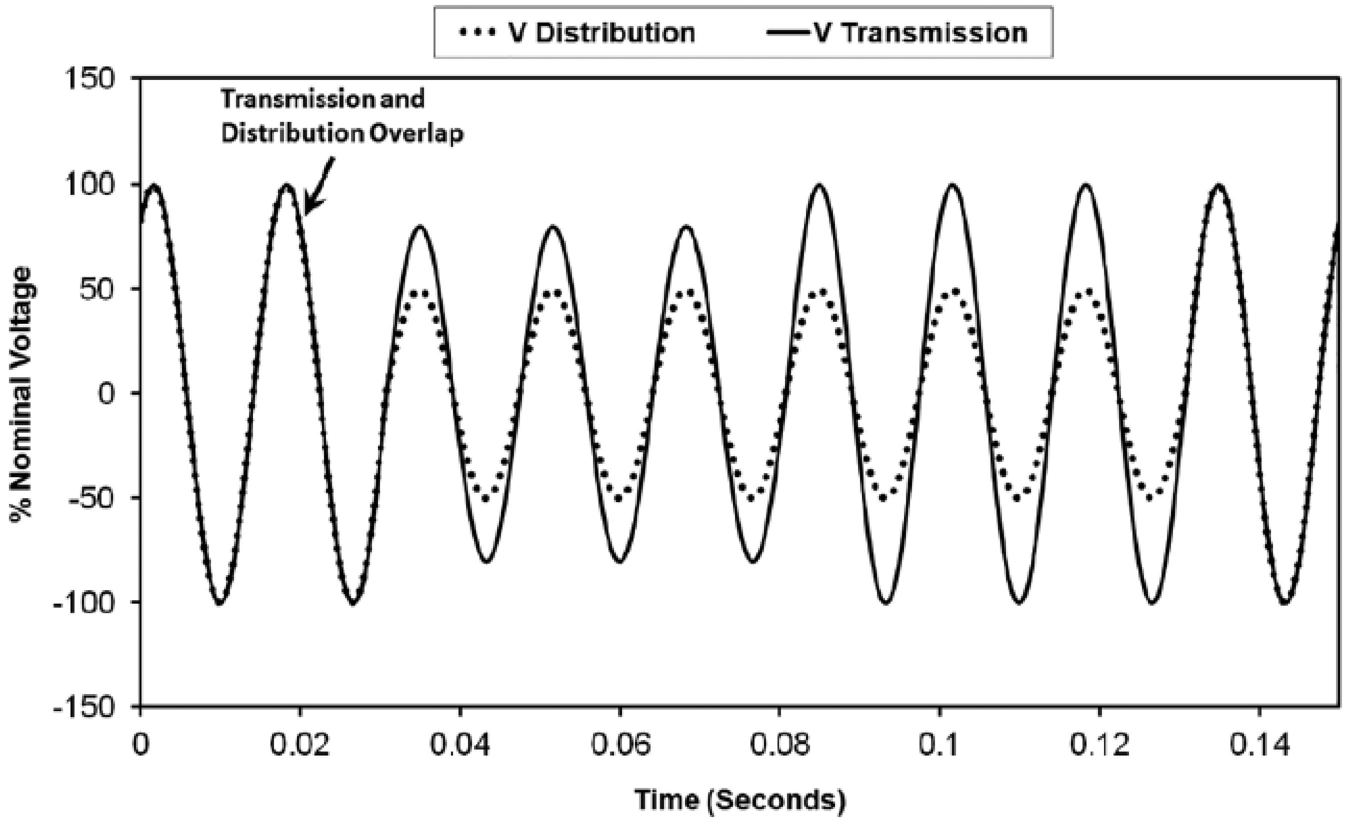


Figure 8—Example of voltage sags and fault clearing timesfor distribution and transmission lines

Transmission Systems May Clear Faults Quicker (3-cycles) Due to SF-6 Breakers Capability

Older Oil, Circuit Distribution Breakers May Clear Faults Slower (6-cycles)

Distribution Circuits With Line Reclosers
A Number of Voltage Sags Occurring In a Short Time

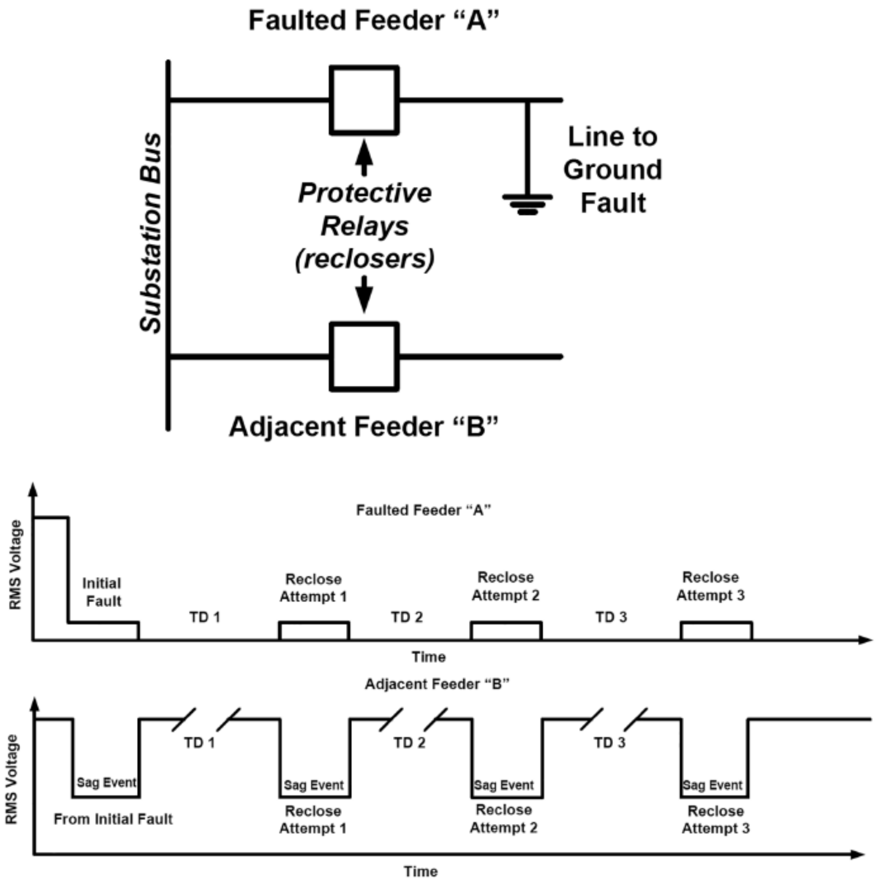


Figure 12—Example fault scenario and timing diagram

Automatic Recloser Installed to Re-energized Faulted Line – act to test circuit and hopefully clear the fault – Example:

- Feeder A Fault – Line Opens and A Short Time Later Recloses
- If Fault Still Present, Re-opens
- Later Recloser Tries Reclosing Again
- This Process Repeated Three Times
- After Third Reclose Attempt, Recloser Locks Line Open
- Note If You Are Fed From Feeder B, You See The Same Relative Voltage Sag Four Times In A Row

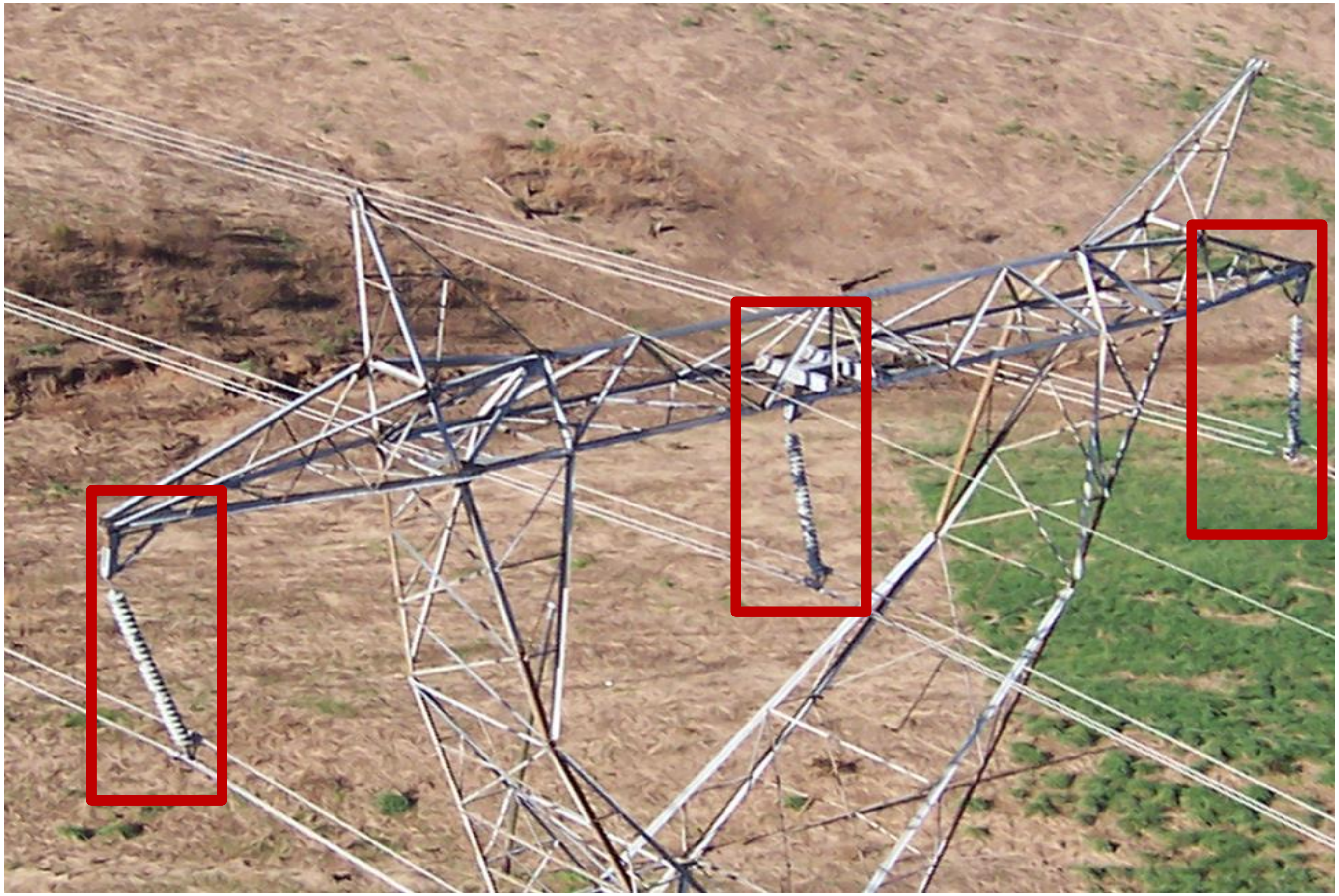
Distribution Circuits With Line Reclosers Minimum Recloser Time is Based on The Time Delay Required to Extinguish The Fault

Table 3—Four representative recloser schemes

Recloser scenario	Types of recloser schemes	Time delay 1 (TD1)	Time delay 2 (TD2)	Time delay 3 (TD3)
1	Instantaneous	30 cycles	15 s	30 s
2	Fast	2 s	15 s	30 s
3	Delayed	5 s	30 s	60 s
4	Hydraulic	2 s	2 s	2 s

IEEE Distribution Protection Practices Industry Survey and a Survey of Various Utility Recloser Schemes by The Voltage Sag Ride-Through Working Group

500-kV Bulk Transmission Line Reclosing Following 3-Phase Fault
728-kA Lightning Strike Hit Tower-- 3-Line Insulators Flashed Over
Insulators Were Damaged But Line Reclosed



Note:
Discoloration
Of
Insulators

UTILITY SUPPORT COMMITMENT

Enlighted Utilities Response to Customer Concerns About Voltage Sags

Old Statement – "You Can't Have A Problem Because your Line Did Not Operate" – Does Not Work Today – "**If your customer has a problem – you have a problem"** (Duke Energy Theme – 1990!)

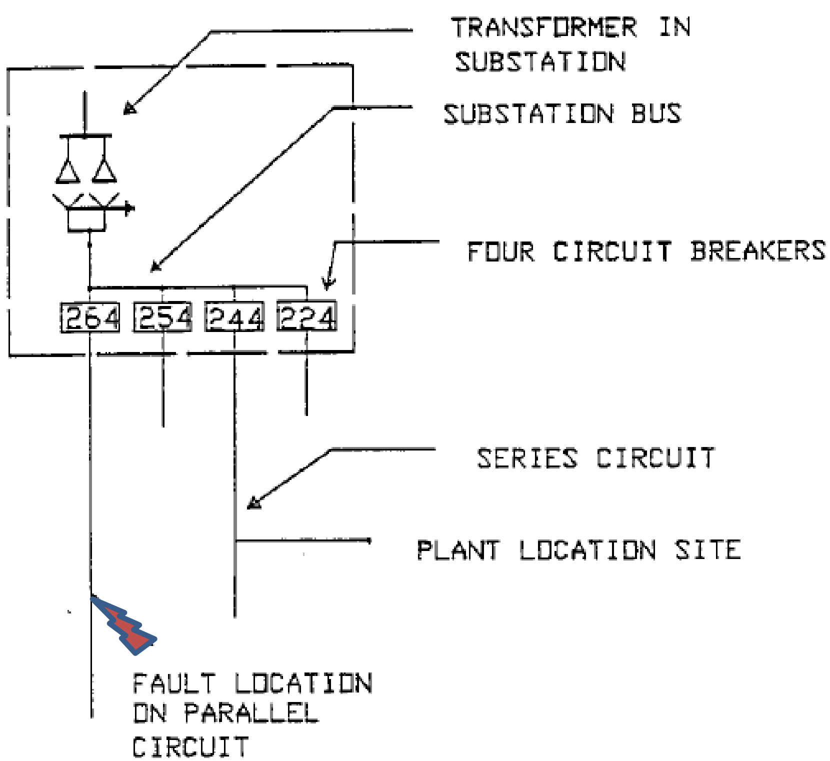
Enlightened 5-Step Approach

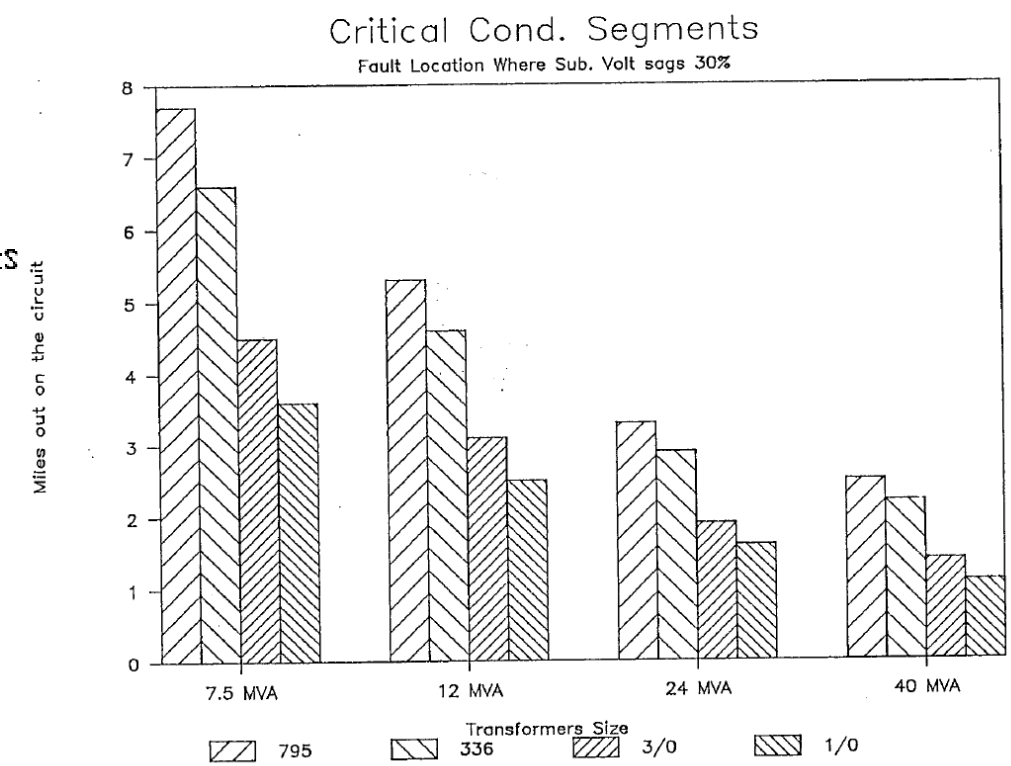
1. Focus on Lines/Busses Known to Cause Voltage Sags Below 70% of Nominal- Called Area of Vulnerability (AOV)
2. Focus on Reducing Number of Events
3. Consider service changes – maybe serve sensitive industry at higher voltage with less events
4. Support efforts to de-sensitize controls at industrial sites
5. If required, support efforts to install premium equipment

UTILITY SUPPORT
AREA OF VULNERABILITY
IDENTIFYING THE CRITICAL LINES

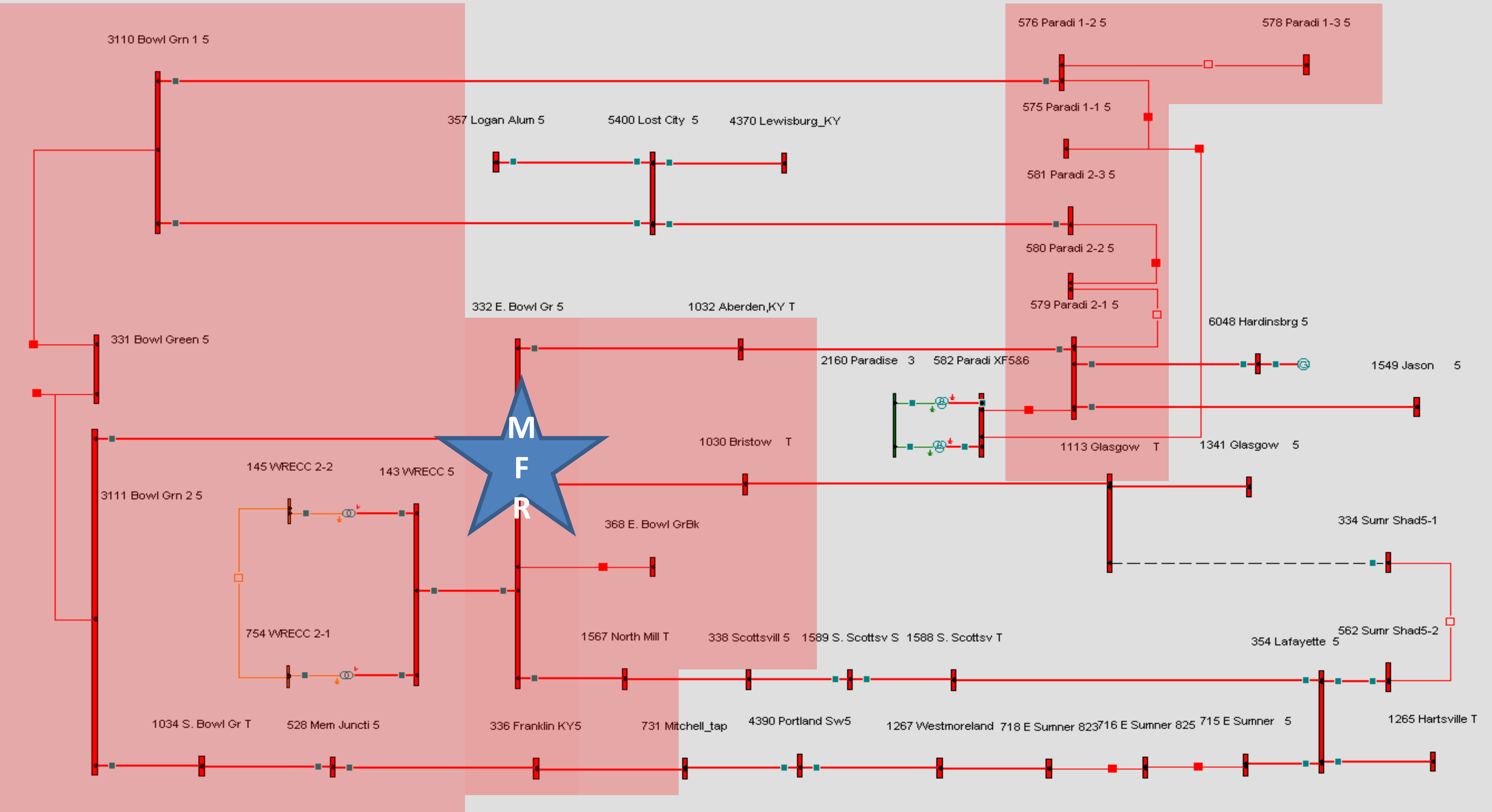
Concept of Distribution Area of Vulnerability (AOV)
Small Distribution Transformers Provide for Long Critical Line Distances from the Substation

Smaller the Transformer – Longer Critical Distance From Substation





161-kV System - Area of Vulnerability Below 70% Of Nominal Voltage During Fault - Simulated in CAPE - **Measured at MFR – VLL, Fault Type - VLL**



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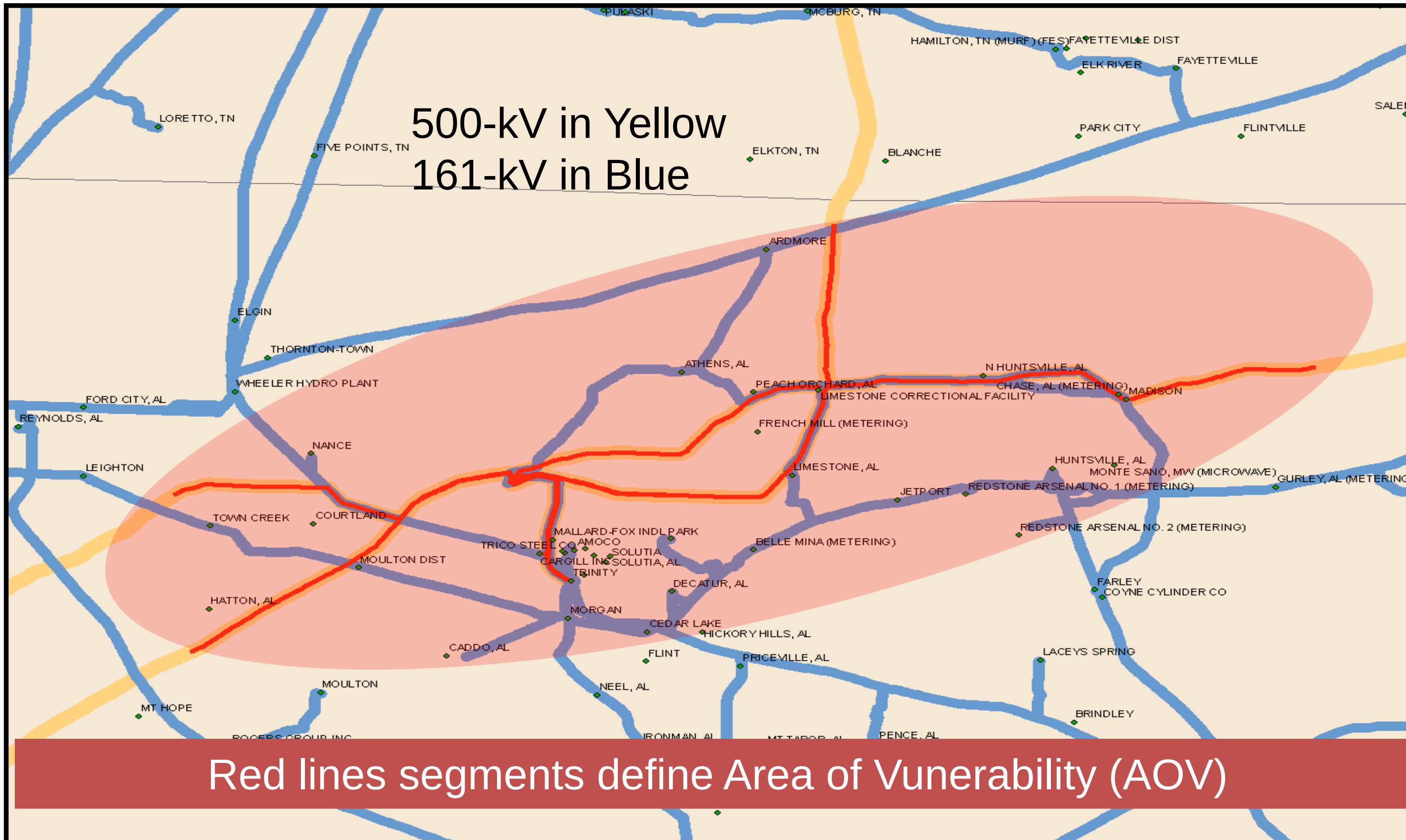
Concept of Transmission AOV – Note: 500-kV Lines Identified as Well as 161-kV Lines –The Stronger The Network – The Smaller the Elipse



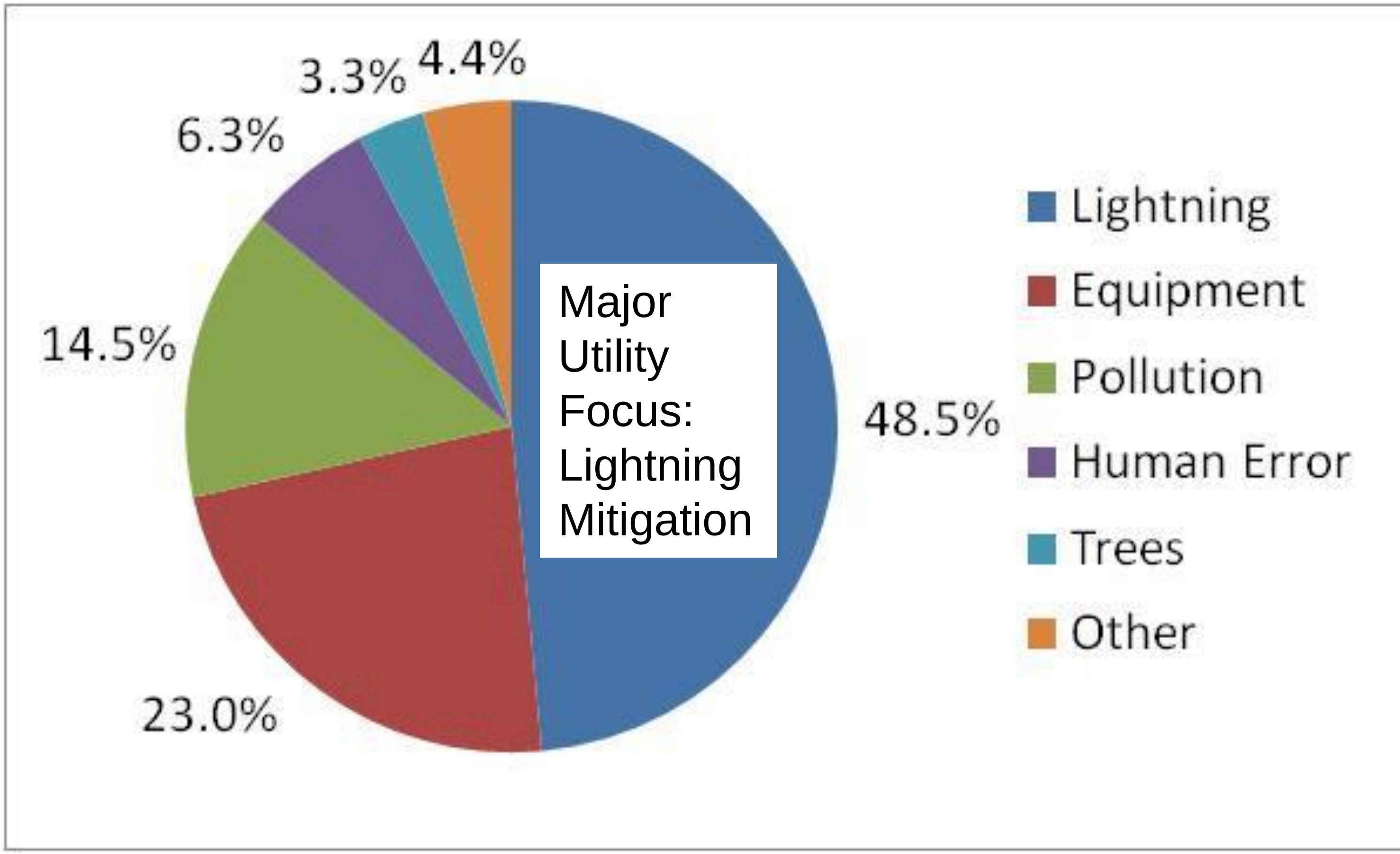
UTILITY SUPPORT
TRY TO REDUCE EVENTS
IN AREA OF VULNERABILITY
EXAMPLE – I-75 CORRIDOR TEAM

Where do Voltage Sags Originate From?

(And what are their characteristics)

- Characteristics based on the cause & location
  - Forestry/Tree Branches –
    - Multiple trip and reclosure
    - More shallow unless the conductor breaks and drops or conductors touch
  - Animal Intrusion
    - Commonly single phase migrating into multiple phase due to plasma and gases generated and shrapnel
  - Weather (High Winds, Snow & Ice)
    - Multiple recurring brief events as multiple conductors contact (Aggregation periods)
  - Lightning Strike (Strike and Backflash) – Single or multiple phase
  - Vehicle Pole incident
    - Typically results in a downed conductor or conductors – Arcing Fault
  - Downed Conductor
  - Equipment Failure (Both Service Provider and other Customers)
  - Human Error
  - Factors influencing duration:
    - Is it Transmission or Distribution
    - Is it Radial or Looped/Grid
    - What is the circuit protection strategy
    - Circuit protection technology

I-75 Corridor Study Root Cause Identification
Classification of Causes for Industrial Downtime by Cause



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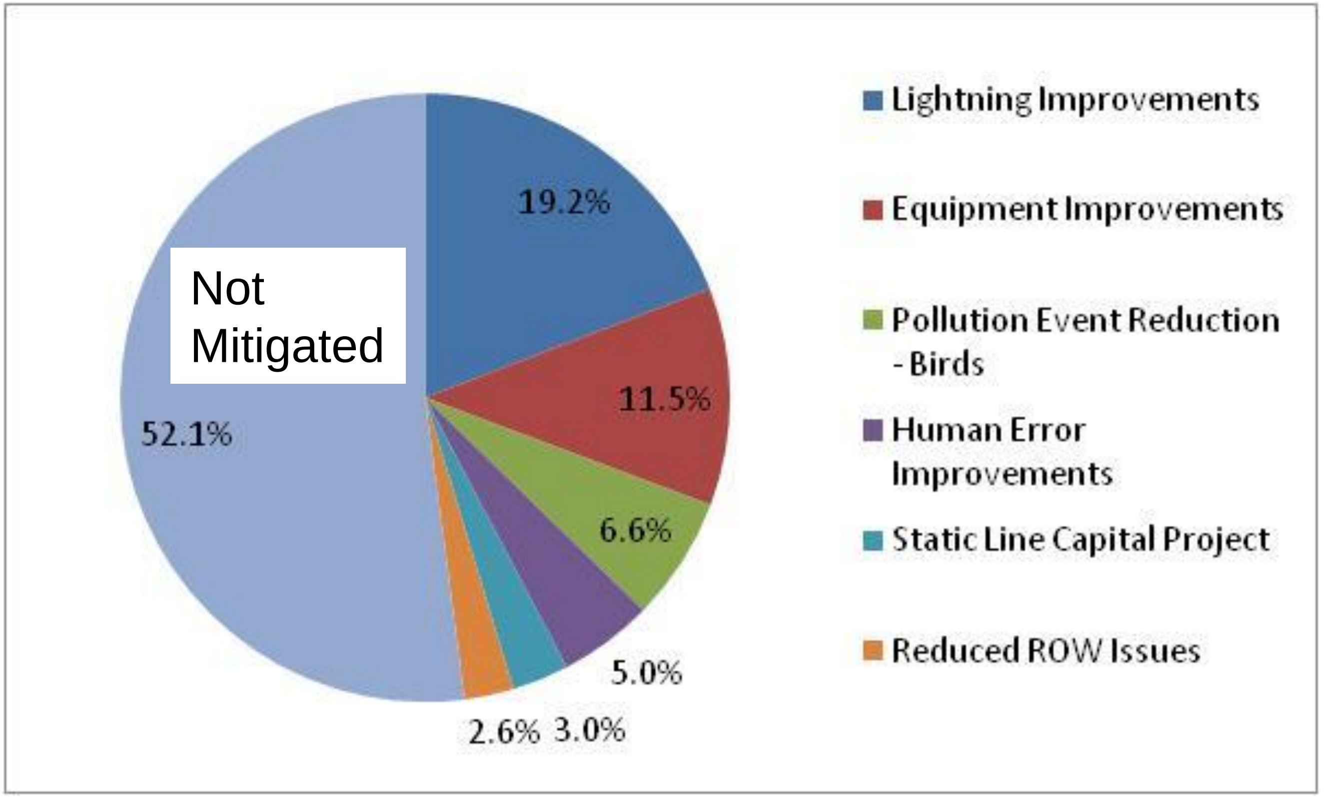
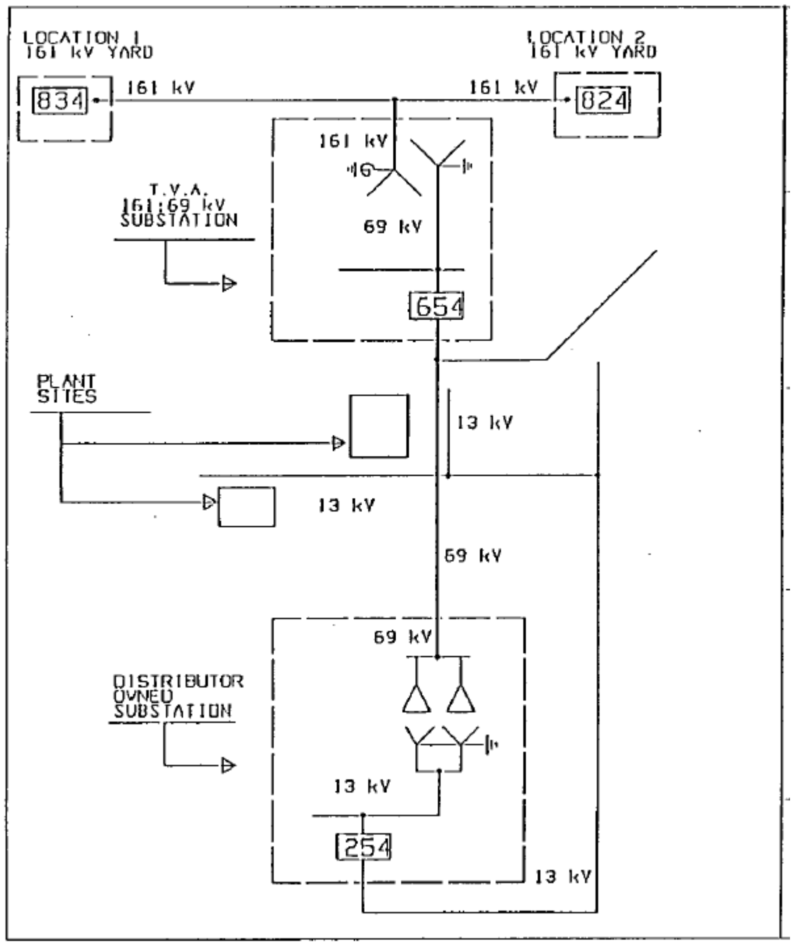
I-75 Corridor Study Solution Implementation
Team Identified Mitigation Strategies Estimated to Reduce Customer Downtime 47.9% Associated with Utility System Operations



UTILITY SUPPORT
REDUCE AREA OF VULNERABILITY

Concept of Moving Upstream to Reduce Events < 70% of Nominal
Real Site, Real Data – LPC Moved Their Customer to 69-kV Delivery



MONTHS / VOLTAGE	JAN.-MARCH 1987	APRIL-JUNE 1987	JULY-SEPT. 1987	OCT.-DEC. 1987	TOTAL
161 kV	1	1	0	0	2
69 kV	1	2	5	1	9
13 kV	1	1	6	1	9
TOTAL	3	4	11	2	20

Compared to 13-kV with 20 Events:
69-kV – 11/20 Events – 45% Reduction
161-kV – 2/20 Events – 90% Reduction

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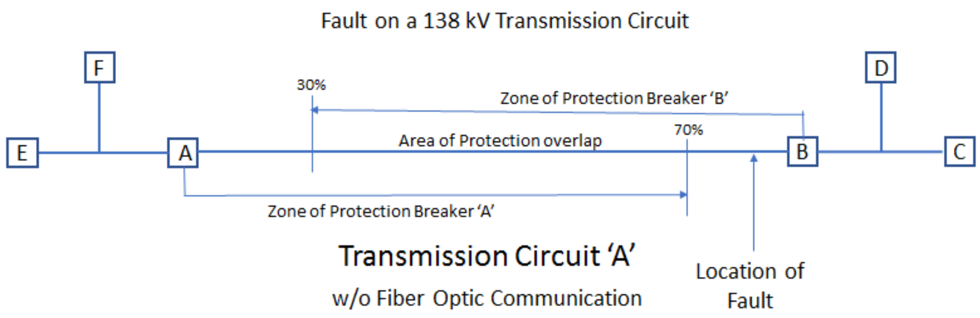
UTILITY SUPPORT
CONSIDER MODIFYING RELAY SCHEMES FOR FASTER CLEARING TIMES

Impact of Protection Strategy and location of Facility Tap with Respect to System Fault on Sag Duration

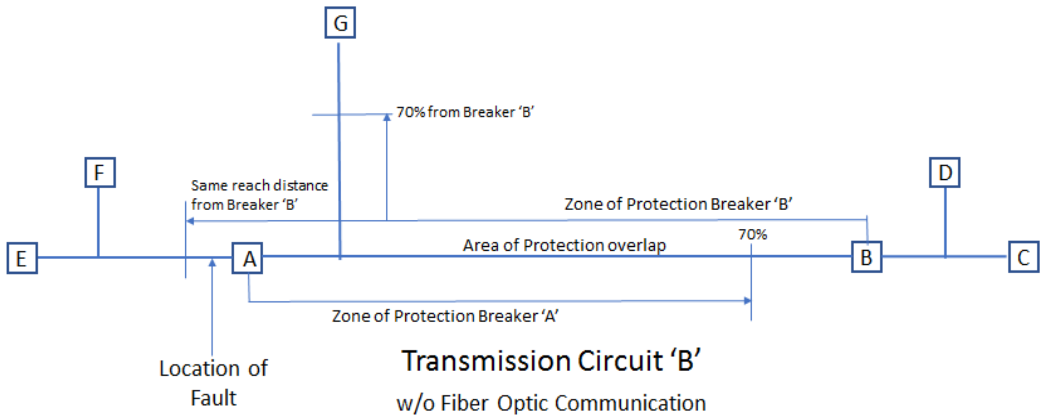


Transmission Example 'A' represents a simple circuit, "Zone of Protection" for each Breaker is the "Instantaneous" zone.

"Reach" distance is the zone of "long Time" setting.

If the system fault is in the Reach of 'B' but the Zone of Protection of 'A', 'A' will clear quickly but 'B' will take much longer. A facility with a service tap to the left of 'A' will experience a very short sag but a facility with a service tap to the right of 'B' will experience a much longer sag..

Impact of Protection Strategy and location of Facility Tap with Respect to System Fault on Sag Duration



Transmission Example 'B' represents a more complex circuit, "Zone of Protection" & "Reach" Are as described in the previous slide.

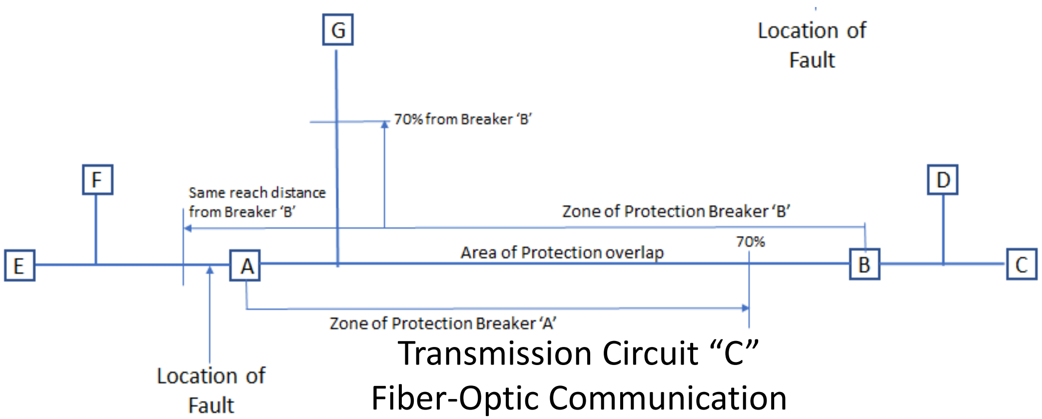
The difference is that in this case, Relaying for Breaker "B" must look past Breaker "A" in order to have a correct zone of protection and reach for the leg to Breaker "G"

If the system fault is to the left of 'A' but still within the zone of protection or reach for breakers 'B' and 'G', they will clear even though they do not need to.

There may be a bit of a "Clearing Race" so that hopefully Breaker 'A' clears before Breakers 'B' or 'G'.

Location of your facility tap will determine how this fault affects you.

Even With Quick Breakers, If Fault Not Detected Quickly, Clearing is Delayed - Reducing Clearing Time is Critical - Pilot Relaying Speeds Up Clearing Faults and Reducing Voltage Sag Duration Times



Transmission Circuit "C"
Fiber-Optic Communication
Between Bkr/Relay A and
Bkr/Relay B

If Breakers A and B can instantaneously communicate during faults, they can both detect the need to operate together and clear the line fault quicker – this concept is called pilot relaying

The quicker the utility
Can clear the fault, the better chance for equipment to ride-through the event

Note – in IEEE 1668 Table 11 3-Phase Voltage Sag to 50% level is ok (by spec) if cleared in 3 cycles or less

This may require pilot relaying to speed up the detecting and clearing of transmission faults

Applying the New IEEE Std. 1668

IEEE 1668 Section 4: Primer On Voltage Sags

Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 V

Presented by: John Mentzer, PE
IEEE 1668 Working Group Member
April 23, 2018

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Testing Goal of IEEE 1668 Recommended Practice

To present an recommend voltage-sag test levels and test methods that best represent actual voltage sags to the following audiences:

- The equipment owner
- System integrators & original equipment manufacturers (OEMs)
- Test engineers who want a defined process to test systems

Back to Basics for the Industrial User

- Norms for Statistical Purposes
  - Sag characteristics expressed as Depth and Duration
  - Depth defined as percent retained voltage
  - Duration based on time voltage drops below 90% and rises back above 90%
  - Phases affected stated as worst case of occurrence of worst phase & maximum number of phases affected
  - Point on wave not currently statistically tracked
- All sags are not created equal
  - "The simplified approach (worse phase only, max duration) does not help the end user to understand the true mechanics of the event. Such a simplified view can lead to misunderstanding regarding why one event of a certain magnitude and duration can cause an industrial process to shut down, where another of a similar magnitude and duration does not."

Why is there inconsistency in which sags affect my equipment & processes?

- Refer back to "Where do Voltage Sags Originate From?"
- Depending on the cause of the fault, the characteristics of the sag are different
  - A tree limb may only fault a single line or it may push multiple conductors together (single or two phase fault).
  - Animal intrusion typically starts as a single phase fault but shrapnel and plasma gases typically cause it to migrate into multi-phase.
  - Galloping conductors are multiple conductors repeatedly contacting
  - An exploding Arrester typically damages adjacent bushings, insulators or arresters and migrates to more phases
  - Which phase or phases were impacted?
  - How many and type of transformers between the fault and your process equipment

Inconsistency of Affect of Sags (Cont.)

- Some examples
  - One sag occurrence affects a machine where the control transformer is connected ‘A’ to ‘C’ and the next occurrence affects a machine where the control transformer is connected ‘B’ to ‘A’ and a third sag does not affect anything.
  - A Sag that originates at a Zero Crossing affects my machine but a deeper sag that originates near peak voltage on the affected phase does not.

Voltage Sag Data Displayed in Both Graphical and Tabulator Forms – Sensitivity Curve Often Also Added to Chart

Table 1—Example of simplification of voltage-sag events in data analysis, rms voltage variation events (7.56-kV base voltage)

Time stamp	Phase	Magnitude (kV)	Magnitude (pu)	Duration (s)	Duration (cycles)
05/25/2008 14:41:13.0000	A	3.175	0.420	0.067	4.0
07/31/2009 07:58:49:3367	C	0.056	0.007	8.417	505.0
10/30/2009 11:16:47.0767	A	5.901	0.781	0.050	3.0
05/02/2010 13:03:12.2967	B	6.244	0.826	0.050	3.0
05/14/2010 14:47:09.5467	C	5.999	0.794	0.150	9.0
12/14/2010 07:05:20.5167	B	1.092	0.144	0.800	48.0
04/24/2011 06:57:56.8867	B	6.237	0.825	0.217	13.0
05/01/2011 06:14:52.4367	A	5.383	0.712	0.150	9.0
07/06/2011 08:13:52.5567	A	0.084	0.011	4.100	246.0
07/21/2011 16:11:18.0567	C	4.921	0.651	0.133	8.0
11/16/2011 02:15:05.4367	B	5.908	0.781	0.150	9.0
01/20/2012 22:24:57.1567	B	5.257	0.695	0.133	8.0
05/31/2012 17:14:26.9067	A	5.866	0.776	0.050	3.0
06/20/2012 22:26:02.3167	C	3.661	0.484	0.050	3.0
07/02/2012 17:58:48.7467	C	6.384	0.844	0.117	7.0
07/10/2012 16:09:16.7567	A	4.053	0.536	0.683	41.0
07/20/2012 05:07:58.7267	C	5.740	0.759	0.067	4.0
08/05/2012 12:06:24.4667	C	6.153	0.814	0.133	8.0
09/08/2012 00:00:43.3967	A	5.964	0.789	0.100	6.0
10/30/2012 14:05:18.0367	C	5.747	0.760	0.117	7.0

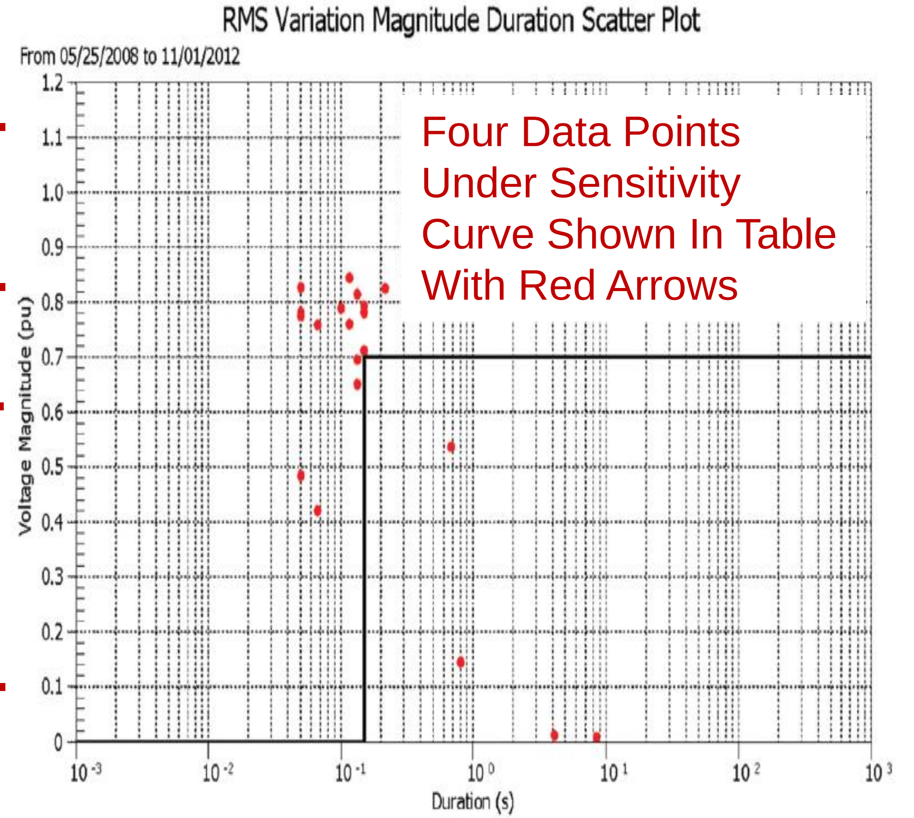
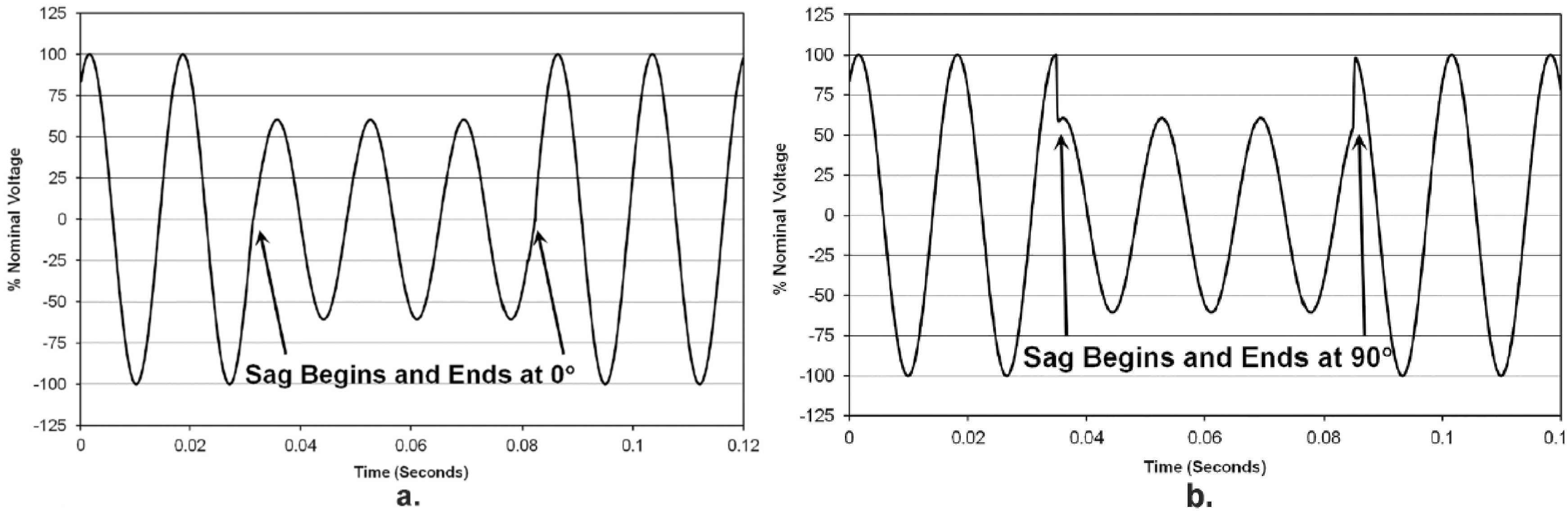


Figure 2—Simplified voltage-sag magnitude duration scatter plot with an example of a 24-V dc power-supply sensitivity overlay

Even Voltage Sags With Similar Characteristics Can Have Different Ride-Through Possibilities



Tabulated Voltage Sag Data for A and B Are the Same – 60% of Nominal for 3 Cycles

In the case of a switched-mode power supply, the point-on-wave of initiation of the voltage sag will determine the energy available for ride-through in the link capacitor.

AC Contactor Point on Wave Graphical Illustration
The 90 Degree Voltage Sag (Dashed Line)
Trips Earlier - Less Holding Energy at 90 Degrees Versus 0 Degrees

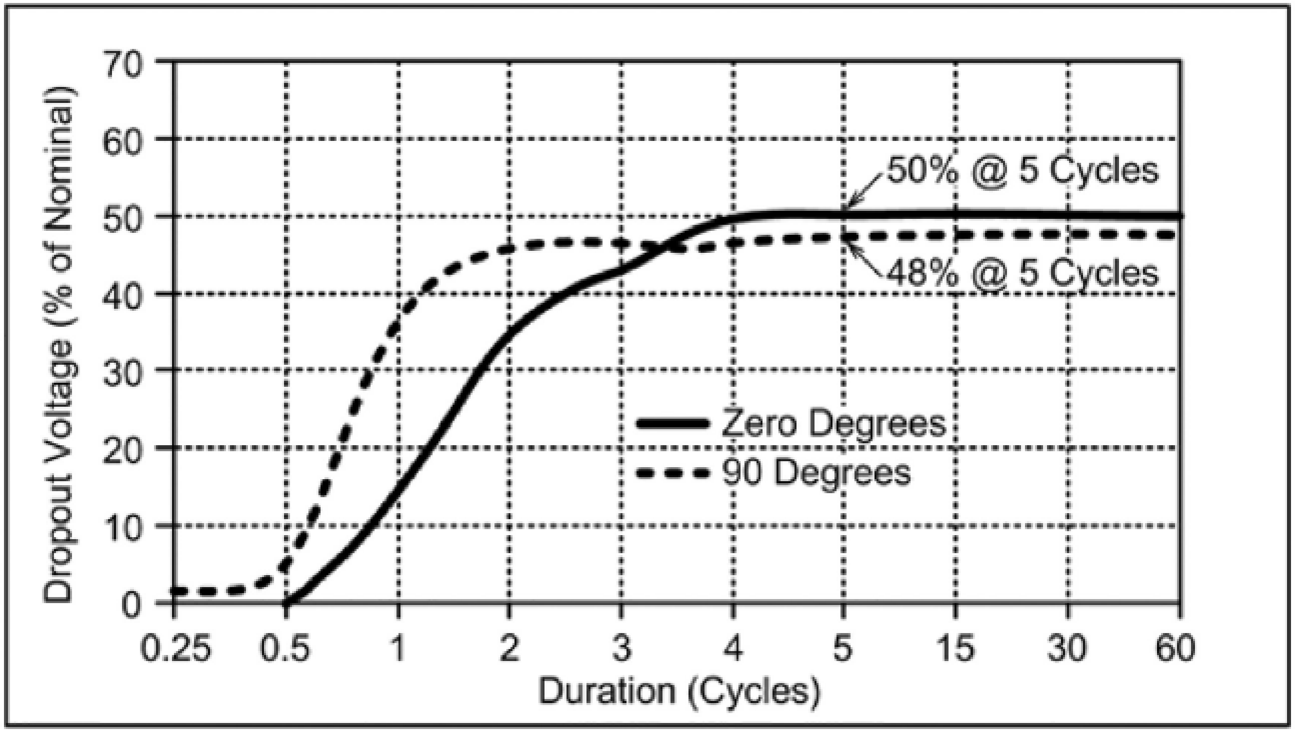
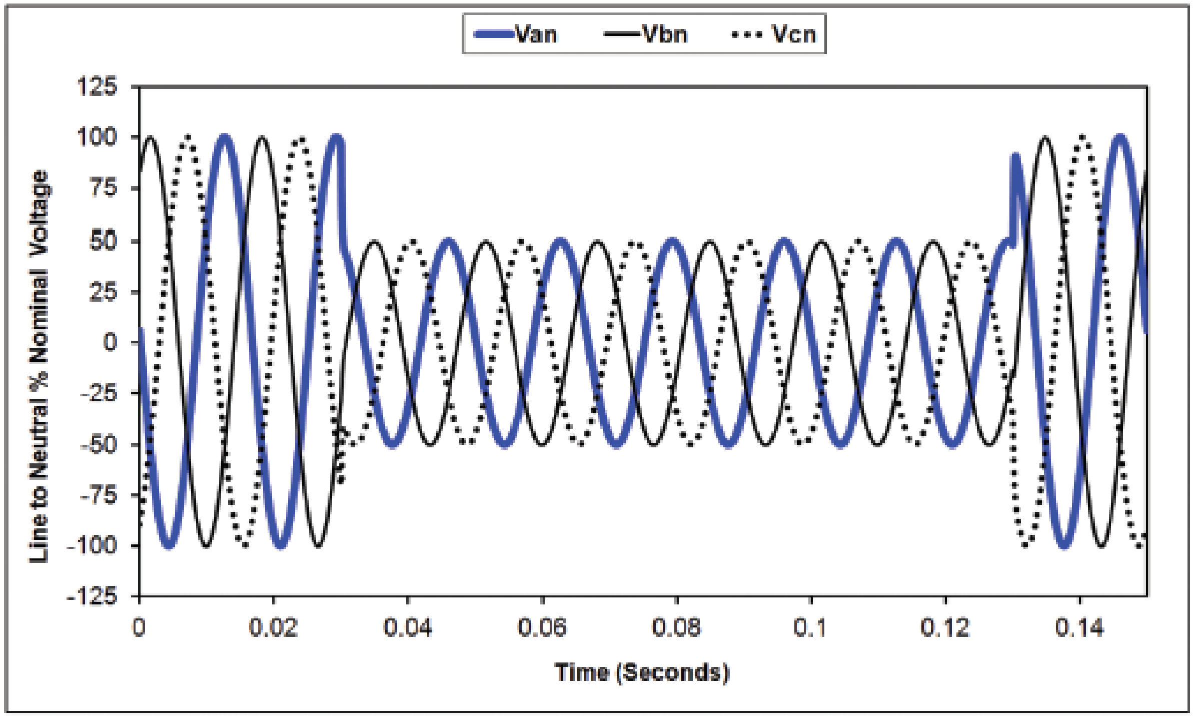


Figure 4—Example of point-on-wave of voltage-sag initiationinfluencing the trip level of an ac contactor [B11]

Three Phase Balanced Voltage Sag Due to System 3-Phase System Fault
Note Phasors Are 120 Degrees Apart For This Type Fault



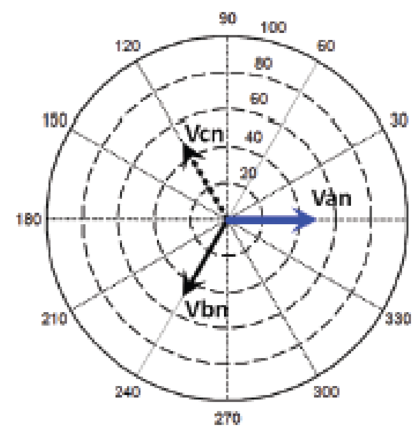


Figure 6—Balanced voltage-sag simulation

Three Phase Unbalanced Voltage Sag Due to System Fault
Note- Phase Shifts During Voltage Sag
Vbn With Negative Shift and Vcn With Positive Shift

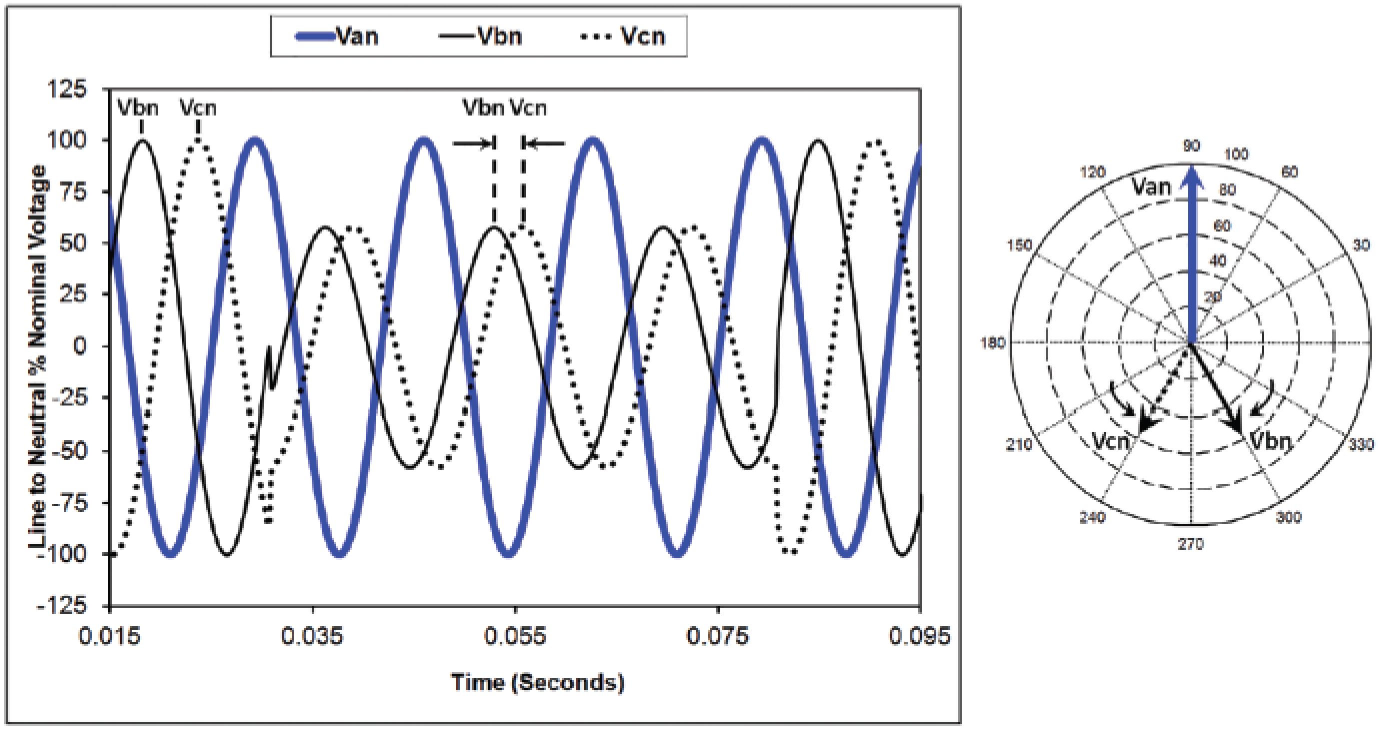


Figure 5—Two-phase voltage sag with positive and negative phase shift

Voltage Sag Duration Times May Be Limited By Distribution/Transmission System Configuration

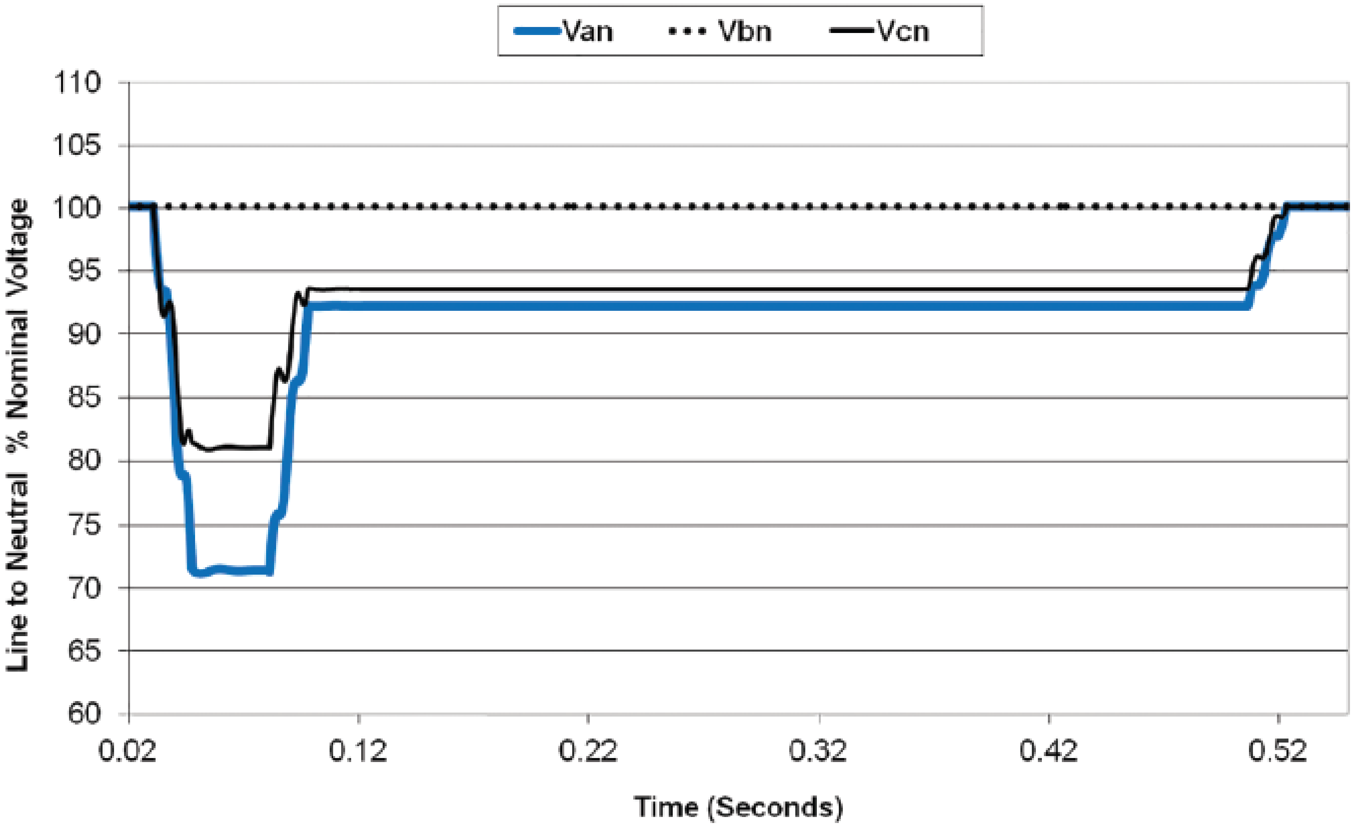


Figure 10—Slow voltage recovery after fault is cleared (simulation)

In This Example Fault Clearing Removes Strong, (Low Impedance) Source --- Remaining Circuits Have High Source Impedance--- The Load Sees This High Impedance and Struggles to Recover

Number & Style of Transformations

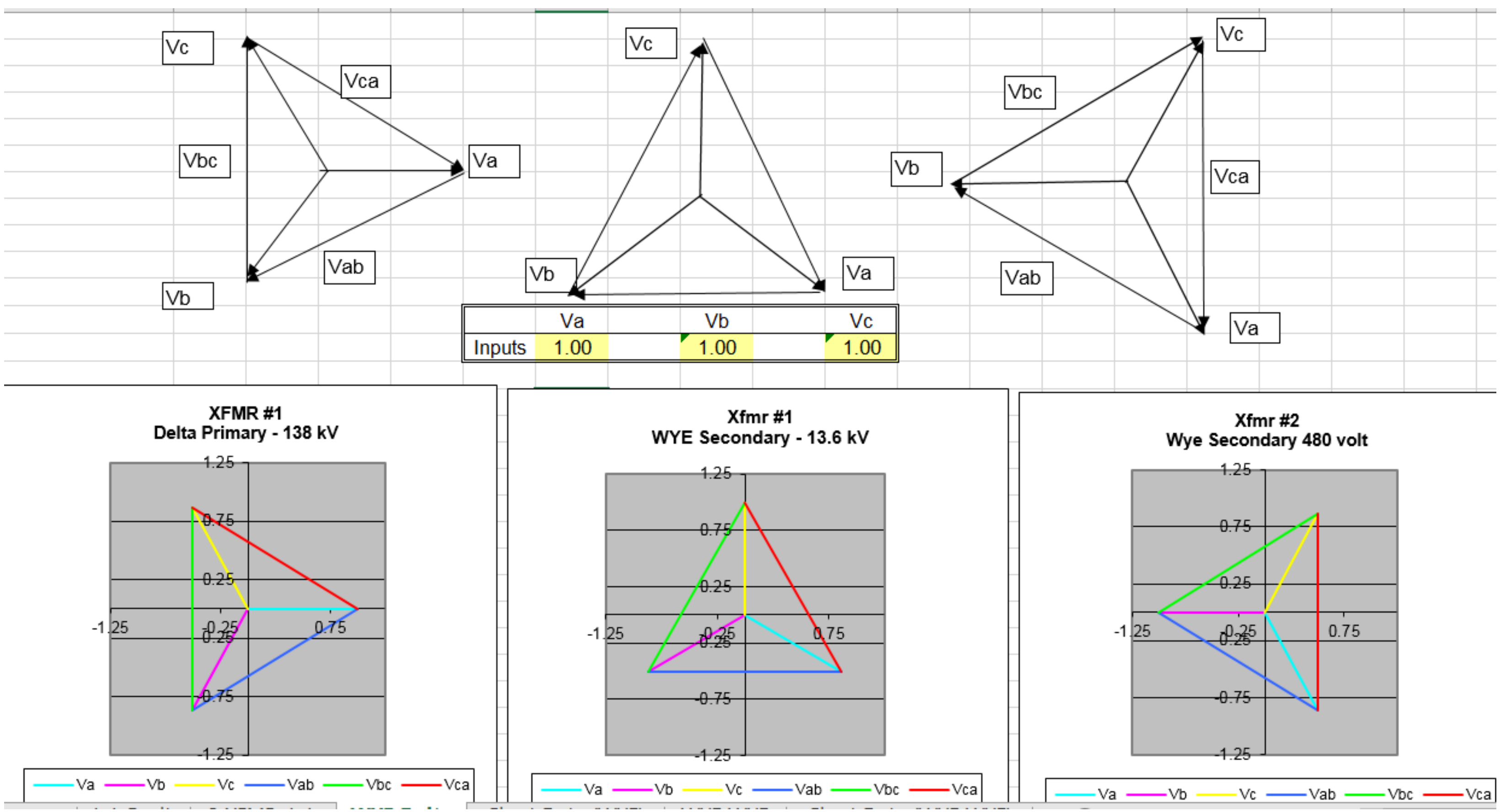
(Ideal bolted fault not considering Circuit Impedance)

Table 2—Secondary transformer voltages (pu) and phase angles from a transmission-system fault (A-G)

Transformation #1	VLL (AB, BC, CA)	VLN (AN, BN, CN)	Transformation #2	VLL (AB, BC, CA)	VLN (AN, BN, CN)
Delta-wye (g)	33% ∠ 180, 88% ∠ 79.1, 88% ∠ 280.9	58% ∠ 300, 58% ∠ 240, 100% ∠ 90	Delta-wye (g)	58% ∠ 120, 58% ∠ 60, 100% ∠ 270	88% ∠ 280.9, 33% ∠ 180, 88% ∠ 79.1
Wye (g)-wye (g)	58% ∠ 240, 100% ∠ 90, 58% ∠ 300	0%, 100% ∠ 240, 100% ∠ 20	Delta-wye (g)	33% ∠ 180, 88% ∠ 79.1, 88% ∠ 280.9	58% ∠ 300, 58% ∠ 240, 100% ∠ 90
Wye (g)-wye (g)	58% ∠ 240, 100% ∠ 90, 58% ∠ 300	0%, 100% ∠ 240, 100% ∠ 120	Wye (g)-wye (g)	58% ∠ 240, 100% ∠ 90, 58% ∠ 300	0%, 100% ∠ 240, 100% ∠ 120
Wye-wye (g)	58% ∠ 240, 100% ∠ 90, 58% ∠ 300	33% ∠ 0, 88% ∠ 259.1, 88% ∠ 100.9	Delta-wye (g)	33% ∠ 180, 88% ∠ 79.1, 88% ∠ 280.9	58% ∠ 300, 58% ∠ 240, 100% ∠ 90
Wye (g)-delta	33% ∠ 180, 88% ∠ 79.1, 88% ∠ 280.9	58% ∠ 300, 58% ∠ 240, 100% ∠ 90	Wye (g)-delta	58% ∠ 120, 58% ∠ 60, 100% ∠ 270	88% ∠ 280.9, 33% ∠ 80, 88% ∠ 79.1

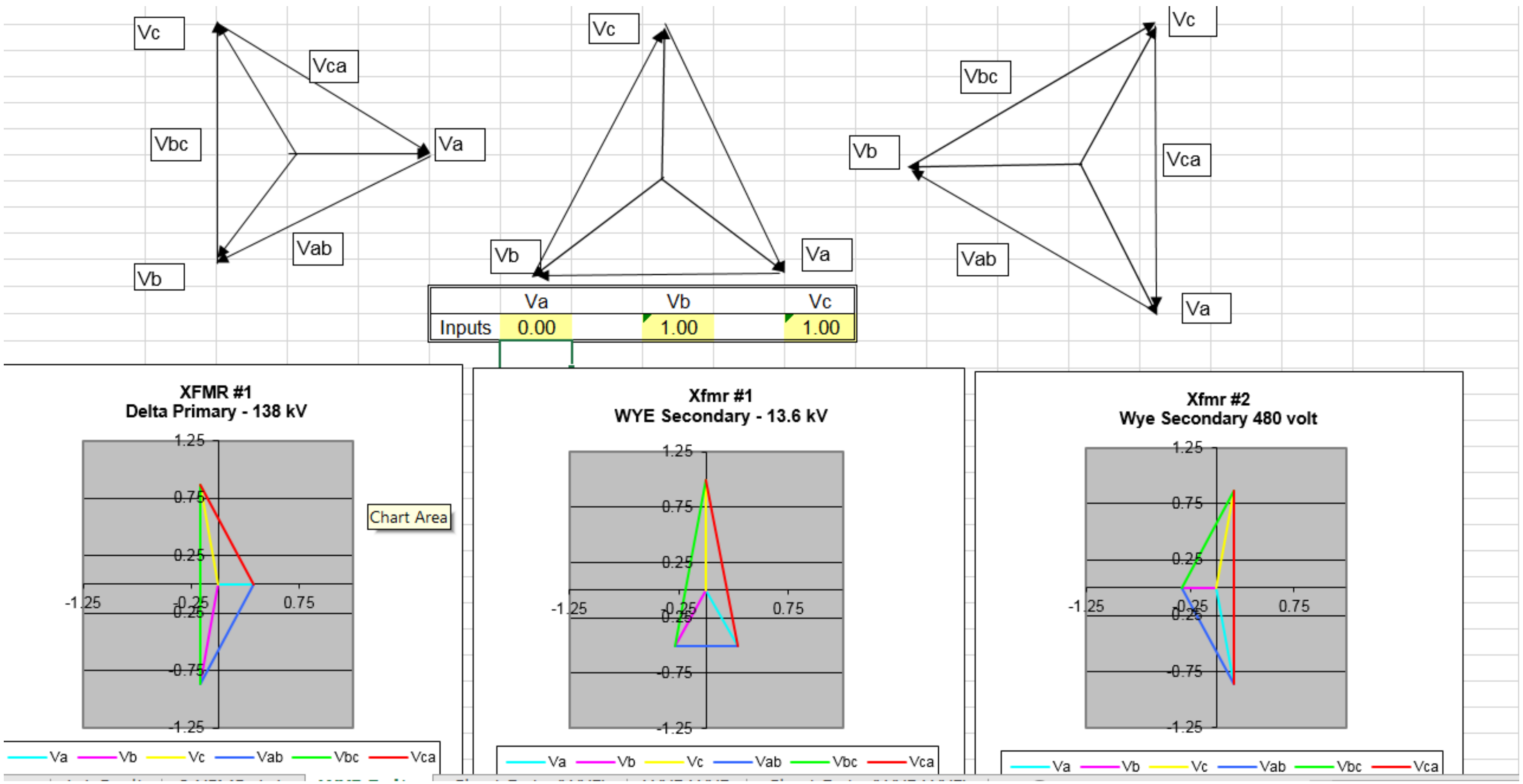
Multi-Transform Base Model

(Multiple Delta – WYE before a Sag)



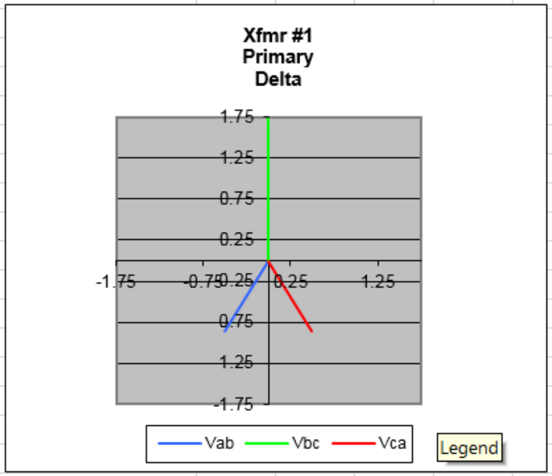
Multi-Transform Model

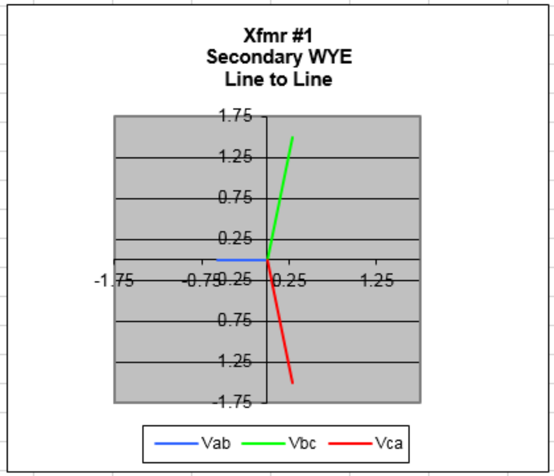
(Multiple Delta – WYE with Fault on Phase 'A')

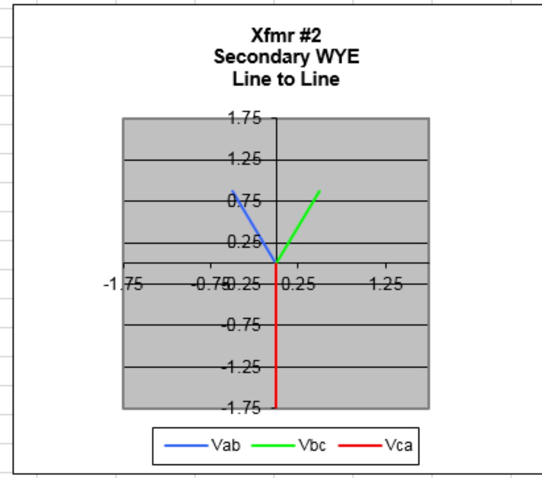


Multi-Transform Model

(Multiple Delta – WYE with Fault on Phase ‘A’)







Vab =	1.00	Vbc =	1.73	Vca=	1.00	Vab =	0.58	Vbc =	1.53	Vca=	1.53		Vab =	1.00	Vbc =	1.00	Vca+	1.73
	58%	240.0	100%	90.0	58%	300.0	33%	180.0	88%	79.1	88%	280.9		58%	120.0	58%	60.0	100%
Va =	0.33	Vb =	0.88	Vc =	0.88	Va =	0.58	Vb =	0.58	Vc =	1.00		Va =	0.88	Vb =	0.33	Vc =	0.88
		0.0		259.1		100.9	58%	300.0	58%	240.0	100%	90.0		88%	280.9	33%	180.0	88%

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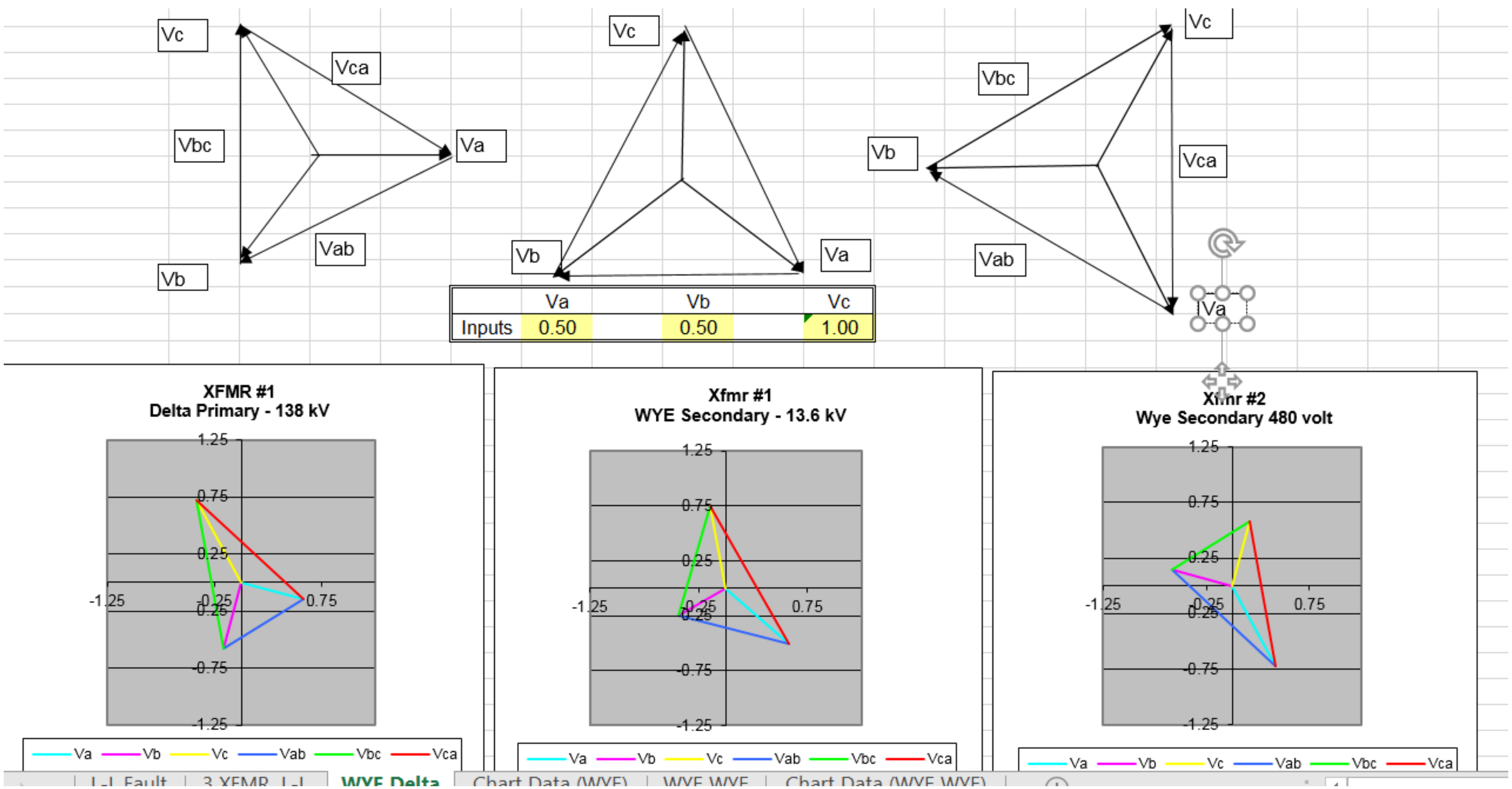
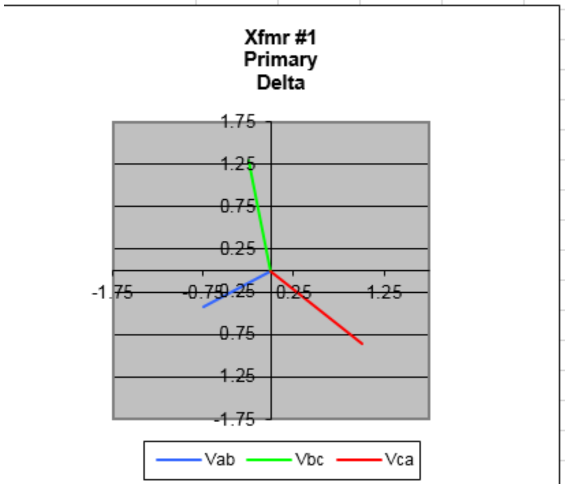
Multi-Transform Model

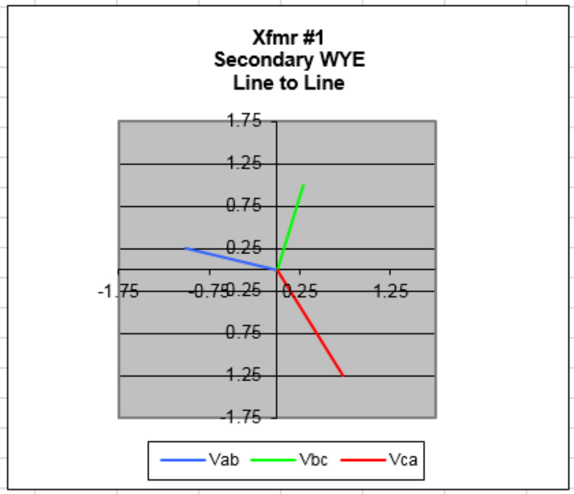
(Multiple Delta – WYE with 50% Faults on Phases ‘A’ & ‘B’)

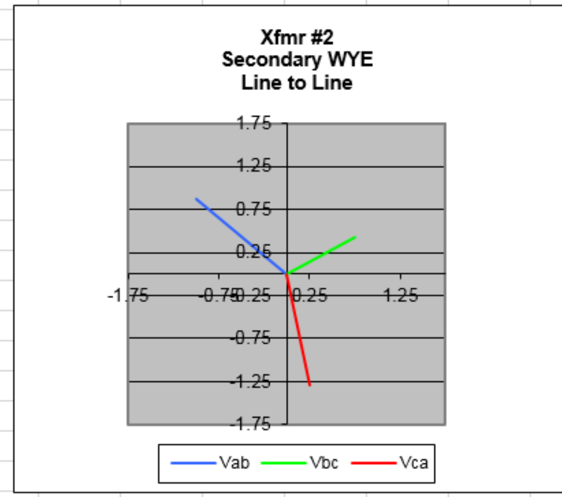


Multi-Transform Model

(Multiple Delta – WYE with 50% Faults on Phases ‘A’ & ‘B’)



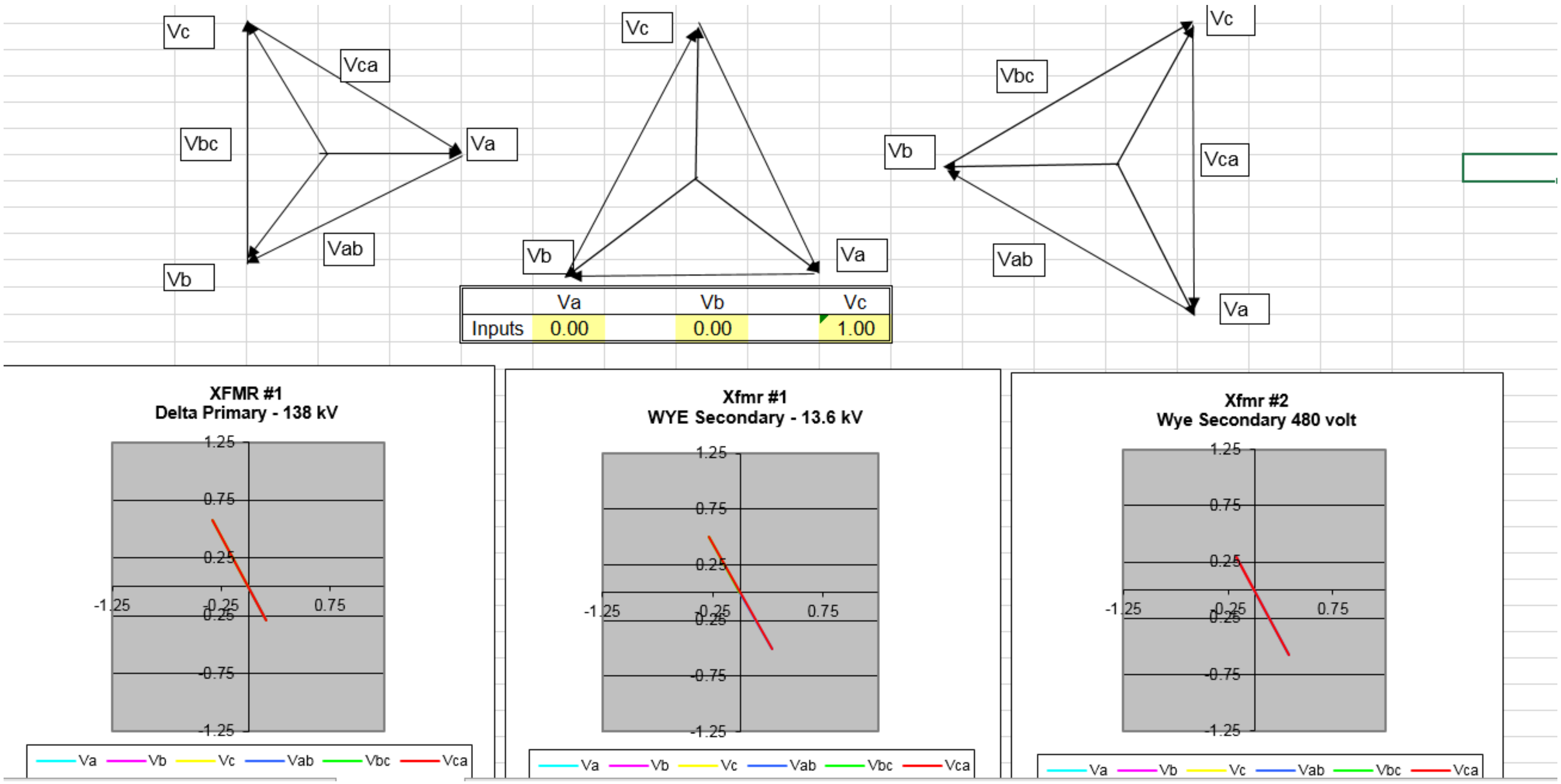




Vab =	0.87	Vbc =	1.32	Vca=	1.32	Vab =	1.04	Vbc =	1.04	Vca=	1.44		Vab =	1.32	Vbc =	0.87	Vca+	1.32	
	50%	210.0	76%	100.9	76%	319.1	60%	166.1	60%	73.9	83%	300.0		76%	139.1	50%	30.0	76%	280.9
Va =	0.60	Vb =	0.60	Vc =	0.83	Va =	0.76	Vb =	0.50	Vc =	0.76		Va =	0.83	Vb =	0.60	Vc =	0.60	
		-13.9		253.9		120.0	76%	319.1	50%	210.0	76%	100.9		83%	300.0	60%	166.1	60%	73.9

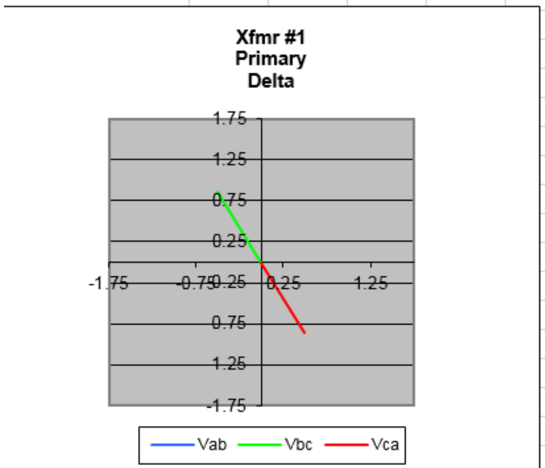
Multi-Transform Model

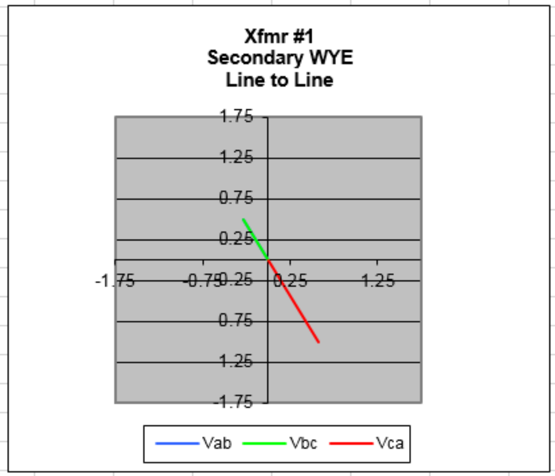
(Multiple Delta – WYE with Bolted Fault Phases ‘A’ to ‘B’)

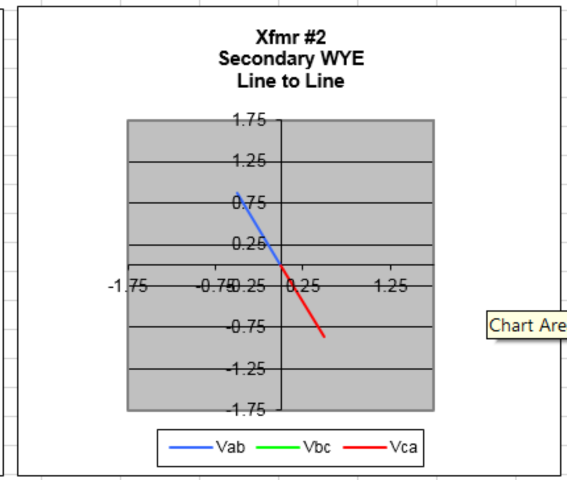


Multi-Transform Model

(Multiple Delta – WYE with Bolted Fault Phases ‘A’ to ‘B’)







Vab =	0.00	Vbc =	1.00	Vca=	1.00	Vab =	0.58	Vbc =	0.58	Vca=	1.15		Vab =	1.00	Vbc =	0.00	Vca+	1.00	
	0%	######	58%	120.0	58%	300.0	33%	120.0	33%	120.0	67%	300.0		58%	120.0	0%	180.0	58%	300.0
Va =	0.33	Vb =	0.33	Vc =	0.67	Va =	0.58	Vb =	0.00	Vc =	0.58		Va =	0.67	Vb =	0.33	Vc =	0.33	
		-60.0		300.0		120.0	58%	300.0	0%	######	58%	120.0		67%	300.0	33%	120.0	33%	120.0

Example of Transmission Fault Propagating Down to Utilization Voltage Level – VLN and VLL at 480-V Level Shown

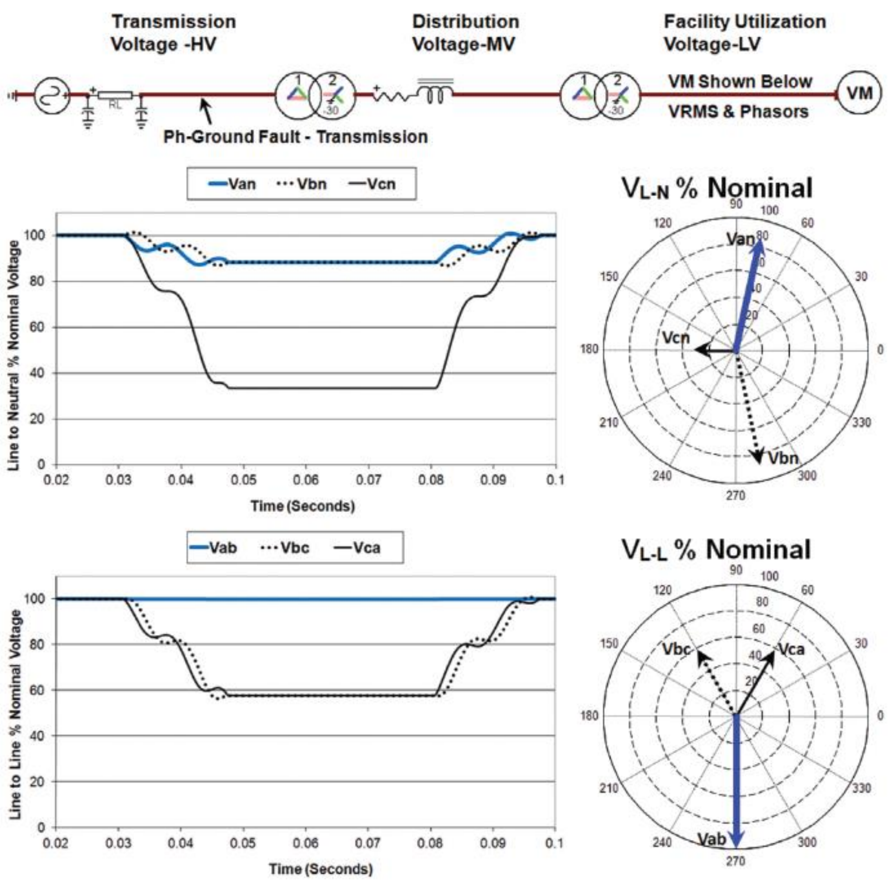


Figure 11—Voltage sag at 480 Vrms utilization voltagefrom a transmission-system fault (A-G) simulation

- A Phase to Ground Fault on Transmission System – Van Reduced to 0% of Nominal
- Delta – Wye Transformation – Transmission to Distribution
- Delta-Wye Transformation – Distribution to Utilization
- Resulting 480-V Utilization Voltages Impacted – Vbc and Vca Reduced to 58% of Nominal

Example of Distribution Fault Propagating Down to Utilization Voltage Level – VLn and VLL at 480-V Level Shown

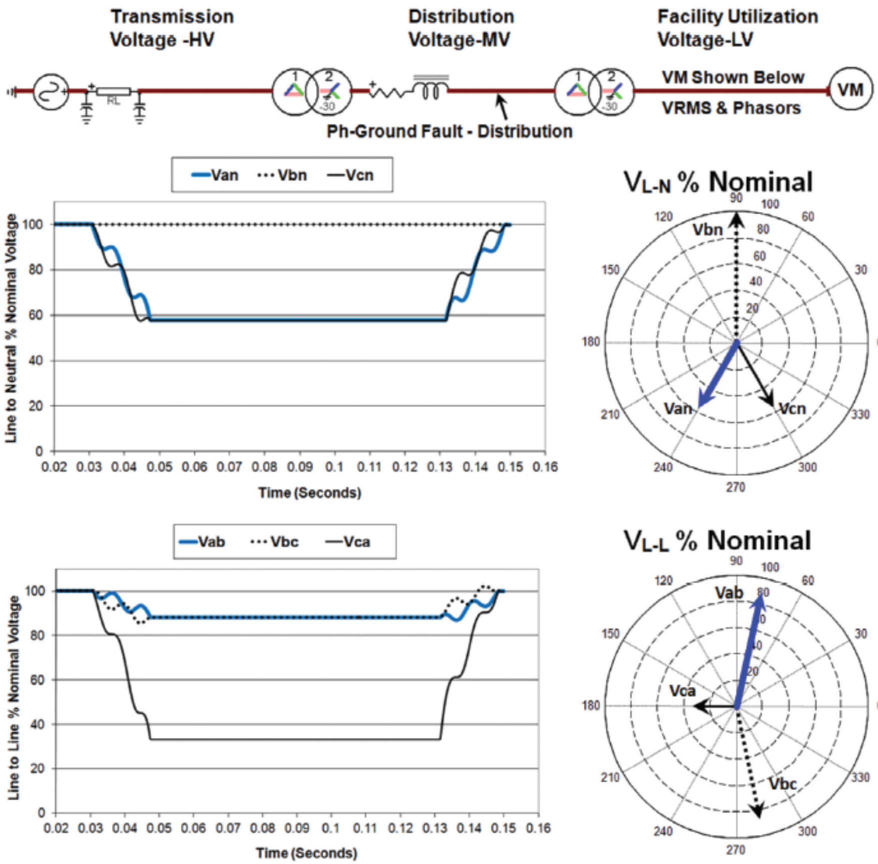


Figure 13—Voltage sag at 480-Vrms utilization voltage from a single-phase faulton the distribution system (Phase A to ground, simulation)

- A Phase to Ground Fault on Distribution System – Van Reduced to 0% of Nominal
- Delta – Wye Transformation – Transmission to Distribution
- Delta-Wye Transformation – Distribution to Utilization
- Resulting 480-V Utilization Voltages Impacted –Vca Reduced to 33% of Nominal

Example of A Phase to Ground, 480-V System Fault VLn and VLL at 480-V Level Shown

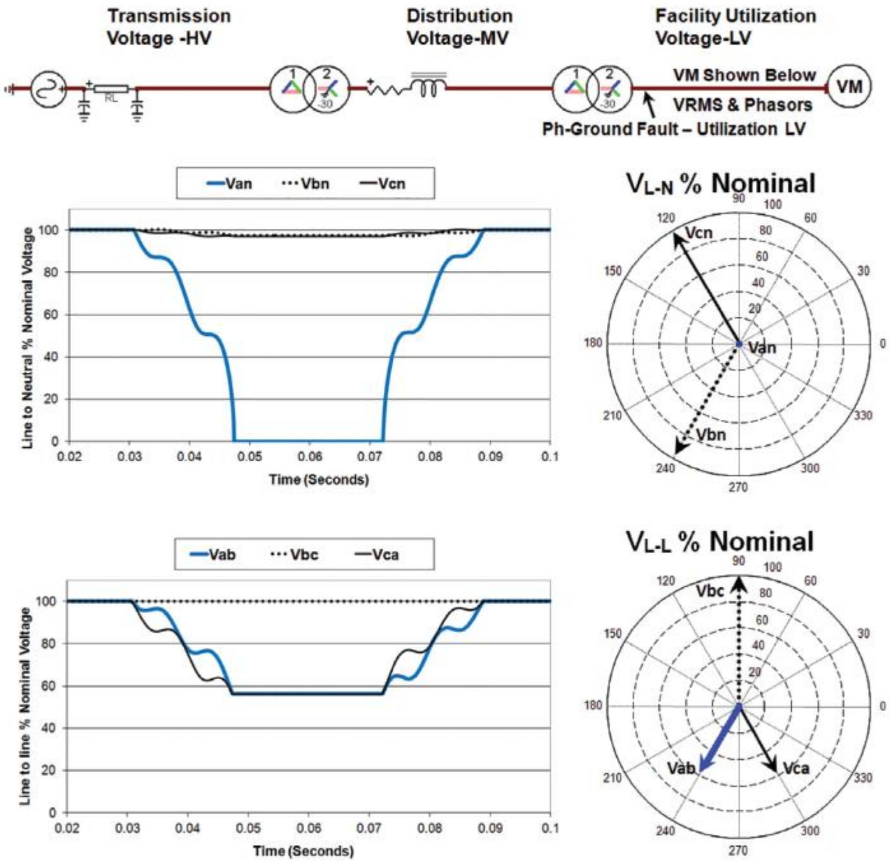


Figure 14—Voltage sag at 480-Vrms utilization voltage from a fault within a facility (simulation)

- A Phase to Ground Fault on 480-V System – Van Reduced to 0% of Nominal
- Delta – Wye Transformation – Transmission to Distribution
- Delta-Wye Transformation – Distribution to Utilization
- Resulting 480-V Utilization Voltages Impacted –Vab, Vca Reduced to 58% of Nominal

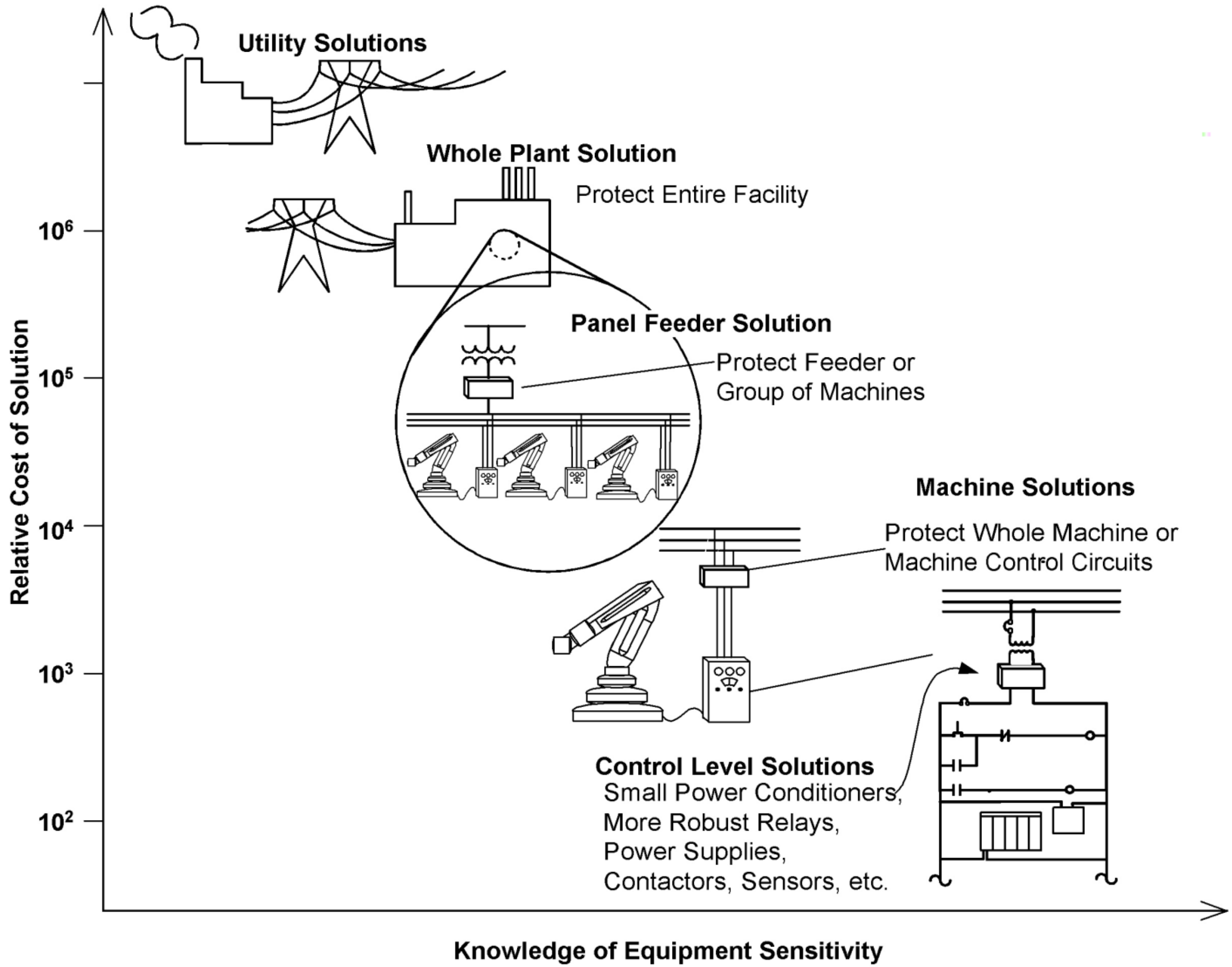
Why does my facility experience what we measured?

- Location of offending fault with respect to my service entrance
- Impedance of network from offending fault to my service entrance
- Location of offending fault within the protection scheme with respect to my service entrance.
- Number and style of transformations between fault and my equipment served.

What are some practicalities of Sag Mitigation?

- The closer you are to the service entrance to your facility, the higher the cost to implement a solution
- Solutions that address the power feed to the machine are magnitudes more expensive than solutions that can be isolated to protecting the control system, i.e. power conditioning to a VFD as opposed to voltage support to the controls serving the VFD.
- Cost effectiveness of mitigating sags may be as dependent upon time required to restore operation or safety concerns

Mitigation Levels



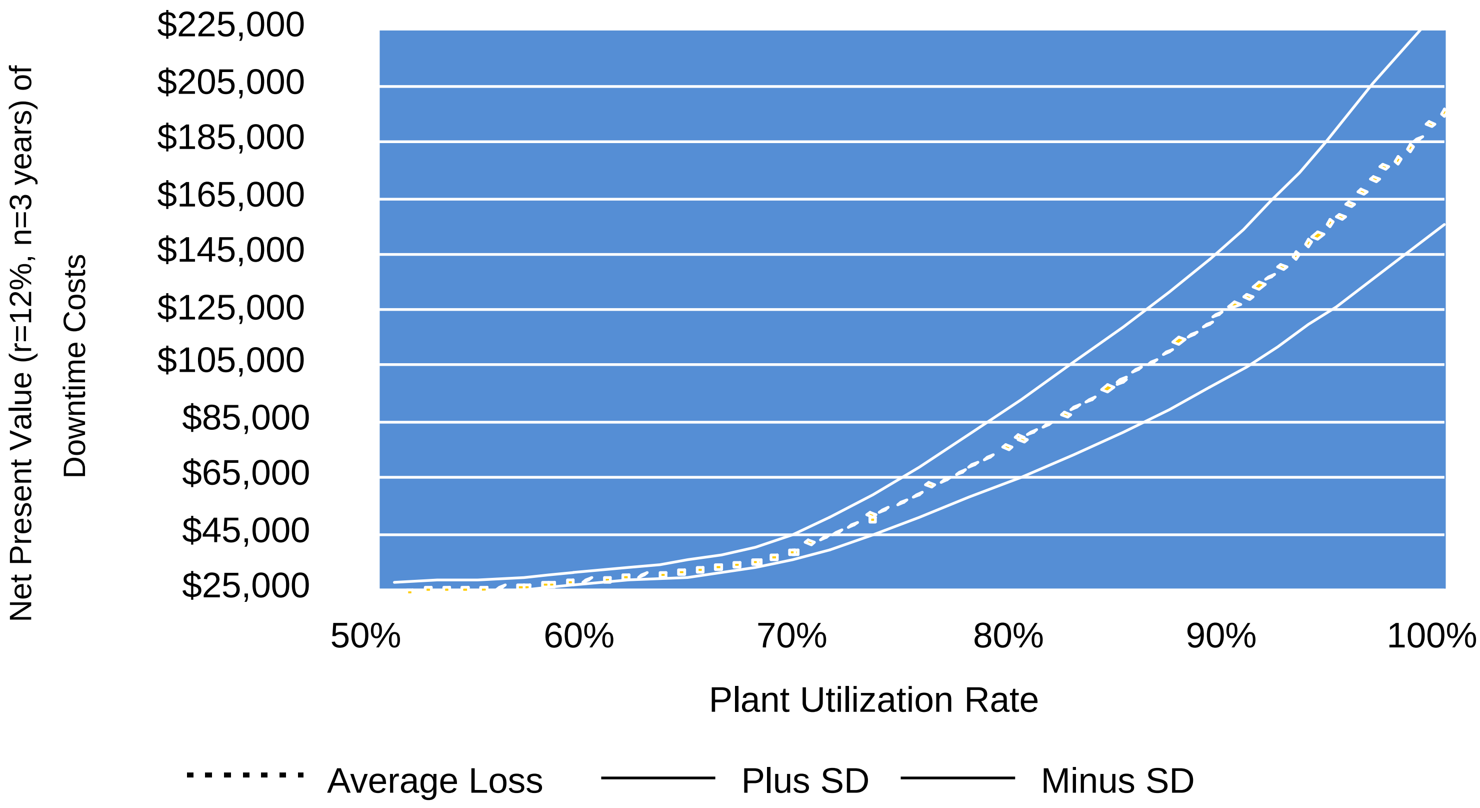
What are some practicalities of Sag Mitigation?

- Cost Effectiveness of Mitigation Solutions (Continued)
  - A multi-arm servo drive takes significant time to re-zero the various arms before restoring operation but the entire power load of the servo must be supported
  - Multiple machines, such as paint ovens, require significant time to walk around to each stage of the oven and reset the pilot safety circuit. The time to purge and restore adequate process temperature are also significant. This example often also has scrap or rework due to incomplete bakes
  - A large high speed grinder typically breaks the tool and requires wheel replacement. Grinding wheels can cost $25,000 to $35,000 plus the labor to install
  - A plastic injection molding machine often solidifies material within the machine and requires component replacement
  - Incomplete chemical processes can create dangerous intermediate products which are hazardous to remove and costly dispose of

What are some practicalities of Sag Mitigation?

- Cost Effectiveness of Mitigation Solutions – True Cost of the Disruption
  - The plant manager is angry, his production plan has been interrupted, what are the losses?
  - What is the true cost of the interruption?
    - Is the operation a 40 hr/wk operation and can the lost production be made up with weekend overtime?
    - If you need to make up 2 hours of lost production, does a union contract require an 8 hour day
    - Is the operation already 3 shifts working 7 days so overtime is not possible?
    - If the interruption is long enough, can lost labor be improved by sending labor home for the shift and cancelling subsequent shifts until the process is restored?
    - How much true scrap is there?
    - Can interrupted parts or assemblies be recovered and reworked?
    - Is the plant committed to “just in time” delivery imposing a penalty for missed delivery schedule?
    - How long does it take to restore normal operation.

Example Electronics Plant:
NPV of DT Costs vs. Plant Utilization Rate



What are some practicalities of Sag Mitigation?

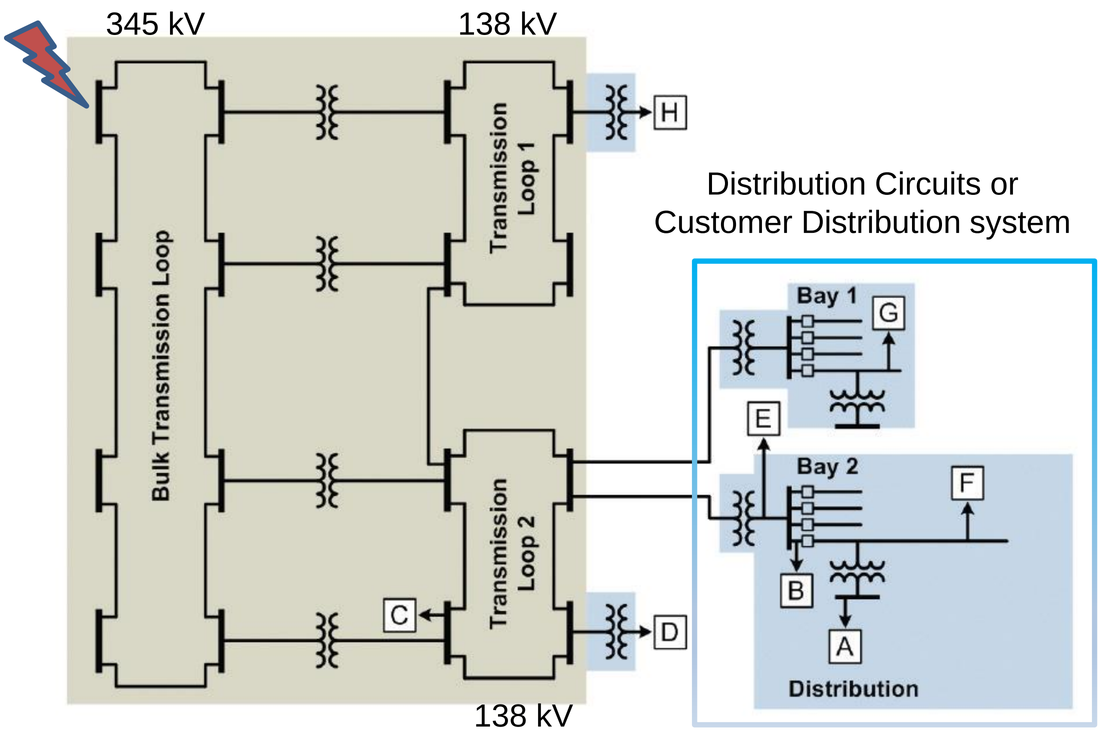
- What can be done on the front end to minimize frequency of disruptions
  - Work with electrical equipment manufactures to develop components that are more robust, i.e. standard grade and premium grade.
    - Now that a Guideline has been published that they can all design to, we need to motivate them to develop improved offerings
    - 1668 provides a standard test method so all equipment manufactures can test to the same testing regiment
  - Consider voltage sag ride-through in designs, especially for controls
    - Battery back-up on PLC memory and active programs to maintain batteries
    - Specify VFD's that include the capability of tuning DC Bus under-voltage trip to minimize disruption by lesser sags.
    - Provide voltage support components at the control transformer in critical process control panels
    - Develop and maintain a uniform "Common Components List" so designs consistently incorporate validated components.

What are some practicalities of Sag Mitigation?

- What can be done on the front end to minimize frequency of disruptions
  - Utilize a "Robust" Root Cause Process that identifies the true root "causes" of the disruption and the corrective actions that will truly minimize probability of recurrence.
    - An event can have multiple root causes
    - External – The utility had an event which could be from any of the previously discussed causes but this is only the initiating event with related root causes
    - Internal –
      - Are we having recurring disruptions on this particular process and what are the commonalties
      - Are there particular components that are commonly interrupted and what can be done to stiffen them cost effectively
      - Are the components of the process equipment consistent with the Common Components List
      - Can an Auto-restart sequence be programmed into the operating sequence?
      - Would modification of maintenance improve component resiliency?

HOW COMMON ARE VOLTAGE SAGS?

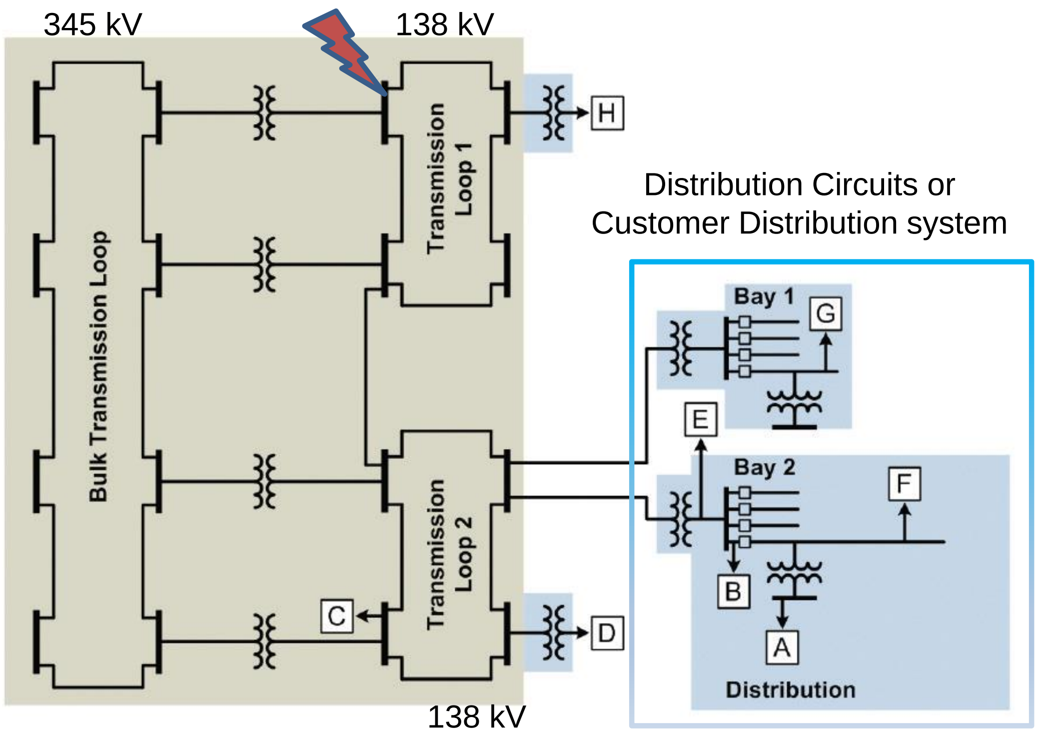
Impact of Fault Location with Respect to my Service Entrance PQ Monitors (PQM) at Locations A Through H



Example One

- Fault to Bulk 345-kV Transmission Loop (Red Lightning Bolt)
- All PQMs Record Event

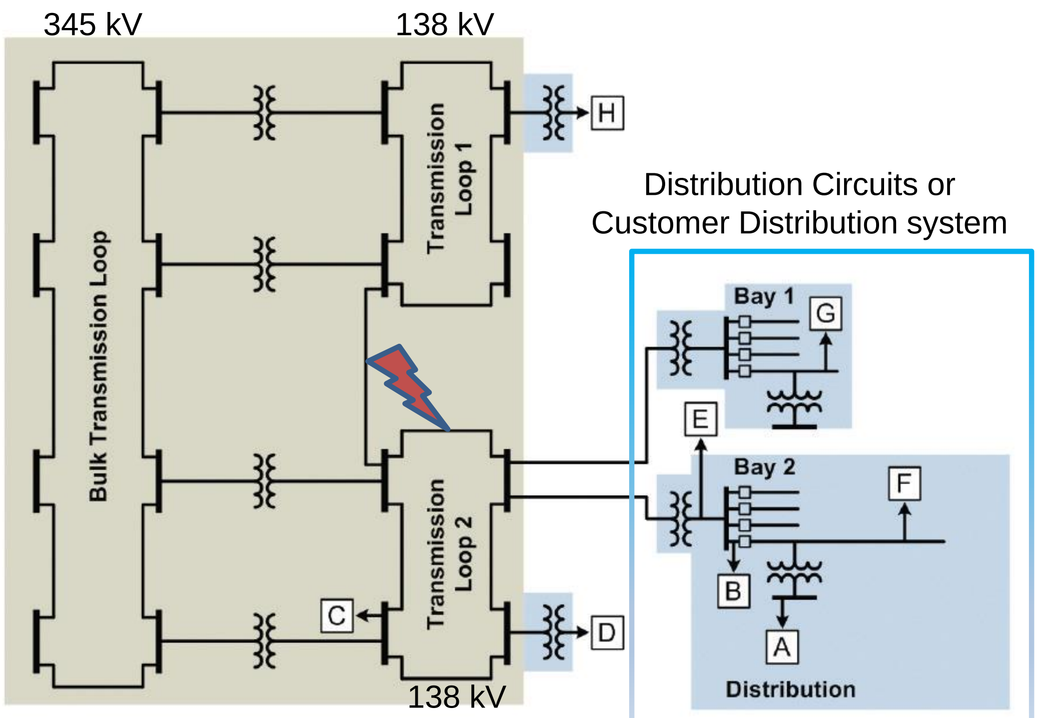
Impact of Fault Location with Respect to my Service Entrance PQ Monitors (PQM) at Locations A Through H



Example Two-A

- Fault to Top 138-kV Transmission Loop (Red Lightning Bolt)
- PQM H Will Record Event – It is on same network as fault
- PQMs A-G May Not Record Event – They Are Somewhat Isolated From The Fault

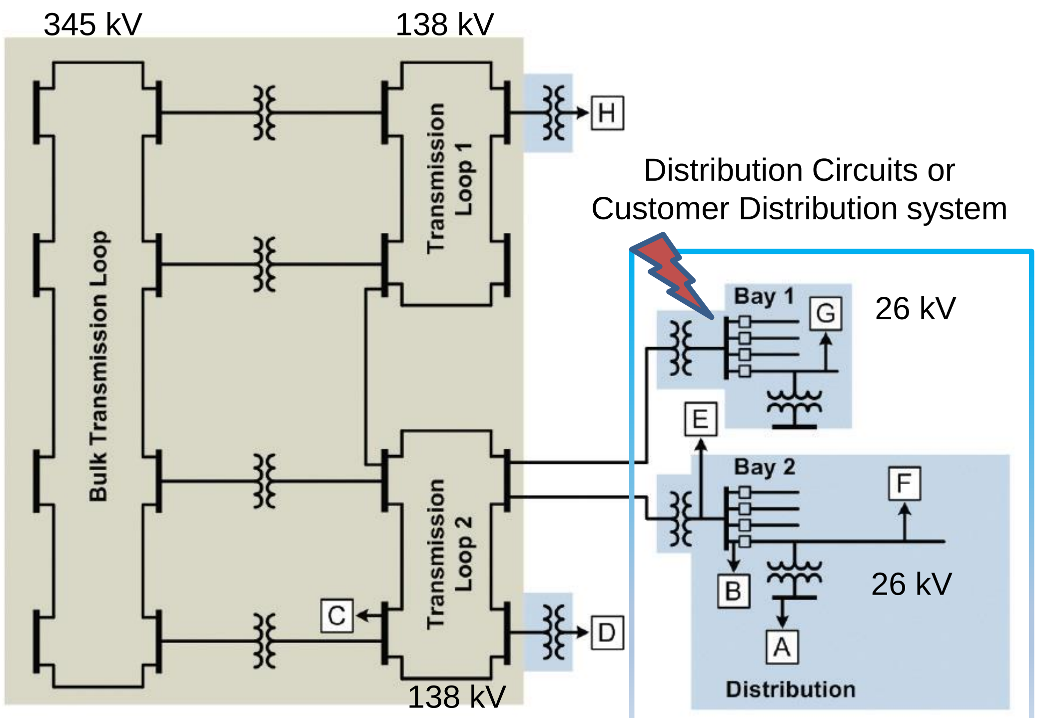
Impact of Fault Location with Respect to my Service Entrance PQ Monitors (PQM) at Locations A Through H



Example Two-B

- Fault to Bottom 138-kV Transmission Loop (Red Lightning Bolt)
- PQMs A-G Will Record Event – It is on same network as fault
- PQM H May Not Record Event – It Is Somewhat Isolated From The Fault

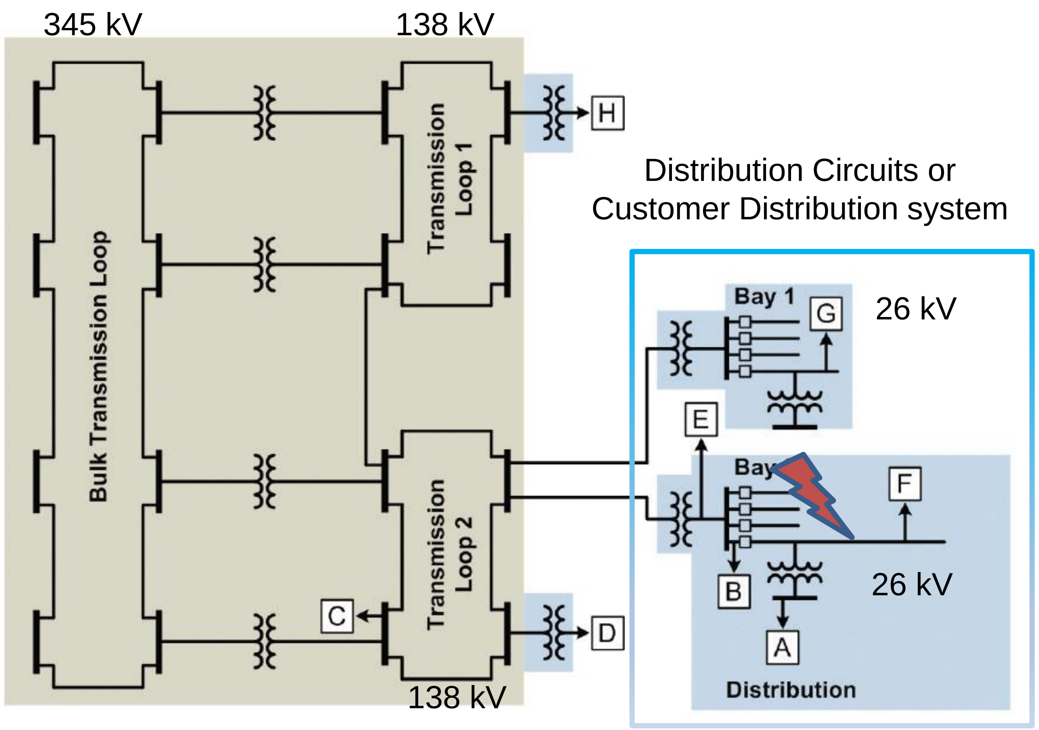
Impact of Fault Location with Respect to my Service Entrance PQ Monitors (PQM) at Locations A Through H



Example Three-A

- Fault to Top 26-kV Distribution System (Red Lightning Bolt)
- PQM G Will Record Event – It is on same network as fault
- PQM A,B,E,F May Not Record Event – They Are Somewhat Isolated From The Fault

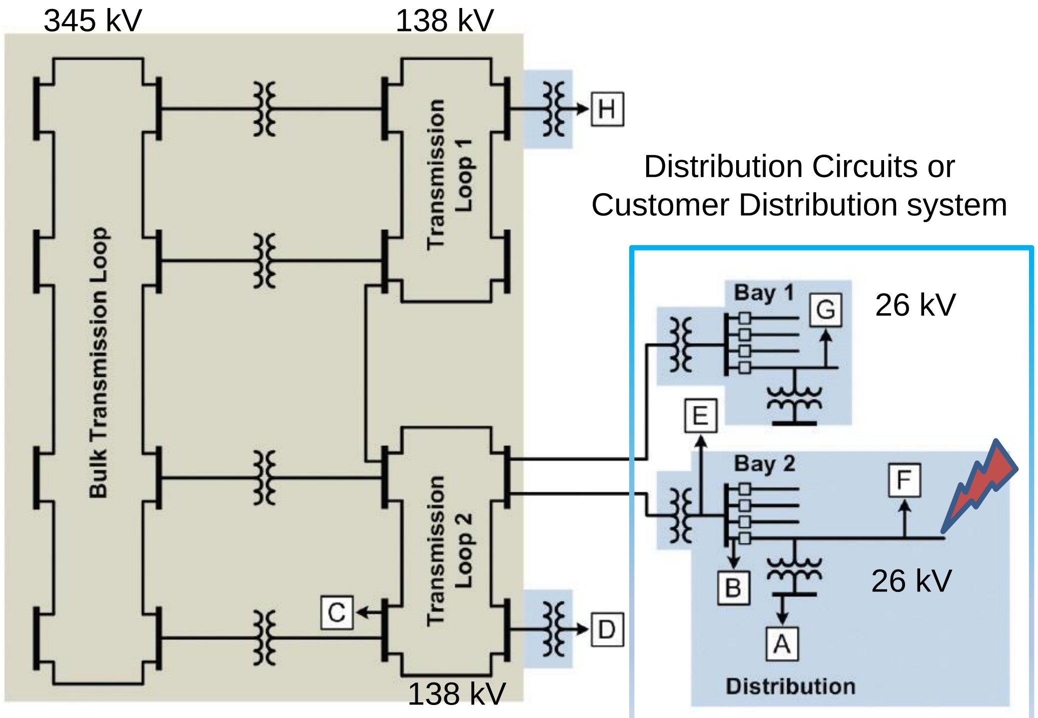
Impact of Fault Location with Respect to my Service Entrance PQ Monitors (PQM) at Locations A Through H



Example Three-B

- Fault to Bottom 26-kV Distribution System (Red Lightning Bolt)
- PQMs A,B,E,F Will Record Event – They are on same network as fault
- PQM G May Not Record Event – It Is Somewhat Isolated From The Fault

Impact of Fault Location with Respect to my Service Entrance PQ Monitors (PQM) at Locations A Through H



Example Four

- Fault to Bottom 26-kV Distribution System (Red Lightning Bolt) – Located Many Miles From Substation
- PQM F Will Record Event – It is on same feeder as fault
- All Other PGMs on Bay 2 May Not Record Event

Summary of Service Illustrations One Through Three

- Example One Shows That Bulk 345-kVTransmission Faults Are Seen My Most PQMs
- But, Service From the Bulk 345-kV Transmission System Would Isolate You From Faults on Transmission 138-kV Loops 1, 2 Plus Faults on Either 26-kV Distribution System
- PQMs Monitoring The Bulk Transmission System 345-kV Will Have The Least Number of Annual Events
- Service From Either 138-kV Loop Exposes You to Events On Your Loop Plus Events On the 345-kV System – You Are Effectively Isolated From Faults On The Other Loop Plus Distribution System Faults
- Many Sensitive Industries Look For This Configuration To Minimize Annual Voltage Sags
- Service From A 26-kV Distribution System Exposes You To Faults Near The Distribution Substation, Faults on The Upstream 138-kV Transmission Loop and Faults On The 345-kV Bulk Transmission System - PQMs Will Record The Highest Number of Annual Voltage Sags In This Configuration

Fortunately, Severe Voltage Sags Are Less Frequent Than Minor Voltage Sags – Shown Below 50% Of The Voltage Sags <70% of Nominal Histogram From EPRI DPQII Study

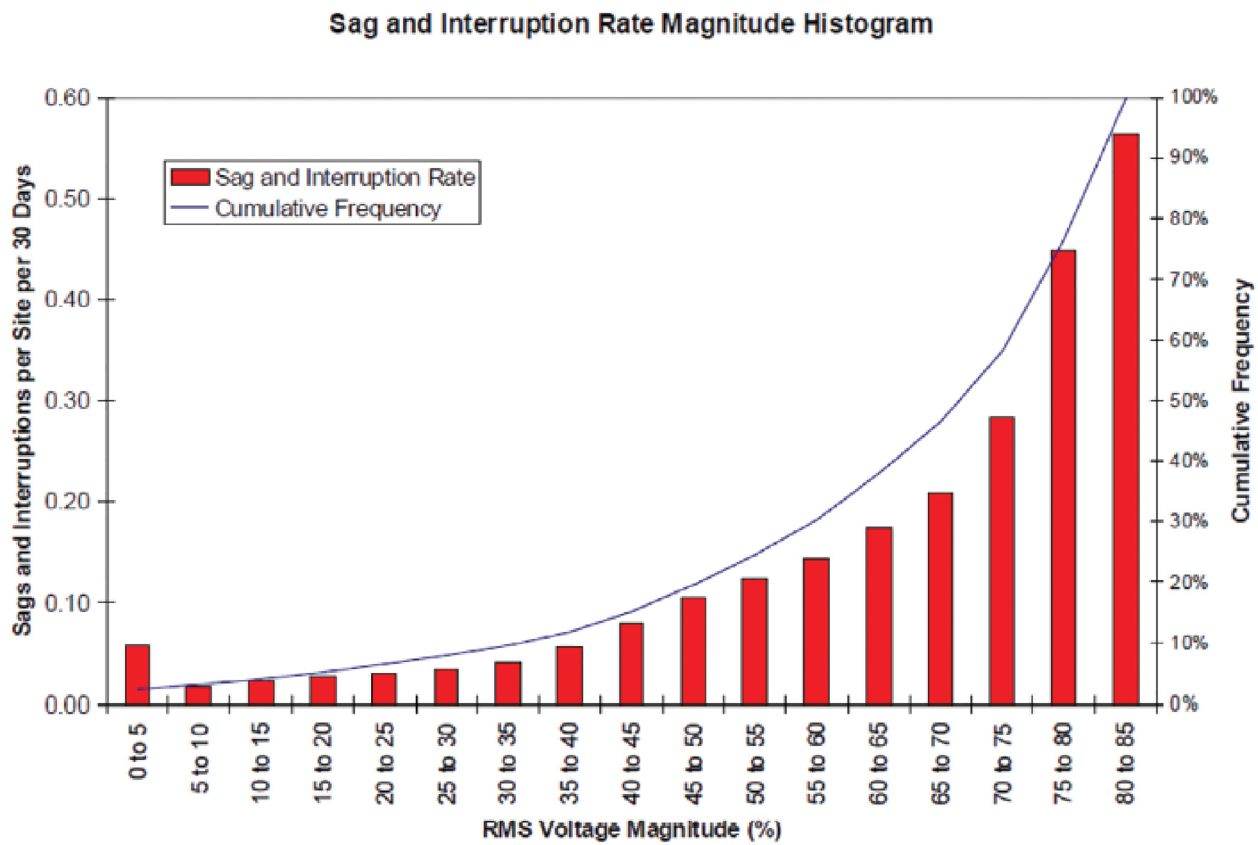


Figure 16—Sag and interruption rate magnitude histogram [B6]

System Average RMS Frequency Variation Index (SARFI)
All EPRI DPQII Study Sites– 13.7 Events/Year <70% of Nominal

Table 5—Annual average SARFI rate of voltage sags (DPQ II—all sites) [B6]

Aggregation period	SARFI-85	SARFI-70	SARFI-50	SARFI-10
60 s	28.49	13.69	5.74	0.91
5 min	26.83	13.02	5.49	0.83
1 d	17.85	9.84	4.49	0.62

Table 6—Yearly SARFI rates(60-s aggregate period, DPQ I, DPQ II, and DPQ II Group 1 sites) [B6]

SARFI level	DPQ Phase I	DPQ Phase II	DPQ Phase II Group 1 (A, F, and G sites)
SARFI-70	23.4	13.7	22.4
SARFI-50	12.2	5.7	13.2
SARFI-10	5.8	0.9	3.4
SARFI-ITIC[a]	23.5	13.9	23.9
SARFI-SEMI[b]	17.0	8.3	19.9

[a]SARFI-ITIC refers to the number of times per site per year that the voltage drops below the ITIC curve.
[b]SARFI-SEMI refers to the number of times per site per year that the voltage drops below the SEMI F47 curve.

Figure 16 displays a histogram of data collected over a 1 min aggregation period from the DPQII [B6] study. The graph shows the percentage cumulative frequency on the right-side vertical axis, while the horizontal axis illustrates the percentage of the rms residual voltage. Further, a left-side vertical axis indicates a 30-d voltage sag and interruption rate per site.

Need for Single, Two, and Three-Phase Voltage Sag Testing EPRI DPQII Study Findings

Expected Number of Affected Phases

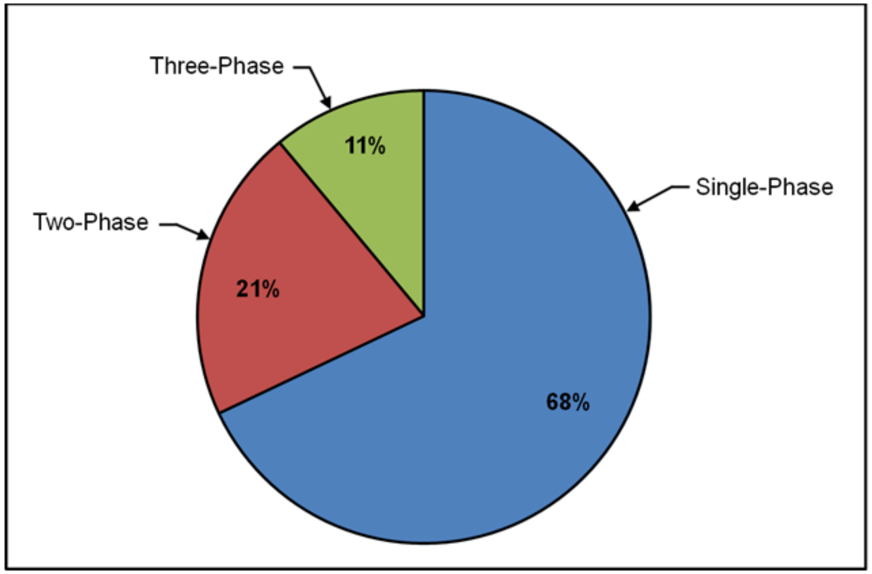


Figure 17—Number of affected phases (i.e., voltage sag types) for voltage sags with at least one remaining voltage below 85% of nominal [B8]

Percent Residual Voltage By Type Sag

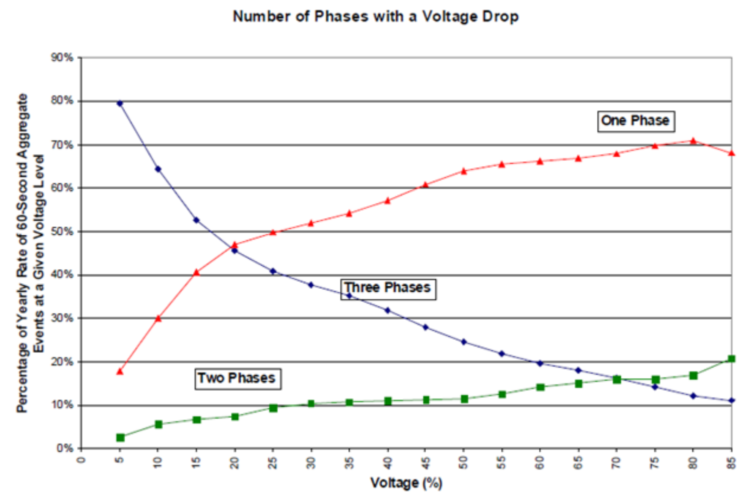


Figure 18—Percent residual voltage by type of sag [B8]

Alternative to EPRI DPQII Study - CIGRE C4.110 Working Group Primarily European Transmission/Distribution Systems

Table 7—Breakout of voltage sag types [B1]

Sites	Voltage range	Number of sites	Single-phase (Type I)	Two-phase (Type II)	Three-phase (Type III)
MV and HV sites	6 kV – 230 kV	969	27%	53%	20%
LV Sites	< 1KV	206	64%	25%	11%

Three Phase Faults Can Occur

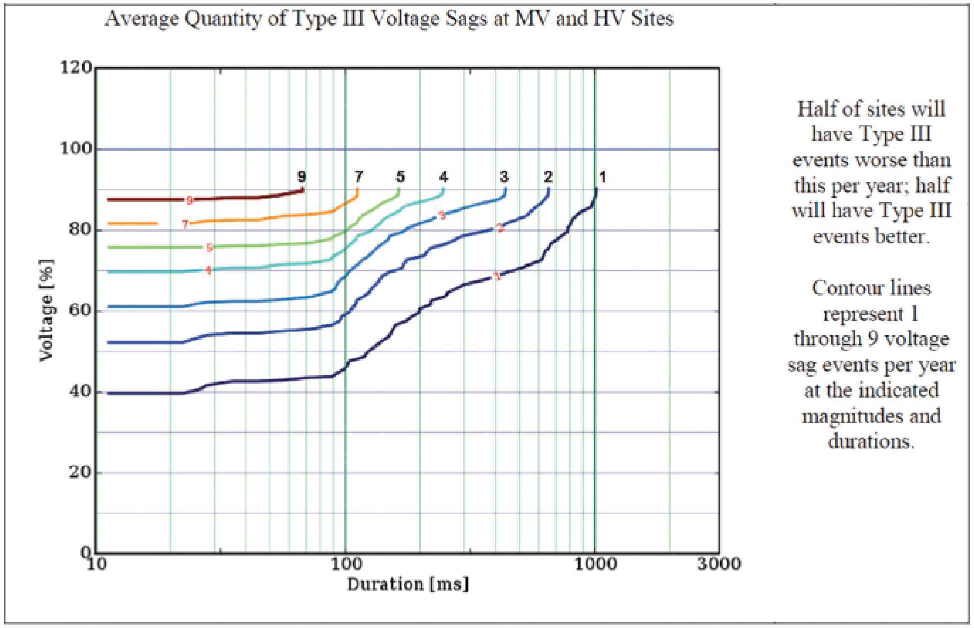


Figure 19—Three-phase (Type III) voltage-sag contour charts [B1]

Three-Phase Fault Breakdown

50% Sites Would See 1-Three-Phase Fault of 40% (or Below) of Nominal Per Year

Applying the New IEEE Std. 1668

IEEE 1668 Section 5:
Recommended voltage-sag test requirements

Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 v

Presented by: Mark Stephens, PE, CEM CP EnMS
IEEE 1668 Working Group Member
April 23, 2018

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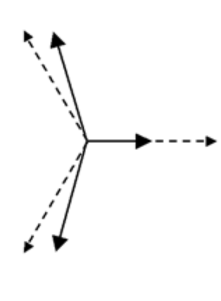
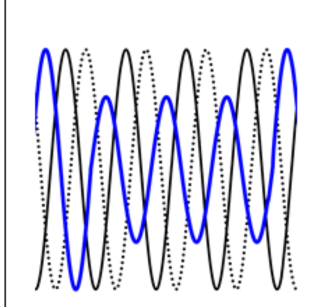
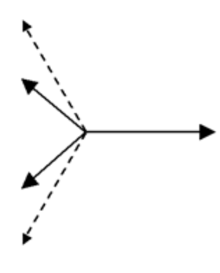
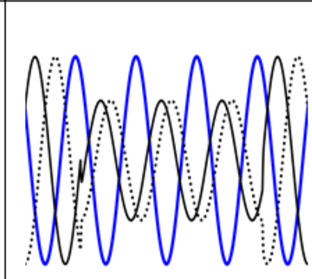
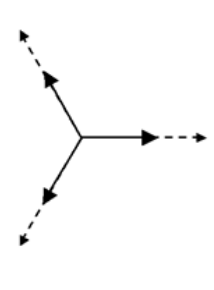
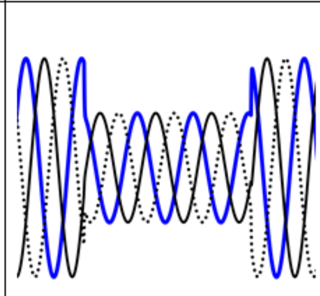
Background on Test Requirements

- This clause details the voltage-sag test requirements of this recommended practice.
- The recommended voltage-sag types and voltage-sag immunity levels are detailed herein.
- All voltage-sag tests should be initiated at 0° point-on-wave with respect to the phase in which the voltage sag is being created during the evaluation of the EUT.
- If multiple phases are being subjected to the sag, the test should be initiated at 0° point-on-wave of the leading phasor.

Classification of Voltage Sags in Three-Phase Systems

Table 8—Recommended Type I, II, and 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. $\overline{U}_a = \overline{V}$ $\overline{U}_b = -\frac{1}{2}\overline{V} - \frac{1}{2}j\overline{E}\sqrt{3}$ $\overline{U}_c = -\frac{1}{2}\overline{V} + \frac{1}{2}j\overline{E}\sqrt{3}$		
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. $\overline{U}_a = \overline{E}$ $\overline{U}_b = -\frac{1}{2}\overline{E} - \frac{1}{2}j\overline{V}\sqrt{3}$ $\overline{U}_c = -\frac{1}{2}\overline{E} + \frac{1}{2}j\overline{V}\sqrt{3}$		
Type III	This is a voltage sag in which there is a drop-in voltage magnitude that is equal for the three voltages. $\overline{U}_a = \overline{V}$ $\overline{U}_b = -\frac{1}{2}\overline{V} - \frac{1}{2}j\overline{V}\sqrt{3}$ $\overline{U}_c = -\frac{1}{2}\overline{V} + \frac{1}{2}j\overline{V}\sqrt{3}$		

[a] Where: V – characteristic voltage of the sag event, E – pre-sag voltage, and Ua, Ub, Uc – phase-to-neutral voltages.

- In its basic form, voltage sags can be classified as three general types that can occur at the terminals of sensitive equipment.
- Classified as Type I, Type II, and Type III, a representation of these three basic are can also be thought of as Single-Phase, Two-Phase, and Three-Phase.

Recommended Type I Test Vector

- When performing voltage-sag testing, alternative voltage-sag vector forms are allowed. When testing three-phase equipment, single-phase sags (i.e., Type I voltage sags) are created on one phase at a time.
- Although the allowed Type I voltage sag has no phase shift with respect to the neutral, this sag is relatively easy to create with standard test equipment and has been used in existing standards such as IEC 61000-4-11, IEC 61000- 4-34, and SEMI F47–0706 to represent Type I events.

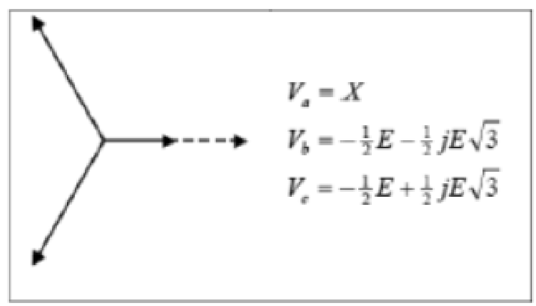


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Figure 20—Recommended Type I test vectorwhere *E* represents the nominal phase-to-neutral voltage, *V* represents the residual voltage or “Dip magnitude”, and *X* represents the residual phase-to-neutral voltage [B1]

Understanding Type II

- Type II sags normally occur on the secondary side of a delta-wye transformer when there is a single-phase fault on the primary side of the transformer. A Type II event can also occur when two conductors are faulted together.
- There are three common methods for creating Type II voltage sags
  - Figure 21 (next slide) shows the recommended two phase test vector (Type II) and two allowable alternatives designated as Type II.A1 and Type II.A2.
  - A Type II.A1 event does not occur often and induces the most phase shift.
  - The Type II.A2 event can occur when there is a simultaneous phase-phase-to-ground fault.
- Because the choice of test vector for Type II sags has been known to change the outcome of the voltage-sag test result, consult Annex A for guidance.

Understanding Type II

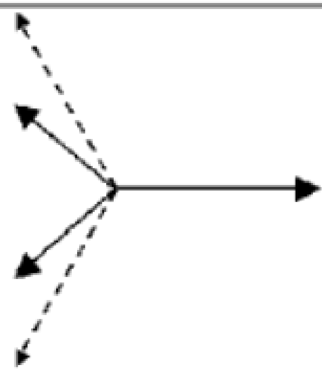
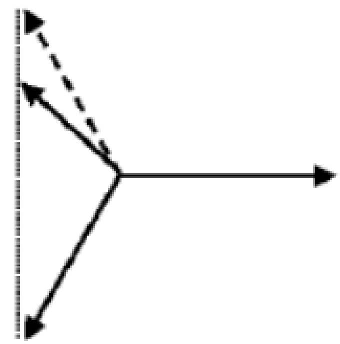
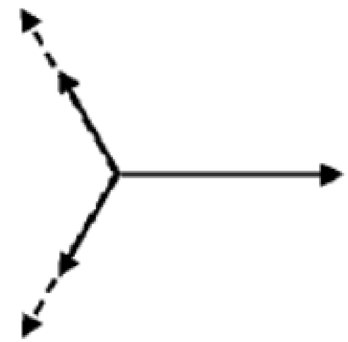
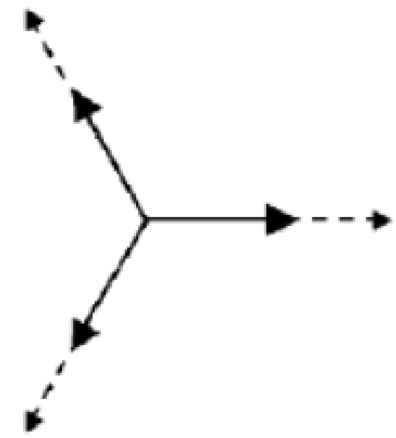
Type II (Recommended)	Type II.A1 (Alternate 1)	Type II.A2 (Alternate 2)
		
$V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}jV\sqrt{3}$	$V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}j(2X - E)\sqrt{3}$	$V_a = E$ $V_b = -\frac{1}{2}X - \frac{1}{2}jX\sqrt{3}$ $V_c = -\frac{1}{2}X + \frac{1}{2}jX\sqrt{3}$

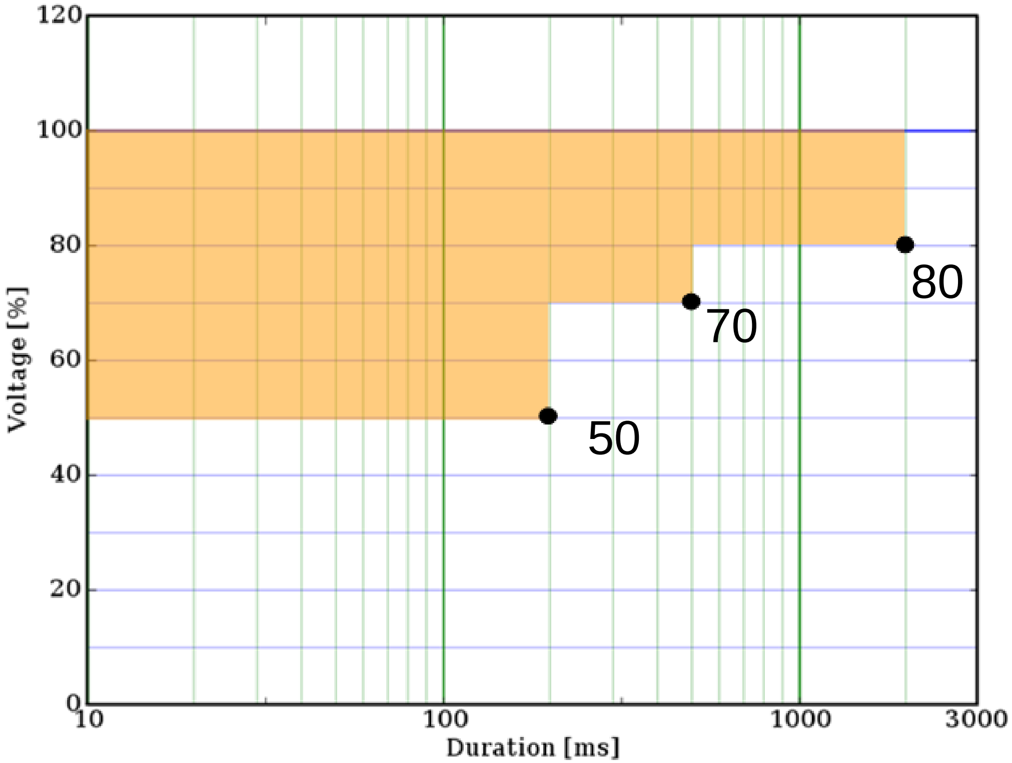
Figure 21—Recommended and alternative Type II test vectors where *E* represents the nominal voltage and *V* represents the residual voltage [B1]

Recommended Type III Test Vectors

Type III	This is a voltage sag in which there is a drop in voltage magnitude that is equal for the three voltages. $\bar{U}_a = \bar{V}$ $\bar{U}_b = -\frac{1}{2}\bar{V} - \frac{1}{2}j\bar{V}\sqrt{3}$ $\bar{U}_c = -\frac{1}{2}\bar{V} + \frac{1}{2}j\bar{V}\sqrt{3}$	

Recommended Type I and Type II voltage-sag test immunity levels (One Phase and Two Impacted Phases)

Minimum test point No.	Residual voltage in percent nominal	Duration in seconds	Duration at 50 Hz	Duration at 60 Hz
1	50%	0.2	10 cycles	12 cycles
2	70%	0.5	25 cycles	30 cycles
3	80%	2.0	100 cycles	120 cycles



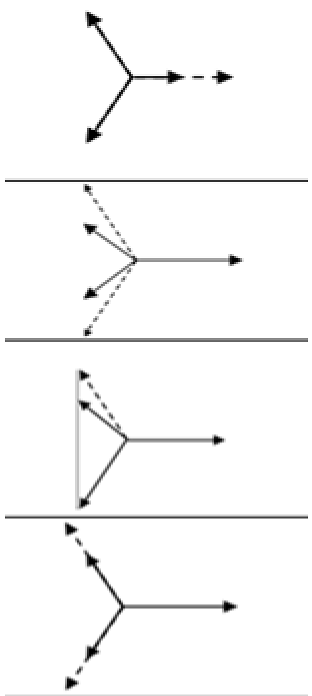
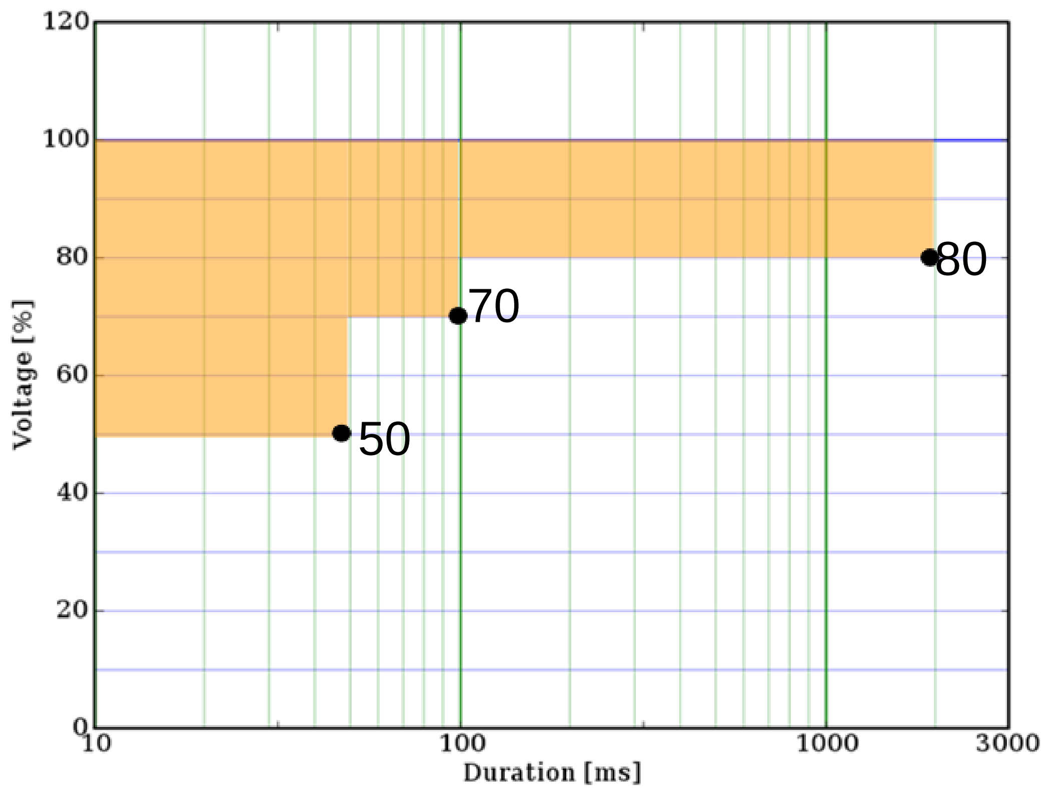


Figure 22—Recommended Type I & Type II test levels

Recommended Type III voltage-sag test immunity levels (Three Impacted Phases)

Minimum test point No.	Residual voltage in percent nominal	Duration in seconds	Duration at 50 Hz	Duration at 60 Hz
1	50%	0.05	2.5 cycles	3 cycles
2	70%	0.1	5 cycles	6 cycles
3	80%	2.0	100 cycles	120 cycles



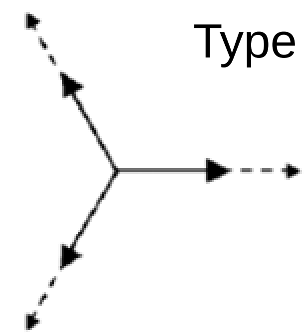


Figure 23—Recommended Type III test levels

Understanding the Pass/Fail Criteria Background

a) Full (normal) operation:
   - Equipment performs as expected or intended and all of its relevant parameters are within technical specifications or within allowed tolerance limits.
   - Equipment performance should be expressed and measured against the set of relevant/critical "equipment outputs" (for example, speed, torque, and voltage level), which have to be defined as per the process requirements.

b) Self-recovery:
   - Equipment does not perform its intended functions, or its outputs vary outside the technical specification/limits, but equipment is able to automatically recover after the end of a voltage sag without any intervention from the user.

c) Assisted-recovery:
   - Equipment does not perform intended functions, or its outputs vary outside the technical specification/limits, and equipment is not able to automatically recover after the end of a voltage sag.
   - Assisted-recovery criteria should be applied only when there are dedicated and/or trained personnel/staff, who either operate the equipment or are responsible for supervising the equipment at all times when equipment is in use.
   - If some external control circuit is applied for automatic restarting of equipment, this should be treated as a self-recovery criterion.

DEMO: ASSISTED-RECOVERY

Equipment does not perform intended functions, or its outputs vary outside the technical specification/limits, and equipment is not able to automatically recover after the end of a voltage sag.

Assisted-recovery criteria should be applied only when there are dedicated and/or trained personnel/staff, who either operate the equipment or are responsible for supervising the equipment at all times when equipment is in use.

If some external control circuit is applied for automatic restarting of equipment, this should be treated as a self-recovery criterion.

Test: 3cycle 50% Type III
Sensitive MCR

DEMO: SELF RECOVERY

Equipment does not perform its intended functions, or its outputs vary outside the technical specification/limits, but equipment is able to automatically recover after the end of a voltage sag without any intervention from the user.

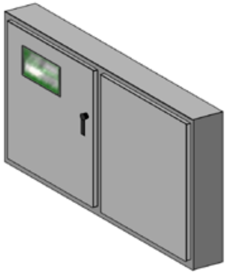
Test: 3cycle 50% Type III
Robust MCR, Drive RT Parameters Set

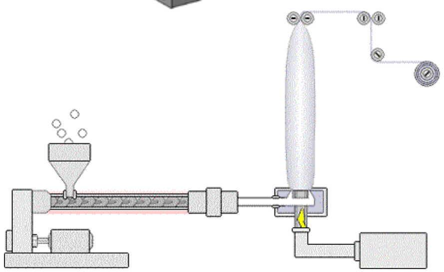
DEMO: FULL (NORMAL) OPERATION

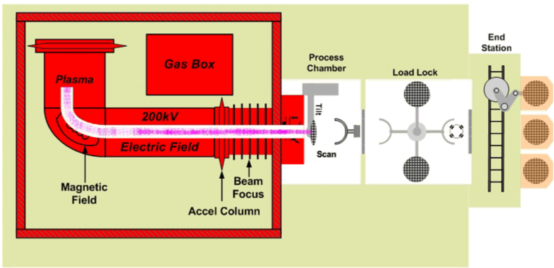
Equipment performs as expected or intended and all of its relevant parameters are within technical specifications or within allowed tolerance limits. Equipment performance should be expressed and measured against the set of relevant/critical "equipment outputs" (for example, speed, torque, and voltage level), which have to be defined as per the process requirements.

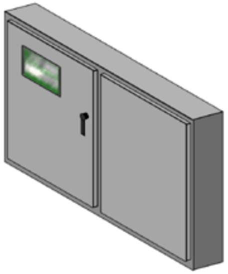
Test: 6cycle 70% Type III
Robust MCR, Drive RT Parameters Set

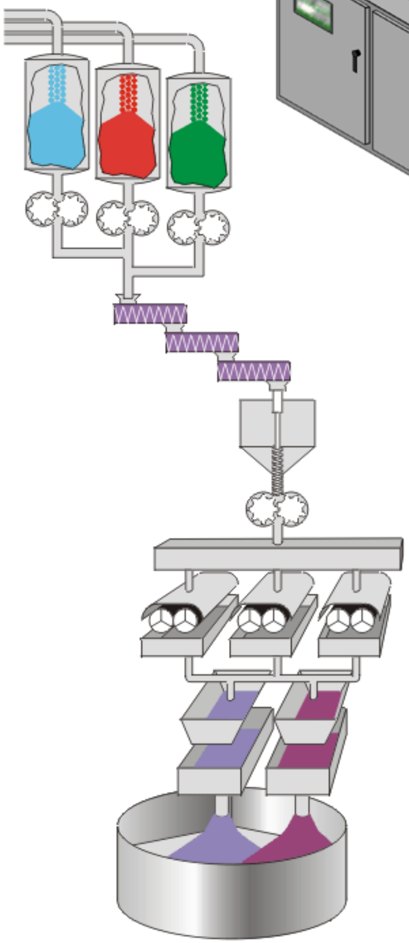
Machines and Processes

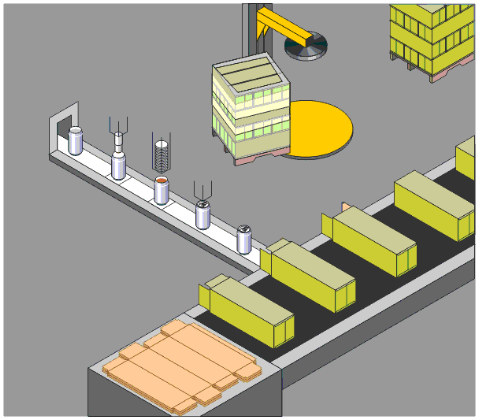


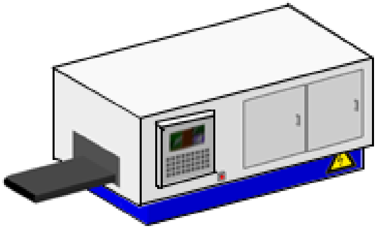


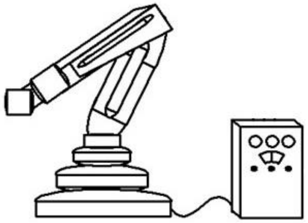






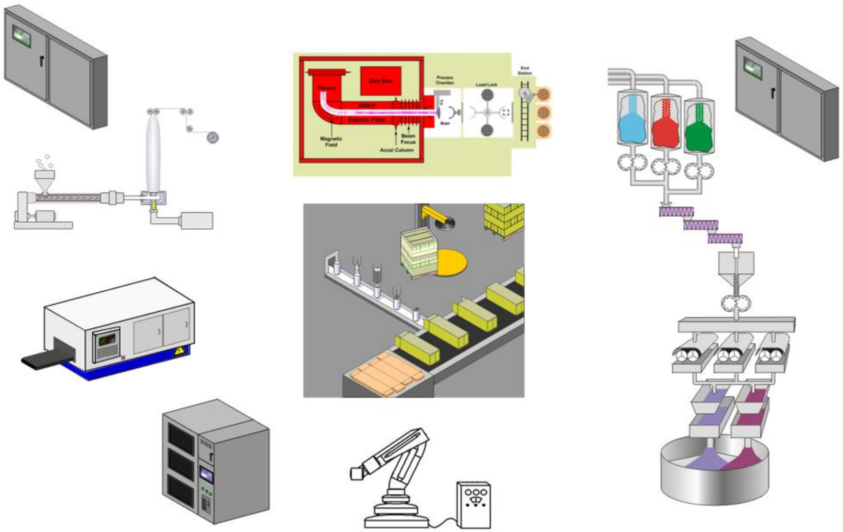






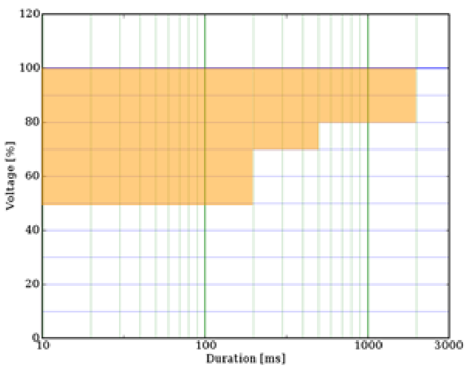
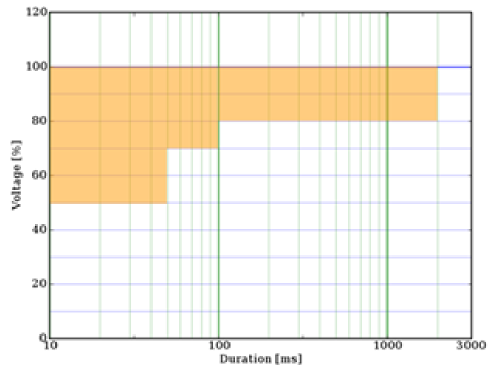
Choosing pass/fail criteria for process machines/equipment

- In the absence of other instructions or requirements, the default pass/fail criteria for the testing of equipment to determine its immunity to voltage sags should be full (normal) operation.
- Table 12 (next page) allows for the buyer to specify the required response of the equipment for Type I and Type II sags as well as Type III sags.
- Table 13 is provided for specifying the requirement for single-phase equipment.



Three-Phase Equipment Specification

Table 12—IEEE 1668™ voltage-sag equipment-immunity specification sheet (for use with three-phase equipment)

<table>
<tr><td colspan="3">Immunity Curve for Type I & Type II Sags

</td><td colspan="3">Immunity Curve for Type III Sags

</td></tr>
<tr><td colspan="3">Type I and II voltage-sag test points:

80% for 2 s
70% for 500 ms
50% for 200 ms

Repeat for test points for each phase-neutral and phase-to-phase combination.</td><td colspan="3" rowspan="4">Testing for Type III voltage-sag required:

80% for 2 s
70% for 100 ms
50% for 50 ms</td></tr>
<tr><td colspan="3">Desired Type II Test Vector</td></tr>
<tr><td>Type II</td><td>Type II.A1</td><td>Type II.A2</td></tr>
<tr><td>☐</td><td>☐</td><td>☐</td></tr>
<tr><td colspan="3">Pass/Fail Criteria</td><td colspan="3">Pass/Fail Criteria</td></tr>
<tr><td>Full Operation</td><td>Self-Recovery</td><td>Assisted-Recovery</td><td>Full Operation</td><td>Self-Recovery</td><td>Assisted-Recovery</td></tr>
<tr><td>☐</td><td>☐</td><td>☐</td><td>☐</td><td>☐</td><td>☐</td></tr>
<tr><td colspan="6">Testing Procedure Requirements: IEEE 1668</td></tr>
</table>

- Table 12 (next page) allows for the buyer to specify the required response of the equipment for Type I and Type II sags as well as Type III sags.

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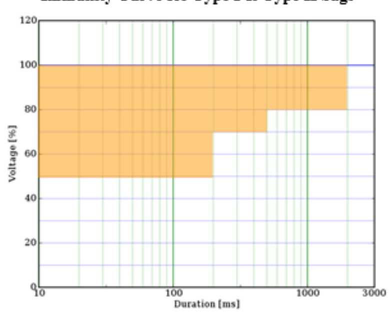
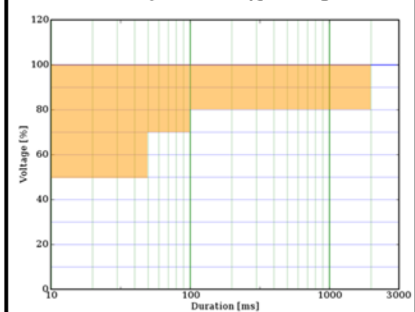
3-Phase Machine – With Full Normal Operation Specified

Specified Machine Response by Buyer

Table 12—IEEE 1668™ voltage-sag equipment-immunity specification sheet (for use with three-phase equipment)

Immunity Curve for Type I & Type II Sags	Immunity Curve for Type III Sags
	
Type I and II voltage-sag test points: 80% for 2 s 70% for 500 ms 50% for 200 ms Repeat for test points for each phase-neutral and phase-to-phase combination.	**Testing for Type III voltage-sag required:** 80% for 2 s 70% for 100 ms 50% for 50 ms

Desired Type II Test Vector

Type II	Type II.A1	Type II.A2
✓	☐	☐

Pass/Fail Criteria (Type I & II)

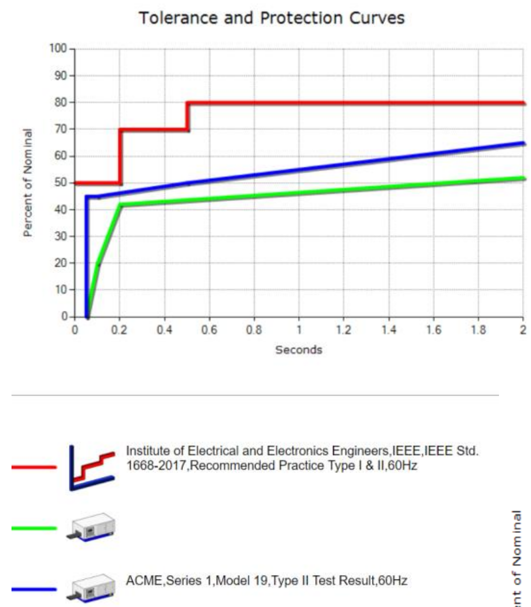
Full Operation	Self-Recovery	Assisted-Recovery
✓	☐	☐

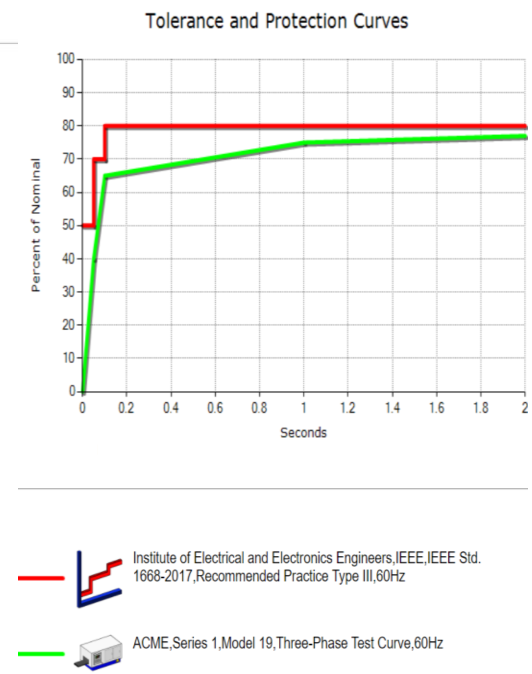
Pass/Fail Criteria (Type III)

Full Operation	Self-Recovery	Assisted-Recovery
✓	☐	☐

Testing Procedure Requirements: IEEE 1668

Example Test Results

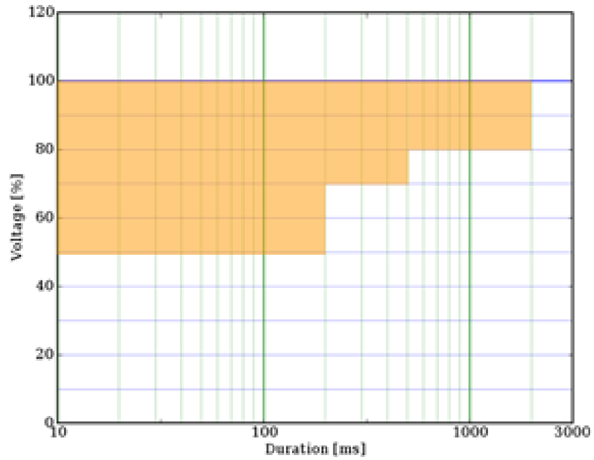




Recommended Voltage-Sag Immunity Levels

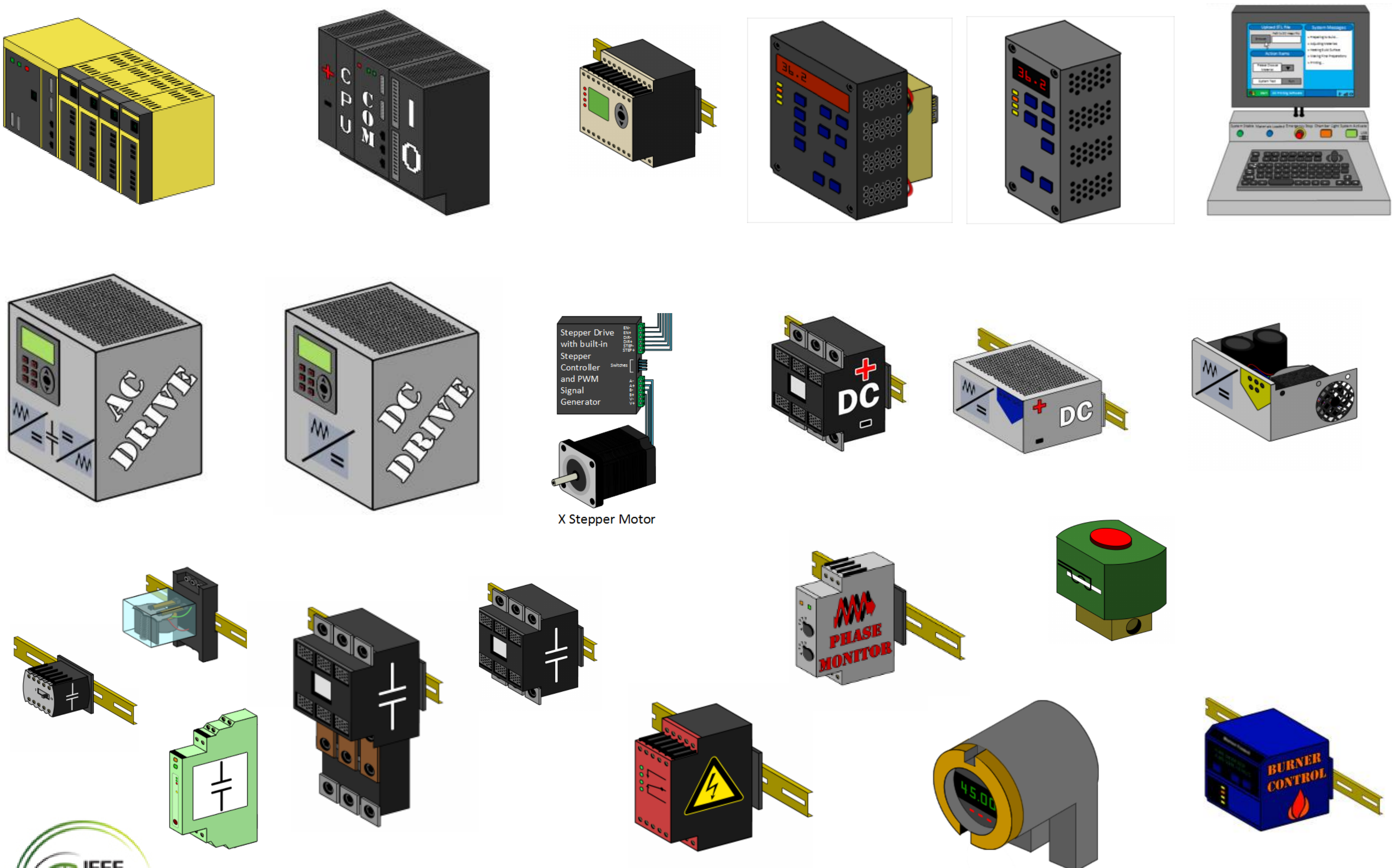
Table 13 —IEEE 1668 voltage-sag equipment-immunity single-specification sheet (for use with single-phase equipment)

Immunity Curve for Type I Sags



Type I voltage-sag test points: 80% for 2 s 70% for 500 ms 50% for 200 ms		
Pass/Fail Criteria		
Full Operation	**Self-Recovery**	**Assisted- Recovery**
☐	☐	☐
Testing Procedure Requirements: IEEE 1668		

How does IEEE 1668 Apply to Components?

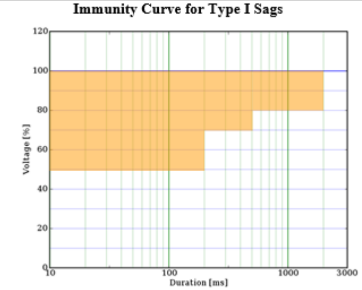


Choosing pass/fail criteria for subsystems and components

- For component testing performed by the equipment buyer/user or system integrator/OEM, the required response of the subsystem or component for Type I, Type II, and Type III sags can be specified as in Table 13.
- When constructing equipment that will comply with this specification, each system integrator/OEM should select components and subsystems that respond appropriately to voltage sags.

Table 13—IEEE 1668 voltage-sag equipment-immunity single-specification sheet (for use with single-phase equipment)

Immunity Curve for Type I Sags



Type I voltage-sag test points:

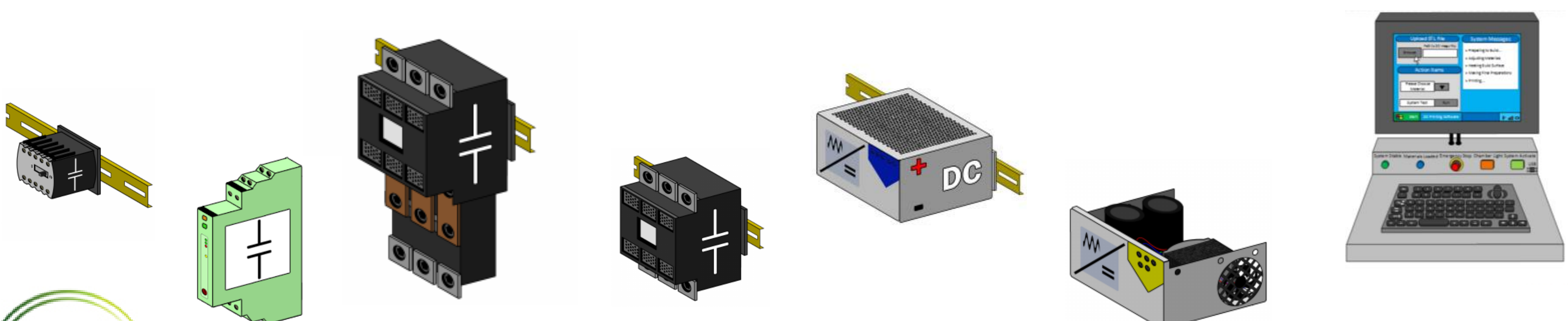
80% for 2 s
70% for 500 ms
50% for 200 ms

Pass/Fail Criteria		
Full Operation	Self-Recovery	Assisted- Recovery
☐	☐	☐

Testing Procedure Requirements: IEEE 1668

Choosing pass/fail criteria for subsystems and components

- The simplest yet most costly approach is to require that all components and subsystems provide full (normal) operation during all required voltage sags.
- Full (normal) Operation malfunction criteria should be chosen by the system integrator/OEM for components whose full specified operation is required for normal operation of finally-constructed equipment during voltage sags.
- For example, contactors with ac coils, relays with ac coils, dc power supplies, and computers often fall into this category.

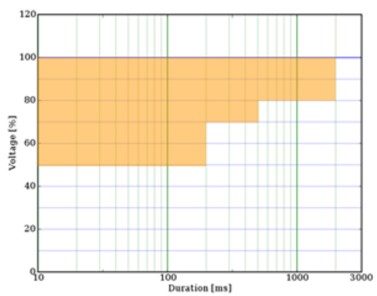


Example Component with Full Normal Operation

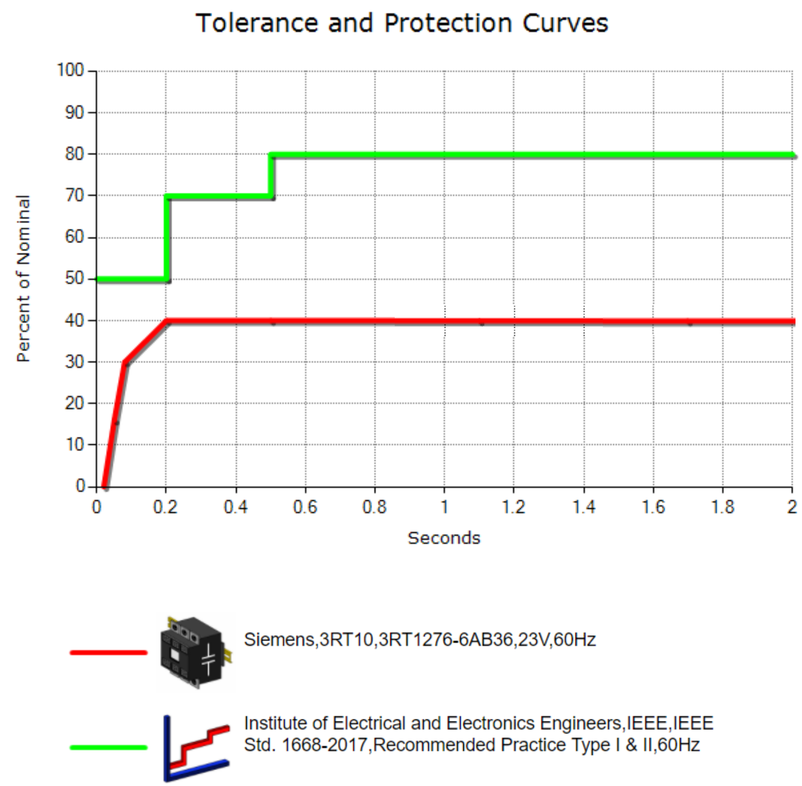
- The contactor is a single-phase device from a controls perspective.
- The Contactor in Question stays engaged for the IEEE Test Points for Type I sags.

Table 13—IEEE 1668 voltage-sag equipment-immunity single-specification sheet (for use with single-phase equipment)

Immunity Curve for Type I Sags

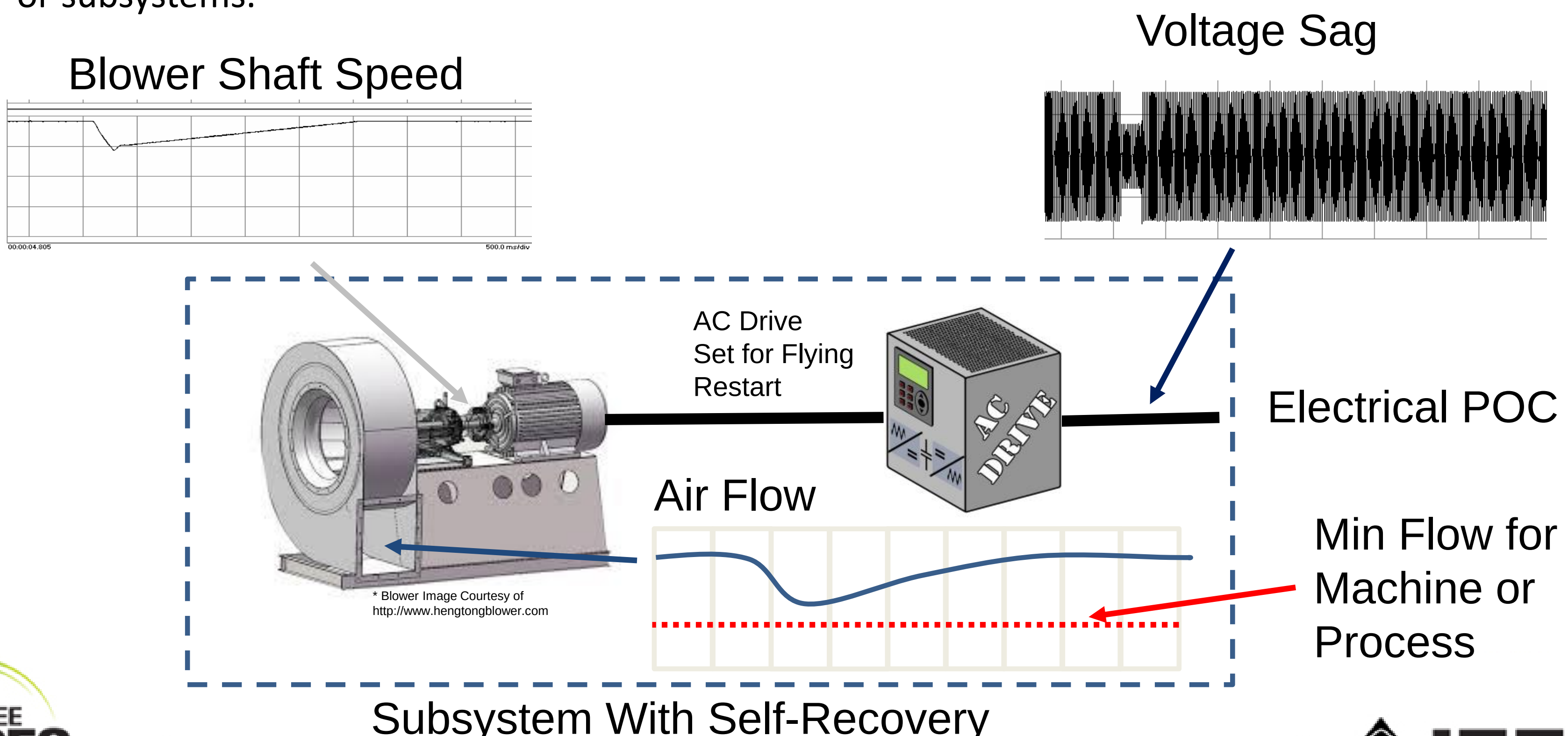


Type I voltage-sag test points: 80% for 2 s 70% for 500 ms 50% for 200 ms		
Pass/Fail Criteria		
Full Operation	**Self-Recovery**	**Assisted- Recovery**
✔	☐	☐
Testing Procedure Requirements: IEEE 1668		



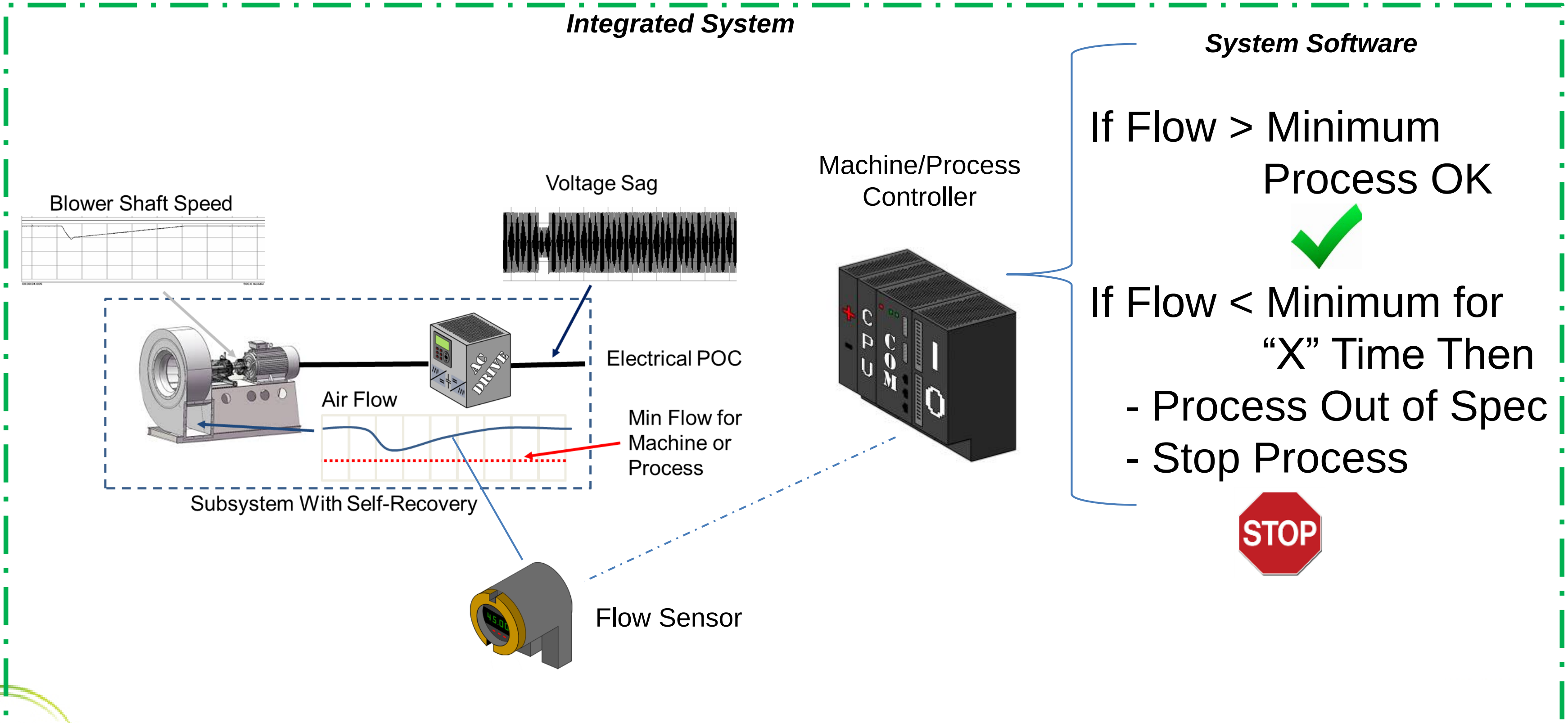
Choosing pass/fail criteria for subsystems and components

- If reasonable engineering judgment determines that equipment is unlikely to shut down due to a brief change in the effectiveness of operation (i.e., malfunction) of a component or subsystem (for example, blowers driven by Adjustable Speed Drives), then the system integrator/OEM might select pass/fail criteria to allow self-recovery for these components or subsystems.



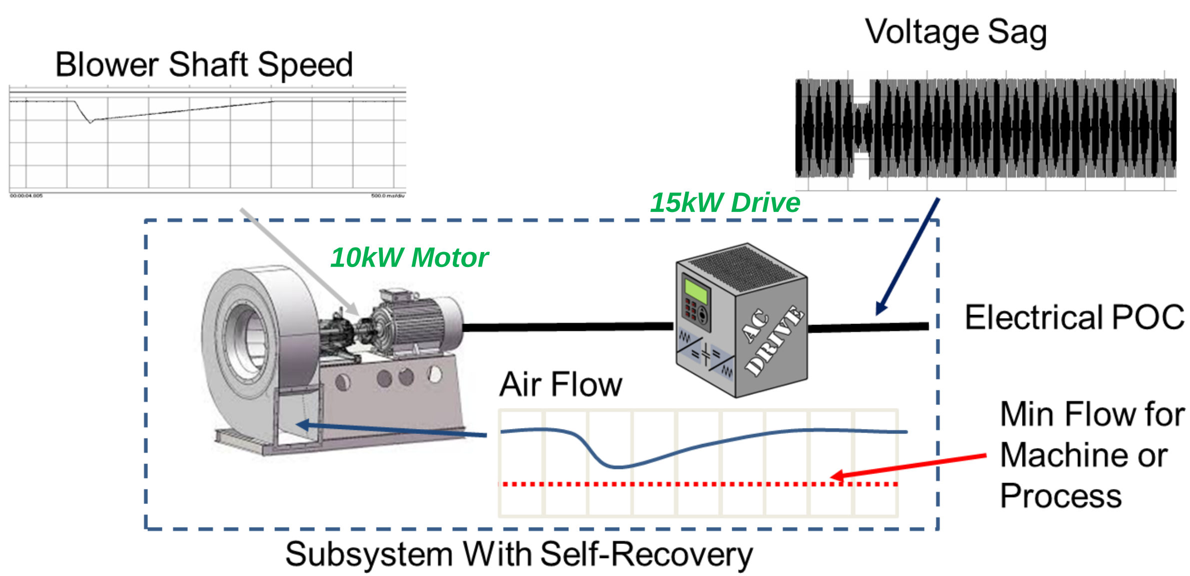
Choosing pass/fail criteria for subsystems and components

- The system integrator/OEM can recognize that the system software will respond appropriately to signals from certain subsystems and components during voltage sags (and will not cause a system shutdown), and therefore might select assisted-recovery pass/fail criteria.



Choosing pass/fail criteria for subsystems and components

- If the system integrator/OEM knows that the component or subsystem will never be used at its full-rated output, the system integrator might consider accepting test conditions under that more closely match the intended application (for example, if an ac drive is rated at 15 kW, but the equipment design only calls for it to be used at a maximum of 10 kW, the system integrator can choose to accept voltage-sag testing at 10 kW load instead of testing at full-load).



Use of this specification for procurement

- With the establishment of the recommended voltage-sag test vectors, immunity levels, and desired equipment performance, it is possible for the equipment buyer/user to specify the desired equipment immunity in a purchase requisition.
- A specification sheet for equipment immunity is provided in Table 12 and Table 13 for use by equipment buyers when purchasing three-phase or single-phase equipment.
- The equipment buyer can use this document to specify requirements for voltage-sag immunity to a system integrator/OEM. In turn, the system integrator/OEM can use this document to specify voltage-sag immunity requirements to their subsystem and component suppliers.
- Specific industries whose requirements are more stringent than the recommended levels can refer to test levels as defined in other documents such as IEC 61000-4-34, Class 3.

Use of this specification for procurement

- Orders for equipment, subsystems, and components should specify the following:
  - a) This recommended practice document number and date of publication.
  - b) The requirement for a certificate per Annex C of this document (optional).
  - c) The requirement for a test report per Annex C of this document (optional).
  - d) Whether a third-party certificate is required, or whether self-certification is acceptable (optional).

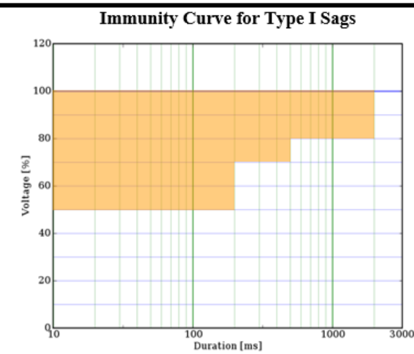
Example Purchase Spec Language*

- The equipment provider (Seller) shall provide documentation that proves that the provided equipment is compliant with the IEEE Std. P1668-2017 Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 V. The qualification testing shall be conducted and completed prior to the first scheduled shipment of new products to Buyer. If Seller has conducted the required testing before and can provide a test report to prove compliance, then retesting shall not be required. Such testing shall occur, at the option of Buyer, either at Seller's facility or on the premises of Buyer and shall be at the expense of the Seller. Qualification testing shall determine the acceptability of the equipment in accordance with the IEEE 1668 specifications and shall be conducted in accordance with the procedures outlined in the standard. In addition to the test results, the Seller must clearly document the test method and test equipment used for creating voltage sags per Annex C of IEEE 1668. Upon written agreement of Seller and Buyer that the qualification tests have been successfully completed, the initial deliveries of production unit(s) of the equipment shall commence in accordance with the scheduled shipment established by issued Purchase Orders.

* Not part of IEEE Std. 1668 – Offered here as an Example

Example Purchase Spec Language*

Requirements for Single-Phase Equipment from Seller: Single-phase powered equipment shall comply with the Type I volt-age sag immunity requirements defined by IEEE 1668 shown in Figure 1. The acceptable pass/fail criteria for single-phase equipment shall be “Full Operation”.



Type I voltage-sag test points:
80% for 2 s
70% for 500 ms
50% for 200 ms

Pass/Fail Criteria		
Full Operation	**Self-Recovery**	**Assisted Recovery**
X		
Testing Procedure Requirements: IEEE 1668		

Figure 1
Voltage Sag Immunity Requirements for Single-Phase Equipment

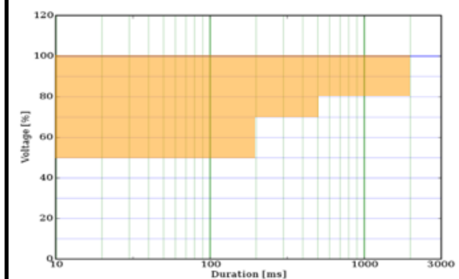
* Not part of IEEE Std. 1668 – Offered here as an Example

Example Purchase Spec Language*

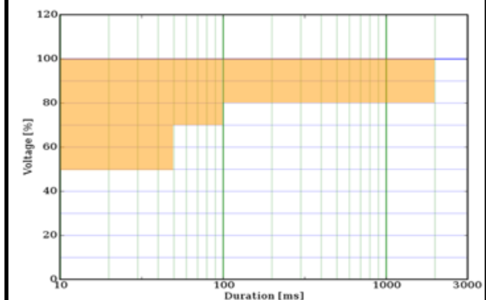
Requirements for Three-Phase Equipment from Seller: Three-phase powered equipment shall comply with the single-phase (Type I) and two-phase (Type II) voltage sag immunity requirements defined by IEEE 1668 as shown in Figure 2. The acceptable pass/fail criteria for the Type I and Type II tests on the equipment shall be "Full Operation". The equipment shall also comply with the three-phase (Type III) voltage sag immunity requirements with a minimum Pass/Fail criterion of "Self-Recovery"**.

*** Note:*
User could specify "full operation" for Type III if desired. This may or may not require stored energy to achieve.

Immunity Curve for Type I & Type II Sags



Immunity Curve for Type III Sags



Type I and II voltage-sag test points:
80% for 2 s
70% for 500 ms
50% for 200 ms

Repeat for test points for each phase-neutral and phase-to-phase combination.

Desired Type II Test Vector

Type II	Type II.A1	Type II.A2
X		

Pass/Fail Criteria (Type I and II)

Full Operation	Self Recovery	Assisted Recovery
X		

Testing for Type III voltage-sag required:

80% for 2 s
70% for 100 ms
50% for 50 ms

Pass/Fail Criteria (Type III)

Full Operation	Self Recovery	Assisted Recovery
	X	

Testing Procedure Requirements: IEEE 1668

Figure 2
Voltage Sag Immunity Requirements for Three-Phase Equipment

* Not part of IEEE Std. 1668 – Offered here as an Example

Applying the New IEEE Std. 1668

Annex A:
Test Procedures and Guidelines
(Informative)

Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 v

Presented by: Mark Stephens, PE, CEM, CP EnMS
Alden Wright, PE, CEM, CP EnMS
Scott Bunton, CPQ, CEM

IEEE 1668 Working Group Member
April 23, 2018

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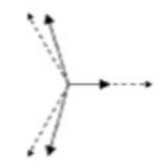
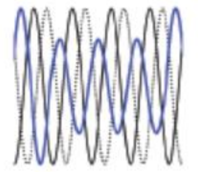
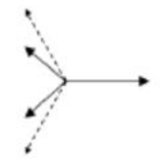
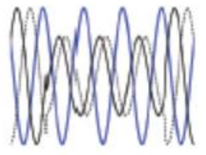
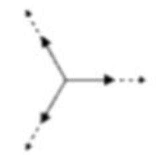
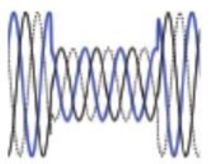
A.1 Considerations and guidance on test vectors

- It is not always practical to reproduce the voltage sags exactly as shown in Table 8 of this recommended practice, approximations might need to be made to allow the use of available test equipment.
- Therefore, the standard presents both recommended and allowed test vectors along with important considerations.

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

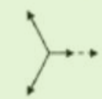
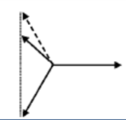
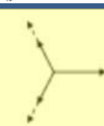
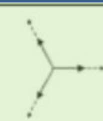
Voltage-sag type	Description[a]	Vector diagram	Waveform
Type I	This is a voltage sag in which a drop in voltage takes place mainly in one of the phase-to-ground voltages. $\bar{U}_a = \bar{V}$ $\bar{U}_b = -\frac{1}{2}\bar{V} - \frac{1}{2}j\bar{E}\sqrt{3}$ $\bar{U}_c = -\frac{1}{2}\bar{V} + \frac{1}{2}j\bar{E}\sqrt{3}$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

[a]Where: V = characteristic voltage of the sag event, E = pre-sag voltage, and Ua, Ub, Uc = phase-to-neutral voltages.

Considerations and guidance on test vectors (Specifically Type II)

- Table A.1 presents both recommended and allowed test vectors and important considerations.
- In many initial system compatibility tests, most Type II tests were completed using what is referred to as Type II.A2 because the first models of voltage-sag generators were based on referencing the voltage sag to a neutral conductor.
  - This method has provided the most severe scenario for phase-vector magnitudes during tests and has been proven to lead to improvements in voltage-sag immunity of end-use equipment.
  - However, Type II.A2 induces little phase shift for the phase-to-phase vectors and no phase shift for the phase-to-neutral vectors. For equipment with active front ends and phase-locked-loop type controls, testing by Type II.A2 could lead to a false sense of robustness for certain types of loads because no phase shifting occurs.

Table A.1—Recommended and allowed voltage-sag test vectors and considerations [B1] (where *E* represents the nominal voltage, *V* represents the residual voltage, *X* represents the residual phase to neutral voltage)

Type description	Example test-vector method	Vector descriptions	Comments
Recommended Type I		$V_a = X$ $V_b = -\frac{1}{2}E - \frac{1}{2}jE\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}jE\sqrt{3}$	This testing is most relevant to single-phase equipment or three-phase equipment with a neutral.
Recommended Type II (IEC Type 3c)		$V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}jV\sqrt{3}$	One study [B1] indicated that this type of voltage sag makes up 82% to 91% of Type II events on HV and MV networks.
Allowed Type II.A1 (IEC Type 3b)		$V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jE\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}j(2X - E)\sqrt{3}$	The previous study [B1] indicated that this type of voltage sag makes up 9% to 18% of Type II events on HV and MV networks.
Allowed Type II.A2 (IEC Type 3d)		$V_a = E$ $V_b = -\frac{1}{2}X - \frac{1}{2}jX\sqrt{3}$ $V_c = -\frac{1}{2}X + \frac{1}{2}jX\sqrt{3}$	This type of voltage sag can occur when two phases are shorted to ground at the same time.
Recommended Type III		$V_a = V$ $V_b = -\frac{1}{2}V - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2}V + \frac{1}{2}jV\sqrt{3}$	Two studies [B1] and xdc [B6] indicated that this is a common type of voltage sag that occurs in 11% to 20% of the events recorded.

Errata Correction to Table A.1 (4/19/2018)

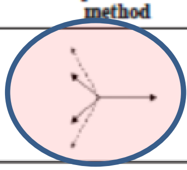
IEEE STANDARDS ASSOCIATION IEEE

IEEE Std 1668™-2017
(Revision of
IEEE Std 1668-2014)

**Errata to
IEEE Recommended Practice for
Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 V**

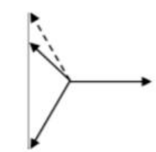
- http://standards.ieee.org/findstds/errata//1668-2017_errata.pdf

Incorrect in Table A.1

Type description	Example test-vector method	Vector descriptions	Comments
Allowed Type II.A1 (IEC Type 3b)		$V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jE\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}j(2X - E)\sqrt{3}$	The previous study [B1] indicated that this type of voltage sag makes up 9% to 18% of Type II events on HV and MV networks.

Corrected Via Errata on 4/19/2018

Replace the figure in the third row, second column of Table A.1 (entire table not shown) in Annex A with the following:

Allowed Type II.A1 (IEC Type 3b)		$V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jE\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}j(2X - E)\sqrt{3}$	The previous study [B1] indicated that this type of voltage sag makes up 9% to 18% of Type II events on HV and MV networks.

IEEE Editors inadvertently put the Type II graphic in the Type IIA.1 Location in Table A.1.

http://standards.ieee.org/findstds/errata/index.html

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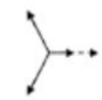
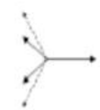
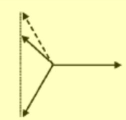
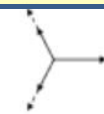
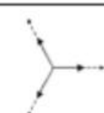
Considerations and guidance on test vectors

- Likewise, testing with the Type II.A1 method can lead to a false sense of robustness for certain three-phase loads in that these loads do not trip during test but could trip during actual voltage sags.
- Again, this is most critical for loads such as the diode-bridge ac drive.
- If tests are conducted for all Type II combinations (i.e., Type II, Type II.A1, and Type II.A2), the weakness of any one test can be offset.
- The most thorough approach would be to evaluate the EUT against all five test-vector scenarios.

Table A.1—Recommended and allowed voltage-sag test vectors and considerations [B1] (where *E* represents the nominal voltage, *V* represents the residual voltage, *X* represents the residual phase to neutral voltage)

Type description	Example test-vector method	Vector descriptions	Comments
Recommended Type I		$V_a = X$ $V_b = -\frac{1}{2}E - \frac{1}{2}jE\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}jE\sqrt{3}$	This testing is most relevant to single-phase equipment or three-phase equipment with a neutral.
Recommended Type II (IEC Type 3c)		$V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}jV\sqrt{3}$	One study [B1] indicated that this type of voltage sag makes up 82% to 91% of Type II events on HV and MV networks.
Allowed Type II.A1 (IEC Type 3b)		$V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jE\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}j(2X - E)\sqrt{3}$	The previous study [B1] indicated that this type of voltage sag makes up 9% to 18% of Type II events on HV and MV networks.
Allowed Type II.A2 (IEC Type 3d)		$V_a = E$ $V_b = -\frac{1}{2}X - \frac{1}{2}jX\sqrt{3}$ $V_c = -\frac{1}{2}X + \frac{1}{2}jX\sqrt{3}$	This type of voltage sag can occur when two phases are shorted to ground at the same time.
Recommended Type III		$V_a = V$ $V_b = -\frac{1}{2}V - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2}V + \frac{1}{2}jV\sqrt{3}$	Two studies [B1] and xdc [B6] indicated that this is a common type of voltage sag that occurs in 11% to 20% of the events recorded.

Test Method Guidance Matrix for Various Equipment and Devices

Equipment/ device type	Example devices	Type I	Type II	Type II.A1	Type II.A2	Type III
Three-phase machine with neutral	Semiconductor tools, computerized numerical controller (CNC) machines, plastic extrusion equipment, conveyor	√	√	√	√	√
Three-phase machine without neutral	Semiconductor tools, CNC machines, plastic extrusion equipment, conveyor	See Note 1	√	√	√	See Note 2
Three-phase passive front-end devices	Electronic motor drives or power supplies with diode-based rectifier front-end sections	√	√	See Note 3	√	√
Three-phase active front-end devices	Electronic motor drives or power supplies with IGBT or SCR based rectifier front-end sections	√	√	√	See Note 4	√
Single-phase passive front-end devices (See Note 5)	Electronic motor drives or power supplies with diode-based rectifier front-end sections	√				
Single-phase active front-end devices (See Note 5)	Electronic motor drives or power supplies with IGBT- or SCR-based rectifier front-end sections	√				
Electromechanical switching devices (See Note 5)	Relays, contactors, motor starters, and solenoids with ac coils	√				

NOTE 1— If the EUT does not have a neutral, Type I voltage-sag testing might not be relevant unless the neutral is again derived internally by the equipment by a local voltage-matching transformer. In this case, if single-phase testing is desired, tests should be done on the secondary of the transformer, or an additional delta-wye transformer can be installed to obtain the neutral reference.

NOTE 2—Type III testing normally requires a neutral reference. If derived internally by the equipment through a local voltage-matching transformer, testing should be done on the secondary of the transformer in order to reference the neutral. Otherwise, an additional delta-wye transformer can be installed to obtain the neutral reference.

NOTE 3— Type II.A1 voltage sags result in one of the phase-to-phase vectors remaining at 1.0 pu. Therefore, the secondary side of a passive front end (rectifier-based) three-phase load will charge to the peak every cycle. This testing might lead to results that are overly optimistic due to the magnitudes of the phase vectors.

NOTE 4— Type II.A2 voltage sags create the minimum phase vectors but do not induce any phase shifting with respect to neutral. If the load contains items sensitive to phase shifts—such as active front-end, three-phase loads—application of this test might lead to overly optimistic results due to lack of phase shift in the voltage sag.

NOTE 5— These specific single-phase loads may be connected line-to-neutral or line-to-line, which would require testing in either Type I or Type II configurations as necessary.

A.2 Safety precautions for voltage-sag testing

- IEEE 1668 does not purport to specifically address safety issues, if any, associated with its use. ***It is the responsibility of the users of this standard to establish appropriate health and safety practices and determine the applicability of regulatory or other limitations prior to use.***
- Basic safety precautions are discussed in this clause to help the reader understand common safety measures when performing voltage sag testing.
- Whether the EUT is a simple device, such as a single-phase power supply, or a complex device, such as a three-phase integrated machine or process-control cabinet, voltage-sag testing requires the connection of monitoring points for both power and data acquisition.
- The system should be first powered down and locked out, the connections made, and power re-applied.

Safety Precautions

- Preplanning is essential. Tests require a written test plan that discusses how the equipment will be tested, main power requirements, and so on. The test plan must be reviewed and approved by all who participate in the testing process.
- Work should be done in an orderly fashion as described in the written test plan.
- No monitoring points or power wires should be connected or wired when electricity is present unless proper personal protective equipment (PPE) is utilized.
- Appropriate arc-flash-rated clothing should be worn as required by NFPA-70E® [B18]. Required PPE shall be as determined by the level of energy source present and level of exposure.
- Safety glasses with integral side-shields or side-shields for those with safety-rated prescription glasses should be worn at all times.
- Lock, tag, and try procedures shall be followed when test leads are applied and the testing is conducted.
- Circuits must be visually inspected before power is restored.
- The immediate area surrounding the EUT must be cordoned off and monitored for intrusion.
- To reduce the chance of accidents, only essential personnel should be allowed within the cordoned test area.

A.3 Test Setup

Before the test setup can begin, a study of the power-distribution diagrams and control schematics should be undertaken.

During this planning phase, the test engineer should locate the EUT components and their interconnections. It is often quite helpful to create a process flow/block diagram that illustrates the interconnections and interdependences of devices such as the following:

- Servo motor drives
- Variable-frequency drives
- Motor drive start, stop, and enable signals
- Pilot relays that can provide those signals
- Programmable logic controllers (PLCs) that can provide those signals or that can control other devices
- Contactors that control the flow of power to the entire process or section such as start or stop circuits
- Contactors that are part of an emergency-stop or master-control relay circuit
- Servo or other controllers
- Power supplies

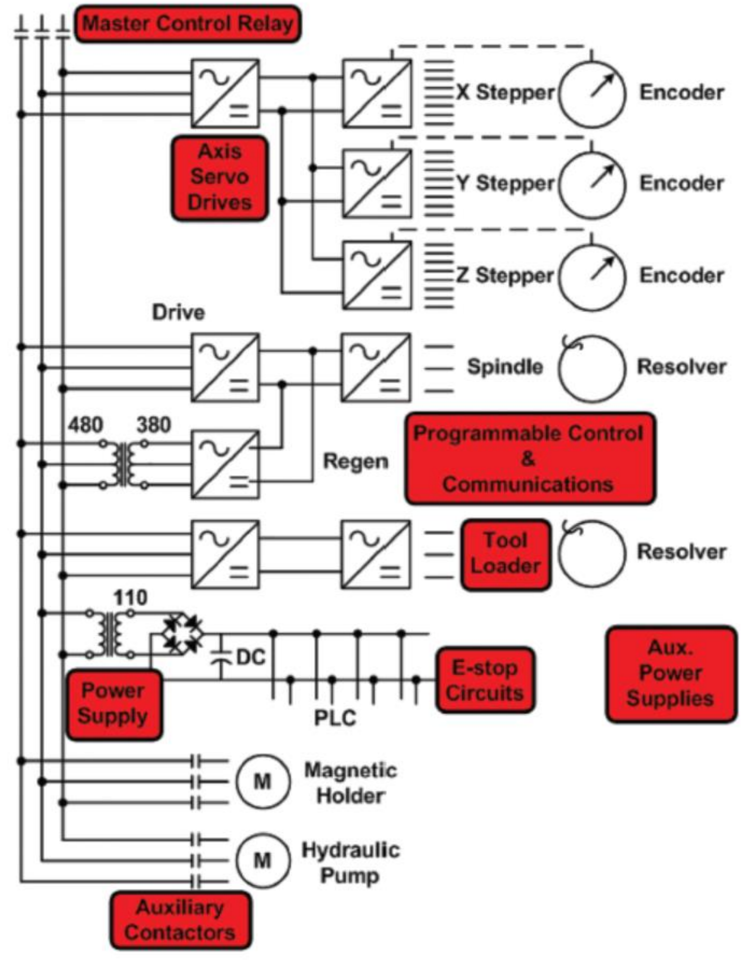
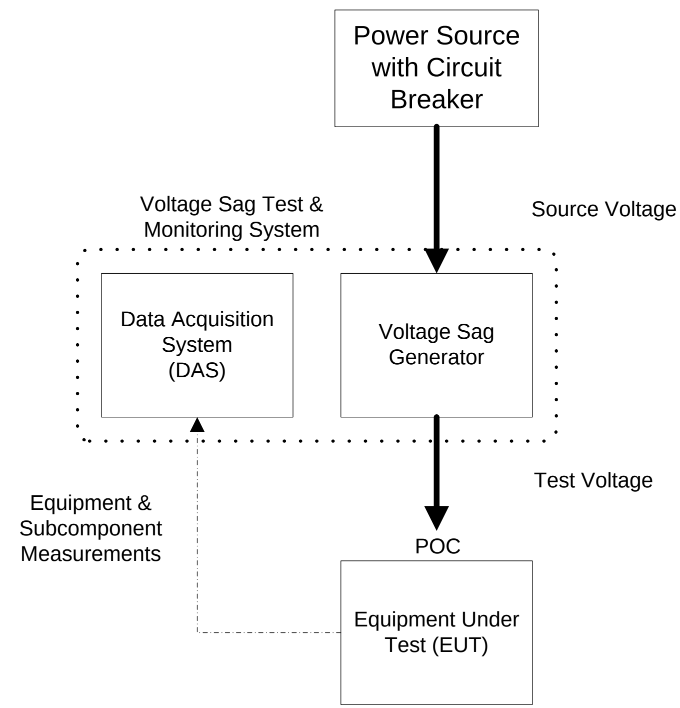


Figure A.1—Example EUT power distribution [computerized numerical controller (CNC) machine]

Example Single-Phase Test Setup

Table A.3—Example DAS monitoring points (three-phase test)

No.	DAS monitoring points
1	Ia, phase A current
2	Ib, phase B current
3	Ic, phase C current
4	V a-n, phase a-n voltage
5	V b-n, phase b-n voltage
6	V c-n, phase c-n voltage
7	V a-b, line a-b voltage
8	V b-c, line b-c voltage
9	V c-a, line c-a voltage
10	Emergency-off circuit/master control relay
11	Equipment power contactor
12	DC power supply output
13	AC drive dc bus voltage
14	Multi-axis drive dc bus voltage
15	PLC run relay status
16	Motor starter status



A.4 Compliance Test Procedures

- Compliance testing should be performed by a qualified test laboratory. Such tests are by nature expensive because the test results must be trustworthy and reproducible.
- The number of tests and the complexity of the tests should not be more than absolutely necessary; however, the results of the tests should give a reasonable prediction of the general performance of the equipment in practical applications and real operating conditions.
- The reader should also refer to Table A.2 to determine the appropriate voltage-sag types that should be administered based on the equipment that is being tested.
- The advocated voltage-sag tests should be initiated at 0° point-on-wave with respect to the phase in which the voltage sag is being created during the evaluation of the EUT.
- Type I compliance testing is relevant for single-phase equipment or single-phase devices that can be bench tested.
- Type I testing is also useful when evaluating three-phase equipment for loads wired between phase and neutral.
- On 208-V ac systems, 120-V ac control voltage is easily derived phase-to-neutral. Table A.4 shows the required test matrix for single-phase equipment while Table A.5 shows the Type I test matrix for three-phase equipment with a neutral.

Type I Compliance Testing

- Type I compliance testing is relevant for single-phase equipment or single-phase devices that can be bench tested.
- Type I testing is also useful when evaluating three-phase equipment for loads wired between phase and neutral.
- On 208-V ac systems, 120-V ac control voltage is easily derived phase-to-neutral. Table A.4 shows the required test matrix for single-phase equipment while Table A.5 shows the Type I test matrix for three-phase equipment with a neutral.

Type I Single Phase Equipment Compliance Test Matrix

Table A.4—Type I single-phase equipment compliance test matrix

Test no.	Duration of voltage sag			$\%V_{nominal}$	Pass/fail response[a]		
	Seconds	60 Hz cycles	50 Hz cycles		Full operation	Self-recovery	Assisted-recovery
1	2.0	120	100	80%			
2	0.5	30	25	70%			
3	0.2	12	10	50%			

[a]The "pass/fail response" results should be documented using the terminology designated in this recommended practice. These designations are: full operation, self-recovered, or assisted-recovery. See 5.3.4 for definitions of the pass/fail criteria.

Type I Three-Phase System Compliance Test Matrix

Table A.5—Type I three-phase system with neutral compliance test matrix

Test No.	Duration of voltage sag			% $V_{A\text{-}N}$	% $V_{B\text{-}N}$	% $V_{C\text{-}N}$	Pass/fail response		
	Seconds	60-Hz cycles	50-Hz cycles				Full operation	Self recovery	Assisted recovery
1	2.0	120	100	80%	100%	100%			
2	0.5	30	25	70%	100%	100%			
3	0.2	12	10	50%	100%	100%			
4	2.0	120	100	100%	80%	100%			
5	0.5	30	25	100%	70%	100%			
6	0.2	12	10	100%	50%	100%			
7	2.0	120	100	100%	100%	80%			
8	0.5	30	25	100%	100%	70%			
9	0.2	12	10	100%	100%	50%			

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Type II compliance testing

- Type II compliance testing is relevant for three-phase and single-phase, line-to-line connected equipment to determine its susceptibility to phase-to-phase voltage sags.
- There are three different ways in which Type II sags can be generated.
- Refer to clause A.1 for the implications of the chosen Type II test vector.
- The ideal vector magnitudes for Type II, Type II.A1, and Type II.A2 are shown.
- In each test case, the test equipment is set to produce the vector magnitude (in grey).
- The other ideal vector magnitudes are shown for reference.

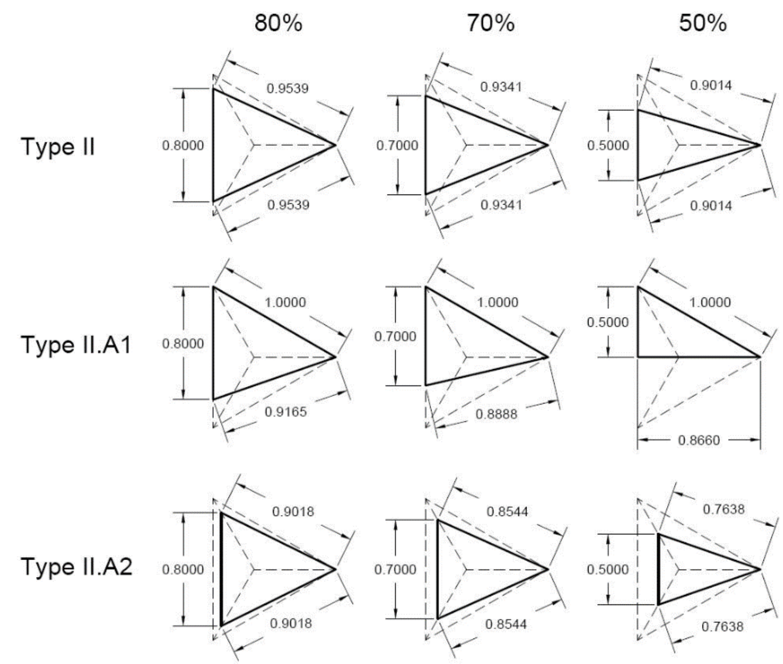

Figure A.3—Ideal vector magnitudes for Type II, Type II.A1, and Type II.A2 voltage-sag compliance test points

Type II compliance testing test matrix

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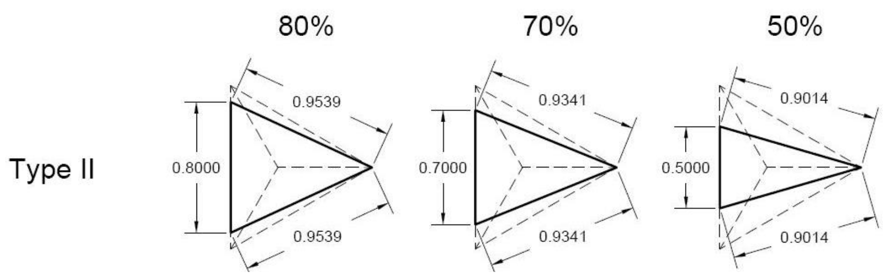
Table A.6—Type II compliance testing test matrix

Test No.	Duration of voltage sag			$V_{A\text{-}B}$	$V_{B\text{-}C}$	$V_{C\text{-}A}$	Pass/fail response		
	Seconds	60-Hz cycles	50-Hz cycles				Full operation	Self recovery	Assisted recovery
1	2.0	120	100	**80%**	95.39%	95.39%			
2	0.5	30	25	**70%**	93.41%	93.41%			
3	0.2	12	10	**50%**	90.14%	90.14%			
4	2.0	120	100	95.39%	**80%**	95.39%			
5	0.5	30	25	93.41%	**70%**	93.41%			
6	0.2	12	10	90.14%	**50%**	90.14%			
7	2.0	120	100	95.39%	95.39%	**80%**			
8	0.5	30	25	93.41%	93.41%	**70%**			
9	0.2	12	10	90.14%	90.14%	**50%**			



- In each test case, the test equipment is set to produce the vector magnitude (in gray).
- The other ideal vector magnitudes are shown for reference.

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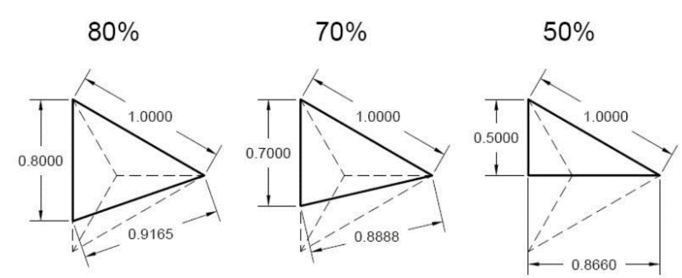
Type II.A1 (Alternative 1) compliance testing matrix

Table A.7—Type II.A1 (Alternative 1) compliance testing matrix

Test No.	Duration of voltage sag			$V_{A\text{-}B}$	$V_{B\text{-}C}$	$V_{C\text{-}A}$	Pass/fail response		
	Seconds	60-Hz cycles	50-Hz cycles				Full operation	Self recovery	Assisted recovery
1	2.0	120	100	**80%**	100%	91.65%			
2	0.5	30	25	**70%**	100%	88.88%			
3	0.2	12	10	**50%**	100%	86.6%			
4	2.0	120	100	91.65%	**80%**	100%			
5	0.5	30	25	88.88%	**70%**	100%			
6	0.2	12	10	86.6%	**50%**	100%			
7	2.0	120	100	100%	91.65%	**80%**			
8	0.5	30	25	100%	88.88%	**70%**			
9	0.2	12	10	100%	86.6%	**50%**			

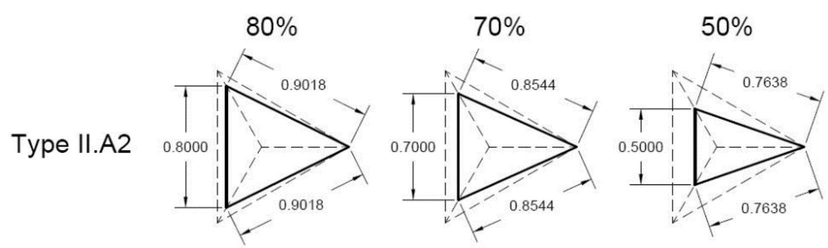
Type II.A1



Type II.A2 (Alternative 2) compliance testing matrix

Table A.8—Type II.A2 (Alternative 2) compliance testing matrix

Test No.	Duration of voltage sag			V_{A-B}	V_{B-C}	V_{C-A}	Pass/fail response		
	Seconds	60-Hz cycles	50-Hz cycles				Full operation	Self recovery	Assisted recovery
1	2.0	120	100	**80%**	90.18%	90.18%			
2	0.5	30	25	**70%**	85.44%	85.44%			
3	0.2	12	10	**50%**	76.38%	76.38%			
4	2.0	120	100	90.18%	**80%**	90.18%			
5	0.5	30	25	85.44%	**70%**	85.44%			
6	0.2	12	10	76.38%	**50%**	76.38%			
7	2.0	120	100	90.18%	90.18%	**80%**			
8	0.5	30	25	85.44%	85.44%	**70%**			
9	0.2	12	10	76.38%	76.38%	**50%**			



Type III compliance testing

- The test matrix for Type III compliance testing is shown in Table A.9. Type III testing normally requires the equipment to have a neutral conductor or that a neutral conductor be derived.
- See Section A.1 for additional guidance.

Table A.9—Type III compliance testing test matrix

Test No.	Duration of voltage sag			V_{ABC}	Pass/fail response		
	Seconds	60-Hz cycles	50-Hz cycles		Full operation	Self recovery	Assisted recovery
1	2.0	120	100	**80%**			
2	0.1	6	5	**70%**			
3	0.05	3	2.5	**50%**			

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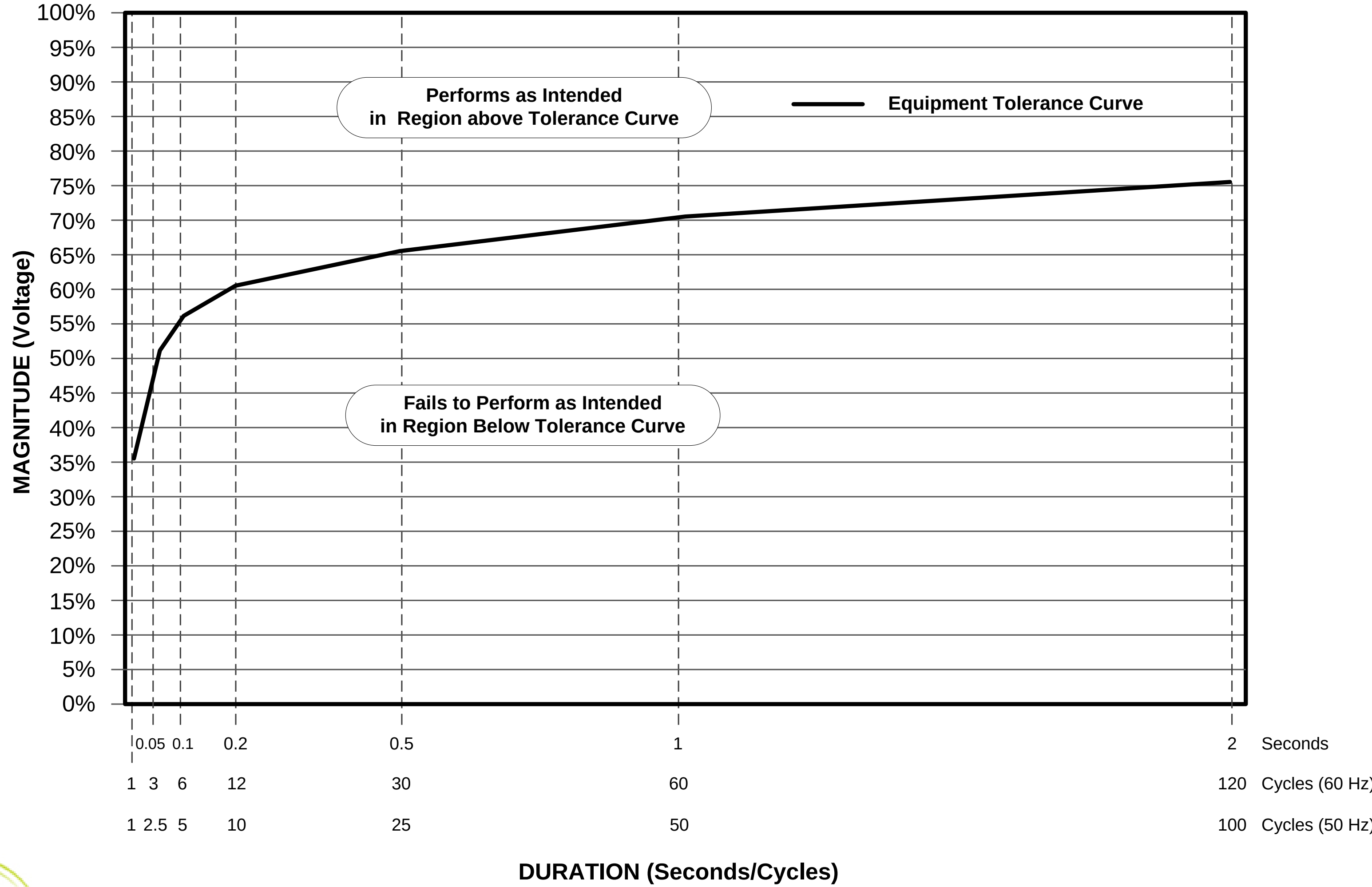
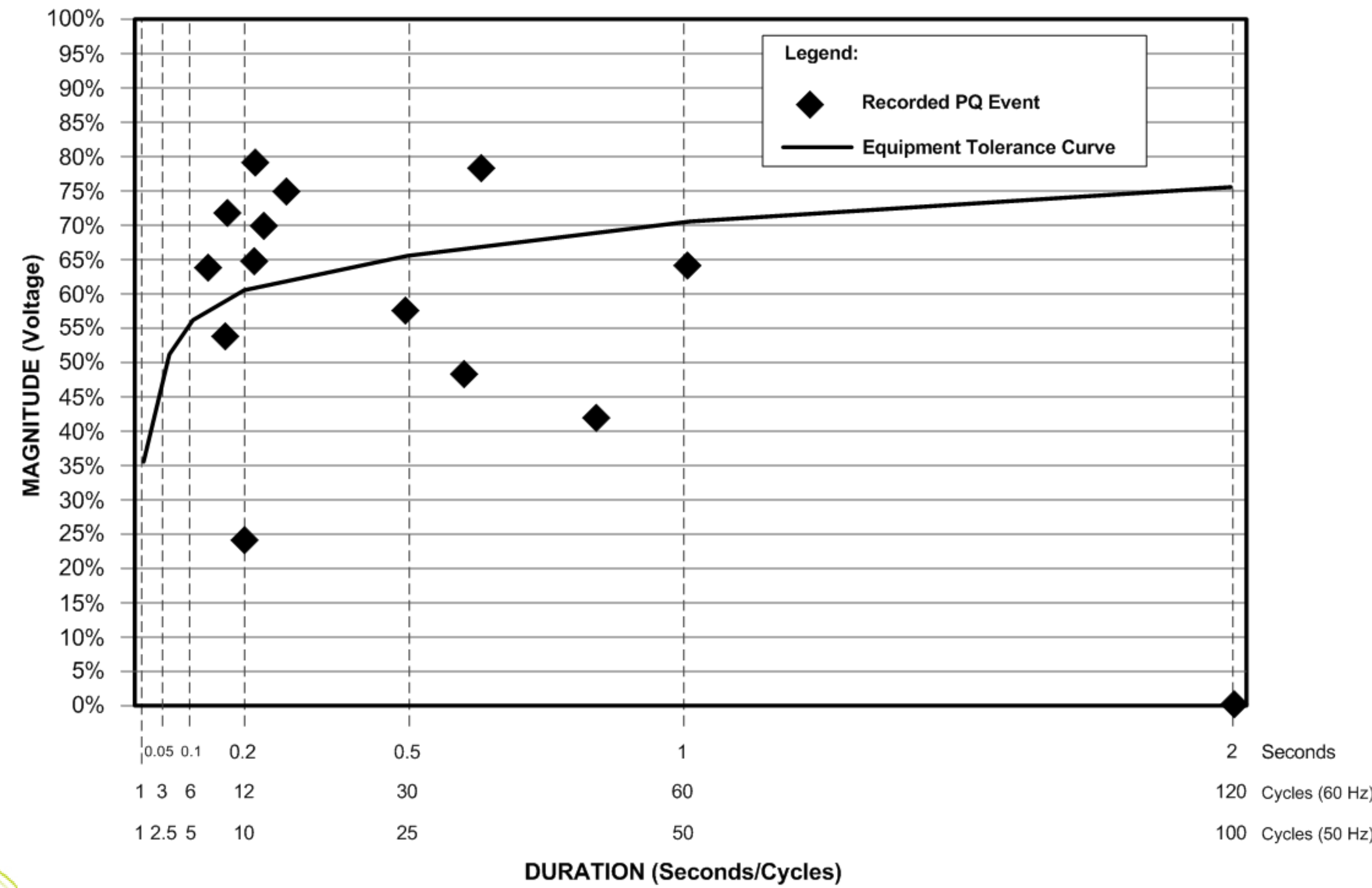
A.5 Voltage-sag immunity characterization test procedures

- Voltage-sag immunity characterization testing should reveal the ability of the equipment to ride through voltage sags at the power terminals of the EUT.
- The “voltage-sag tolerance curve” is an important tool to understand the compatibility between the equipment and the electric power supply at a given location.

Example Characterization Test Curve



Example EUT voltage-sag tolerance curve with PQ data overlay



Characterization Test Plan

- At a minimum, the test plan should reference the following:
  - The most sensitive process states of the EUT
  - EUT loading information (such as 50% loaded)
  - The required test durations (such as 0.05 s, 0.1 s, 0.2 s, 0.5 s, 1.0 s, and 2.0 s)
  - The minimum voltage to be applied (such as 0% or 50%) during tests
  - Voltage-sag voltage incremental change (such as 5%)
  - Phase modes required (such as phase-to-neutral or phase-to-phase)
  - Data-acquisition measurement points (such as in Table A.3)

Initial procedures

a) Connect the EUT into the test setup as shown in Figure A.2. Refer to Clause A.2 for safety precautions.

b) Connect DAS monitoring channels per the test plan using Table A.3 as a general reference.

c) Visually inspect all connections prior to energizing the test setup.

d) Energize the power source and verify source voltage using a digital voltmeter.

e) Energize the voltage-sag generator, measure and record the phase voltages, and confirm the output of the sag generator.

f) Power up the EUT.

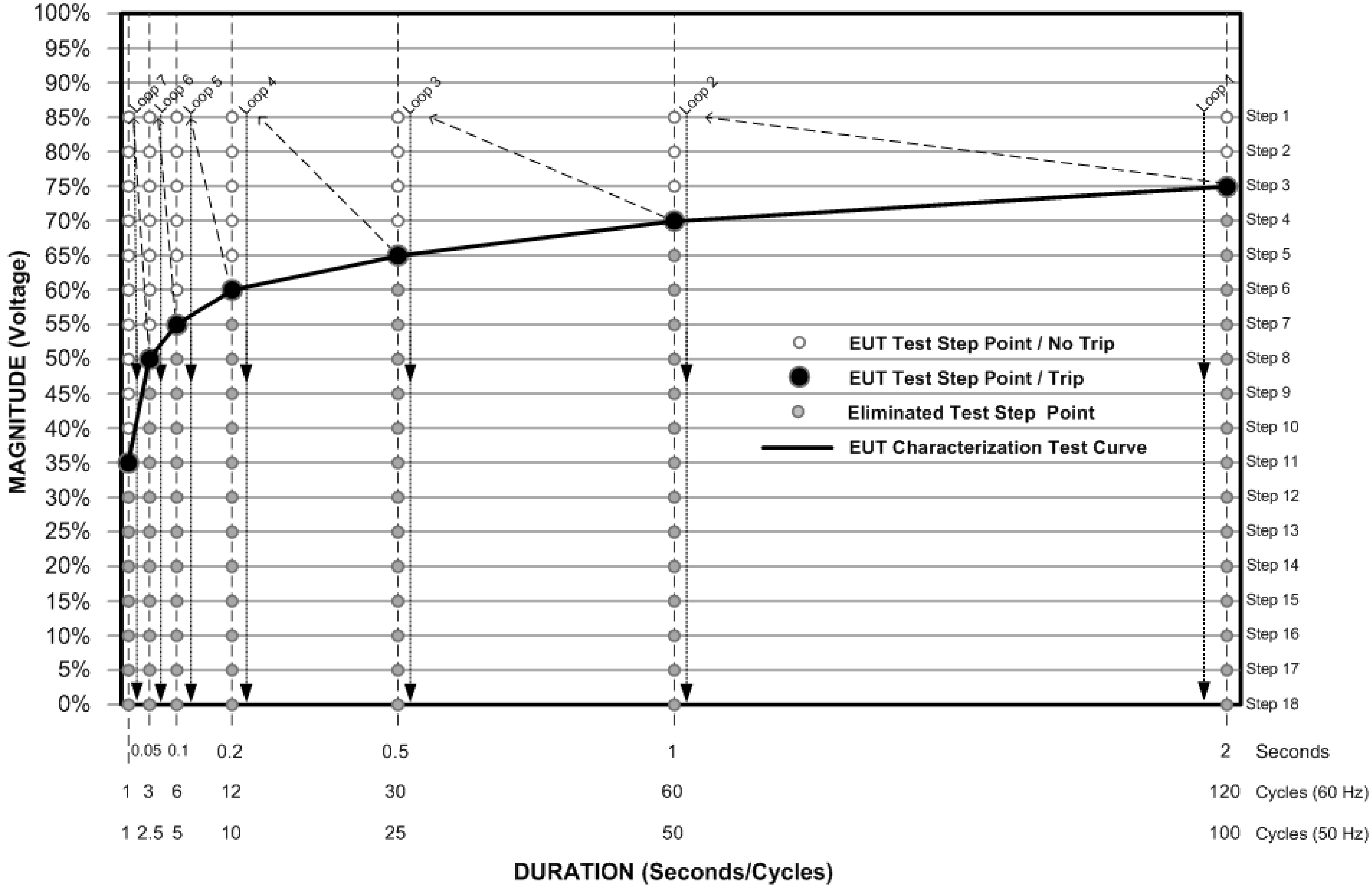
g) Perform any final configuration and setup of the DAS channels and confirm their readings.

h) Verify that the EUT is in a desired process state for voltage-sag testing. Tests should be done in the most sensitive process state as determined by the equipment user or OEM. Tests can be repeated in various states to fully characterize the equipment. These states should be outlined in the test plan.

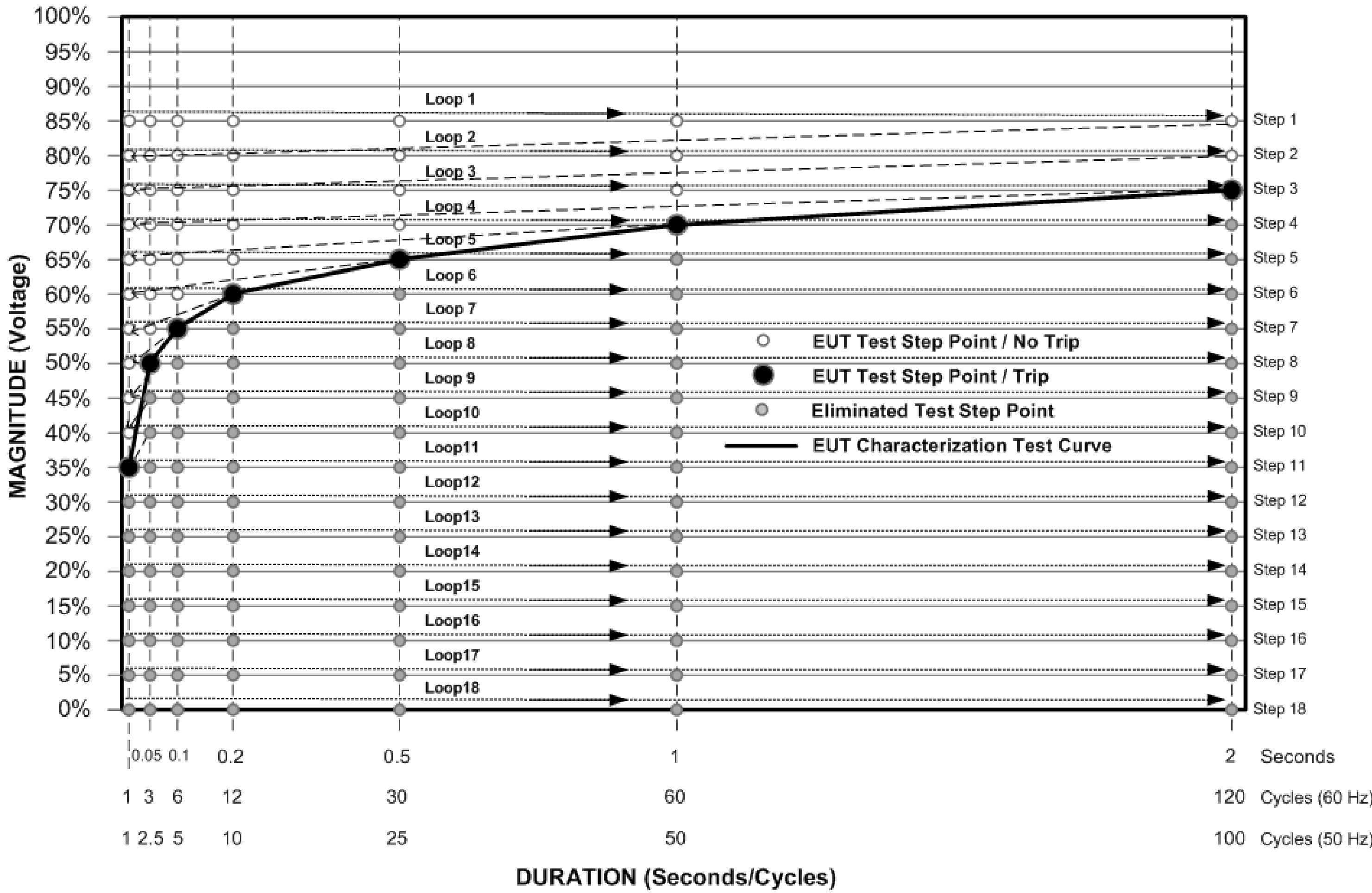
Equipment voltage-sag characterization methods

- Several methods can be used to characterize equipment performance against voltage sags.
- The chosen characterization method can depend on the test location and time available to conduct the test.
- The procedure for each test method is described in terms of “test loops” consisting of a series of tests that can be repeated until the EUT malfunctions, at which time the next successive test loop is conducted.
- The three basic characterization methods used to determine the ride-through performance of an EUT are the top-down, leftright, and box-in methods.

Top-down

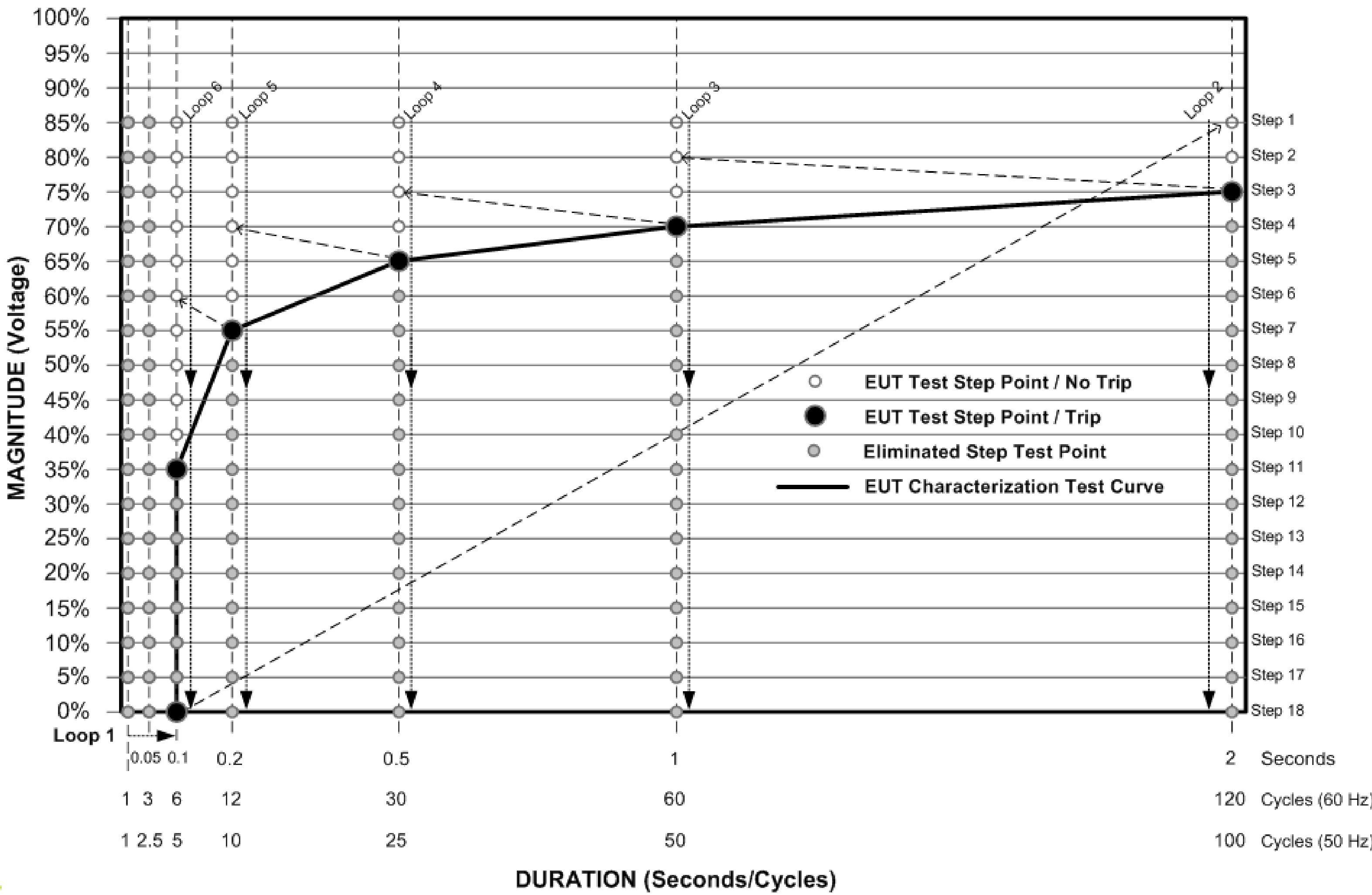

100%
95%
90%
85%
80%
75%
70%
65%
60%
55%
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
MAGNITUDE (Voltage)
Loop 7
Loop 6
Loop 5
Loop 4
Loop 3
Loop 2
Loop 1
Step 1
Step 2
Step 3
Step 4
Step 5
Step 6
Step 7
Step 8
Step 9
Step 10
Step 11
Step 12
Step 13
Step 14
Step 15
Step 16
Step 17
Step 18
EUT Test Step Point / No Trip
EUT Test Step Point / Trip
Eliminated Test Step Point
EUT Characterization Test Curve
0.05 0.1 0.2 0.5 1 2 Seconds
1 3 6 12 30 60 120 Cycles (60 Hz)
1 2.5 5 10 25 50 100 Cycles (50 Hz)
DURATION (Seconds/Cycles)

Left-Right



MAGNITUDE (Voltage)
100%
95%
90%
85%
80%
75%
70%
65%
60%
55%
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Loop 1
Loop 2
Loop 3
Loop 4
Loop 5
Loop 6
Loop 7
Loop 8
Loop 9
Loop10
Loop11
Loop12
Loop13
Loop14
Loop15
Loop16
Loop17
Loop18
Step 1
Step 2
Step 3
Step 4
Step 5
Step 6
Step 7
Step 8
Step 9
Step 10
Step 11
Step 12
Step 13
Step 14
Step 15
Step 16
Step 17
Step 18
EUT Test Step Point / No Trip
EUT Test Step Point / Trip
Eliminated Test Step Point
EUT Characterization Test Curve
0.05 0.1 0.2 0.5 1 2 Seconds
1 3 6 12 30 60 120 Cycles (60 Hz)
1 2.5 5 10 25 50 100 Cycles (50 Hz)
DURATION (Seconds/Cycles)

Box-In (Typically Quickest)



Box-In Demo

***phase under test (PUT)**: The selected phase or combination of phases during a voltage-sag test of equipment under test (EUT).*

Table A.15—Box-in method equipment characterization test matrix, 60-Hz example

Test loop	Step No.	Voltage-sag duration		%$V_{nominal}$ of PUT	Pass/fail response			Notes
		Secs	50-Hz cycles		Full operation	Self recovery	Assisted recovery	
Loop 1	1	0.0167	1	0%				
	2	0.05	2	0%				
	3	0.1	6	0%				
	4	0.2	12	0%				
	5	0.5	30	0%				
	6	1	60	0%				
	7	2	120	0%				If EUT has not tripped at the maximum duration test point, testing can stop.
Loop 2	1	2	120	85%				
	2	2	120	80%				
	3	2	120	75%				
	4	2	120	70%				
	5	2	120	65%				
	6	2	120	60%				
	7	2	120	55%				
	8	2	120	50%				
	9	2	120	45%				
	10	2	120	40%				
	11	2	120	35%				
	12	2	120	30%				
	13	2	120	25%				
	14	2	120	20%				
	15	2	120	15%				
	16	2	120	10%				
	17	2	120	5%				
Loop 3	1→17	1	60	85%→5%				
Loop 4	1→17	0.5	30	85%→5%				
Loop 5	1→17	0.2	12	85%→5%				
Loop 6	1→17	0.1	6	85%→5%				
Loop 7	1→17	0.05	3	85%→5%				
Loop 8	1→17	0.0167	1	85%→5%				

DEMO

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3-phase equipment characterization test procedures

- Either of the test characterization methods presented can be used to guide single-phase, two-phase, and three-phase voltage-sag testing.
- For three-phase equipment, single-phase (Type I), two-phase (Type II), and three-phase (Type III) testing is required for full characterization.
- Three-phase equipment requires a neutral to create single-phase (Type I) and three-phase (Type III) events.
- If the EUT does not have a neutral, Type I voltage-sag testing might not be relevant unless the neutral is again derived internally by the equipment through a local voltage-matching transformer.
- In this case, if single-phase testing is desired, tests should be done on the secondary of the transformer, or an additional delta-wye transformer can be installed to obtain the neutral reference.

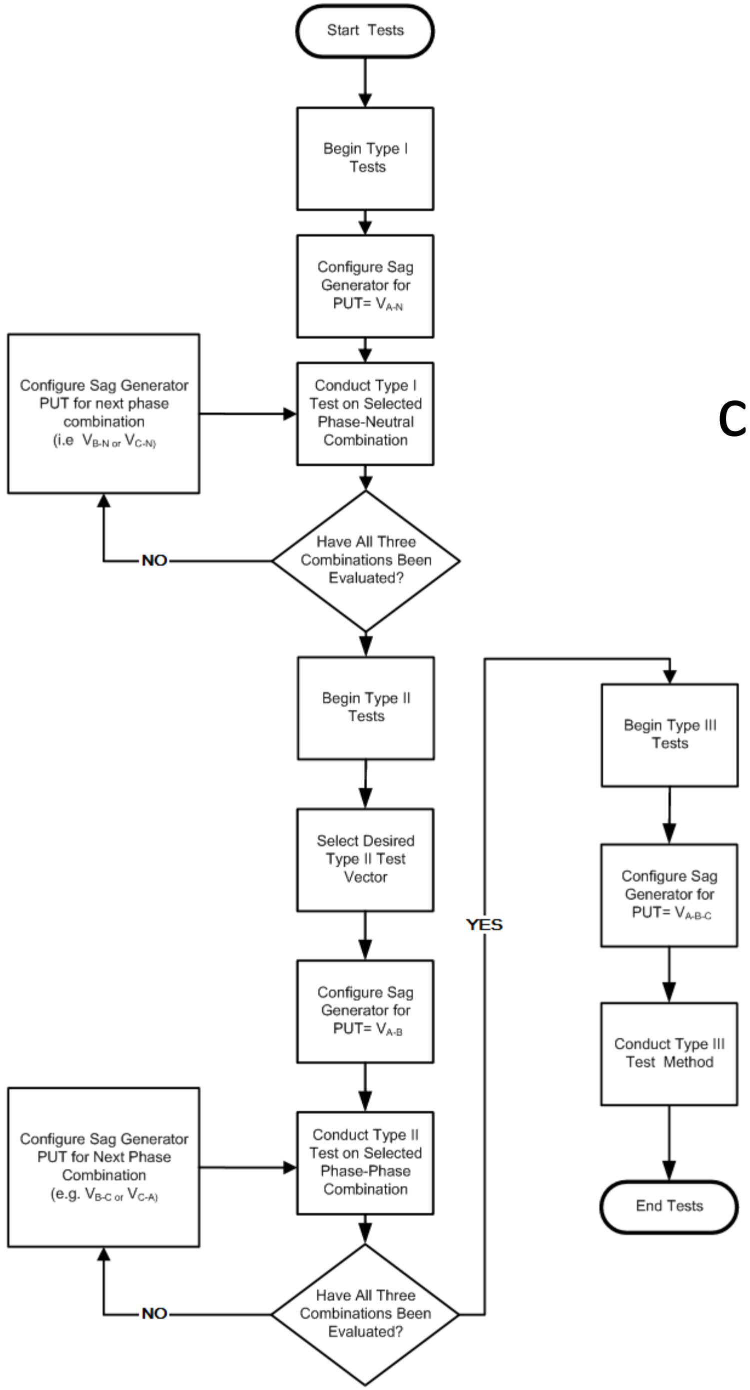
3-phase equipment characterization test procedures

- Type III testing requires a neutral reference. If derived internally by the equipment through a local voltage-matching transformer, testing should be done on the secondary of the transformer in order to reference the neutral.
  - Otherwise, an additional delta-wye transformer can be installed to obtain the neutral reference.
- Voltage-sag testing of three-phase equipment generally begins by first performing single-phase Type I characterization of each of the three phases independently ($V_{A\text{-}N}$, $V_{B\text{-}N}$, $V_{C\text{-}N}$).
- Afterward, Type II characterization is performed independently for each of the three phase-to-phase combinations ($V_{A\text{-}B}$, $V_{B\text{-}C}$, $V_{C\text{-}A}$).
- Finally, three-phase Type III voltage sags are performed until the EUT is fully characterized ($V_{A\ B\ C}$).

Source Requirements for Full Characterization

Voltage-sag test type	PUT combinations	Source requirements for characterization
Type I	$V_{A\text{-}N}$, $V_{B\text{-}N}$, $V_{C\text{-}N}$	**3 phases, neutral, ground**
Type II/ Type II.A1	$V_{A\text{-}B}$, $V_{B\text{-}C}$, $V_{C\text{-}A}$	**3 phases, ground**
Type II.A2	$V_{A\text{-}B}$, $V_{B\text{-}C}$, $V_{C\text{-}A}$	**3 phases, neutral, ground**
Type III	$\mathbf{V_{A\text{-}B\text{-}C}}$	**3 phases, neutral, ground**

Example of a three-phase voltage sag characterization procedure



Applying the New IEEE Std. 1668

Annex B:

Test Equipment Requirements

(normative)

Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 v

Presented by: Scott Bunton, CPQ, CEM

IEEE 1668 Working Group Member
April 23, 2018

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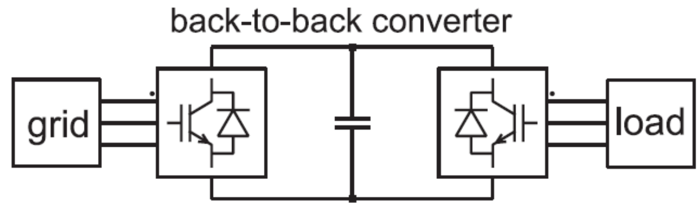
Types of Sag Generators

- Generally three designs of voltage-sag generators that can be used for precision voltage sag testing.
  - Amplifier Type
  - Transformer-Switch Type
  - Impedance Divider Type

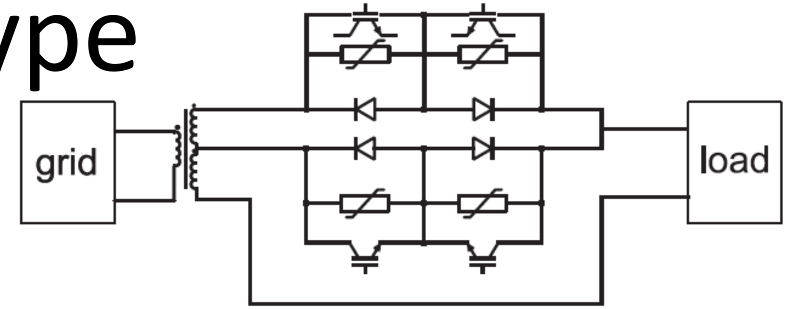
Amplifier Type



Generalized Form

- Amplifier type and includes a controller, a waveform generator, a data-acquisition system, and a power-amplification section.
- This waveform generator can simulate any point-on-wave and provide varying magnitude, duration, frequency, and harmonics, thereby allowing a user more precise control of the voltage-sag characteristics.
- The amplifier sag generator typically employs multiple power conversions—requiring transformer isolation—and is generally limited to lower-power applications.

Transformer-Switch Type

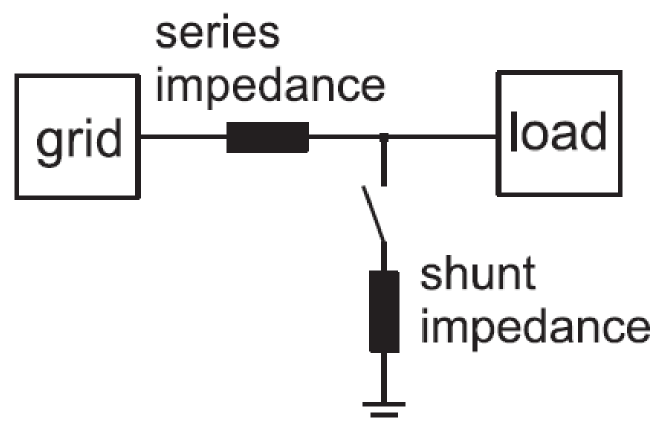


Generalized Form

- The transformer type uses some form of switching to switch from nominal to reduced voltage for the testing.
- Contactors can be used, but typically cannot provide precise switching nor can they allow phase-angle control of sags.
- Most such voltage-sag generators use electronic switches employing either an insulated gate bipolar transistor (IGBT), or a silicon controlled rectifier (SCR).
- Units up to 200A per phase are currently commercially available with larger ones (600A and 1000A) pending.

Impedance Divider Type

- A third form of sag generator is commonly referred to as the impedance divider type, which uses a thyristor-controlled reactor to switch impedances for creating voltage sags.
- Generally, the impedance-divider sag generator weighs less than the other types of sag generators and provides maximum power.
- May have limited available sag depth adjustments.



Generalized Form

Required Parameters

- A sag generator should be able to perform Type I, Type II, and Type III sags Per IEEE Std. 1668-2017.
- Voltage output at no load is per test levels and should be ± 5% of the desired residual voltage.
- Voltage output during test is per test levels and should be ± 10% of desired residual voltage as measured per 1/2 cycle.
- The peak output current drive capability of the voltage-sag generator is a function of the load type. The generator should not inhibit the inrush current of the EUT.
- Instantaneous peak voltage overshoot/undershoot of the actual voltage for the generator loaded with a resistive load should be less than 5% of the test voltage.

Required Parameters (cont.)

- Voltage rise (and fall) times *tr* (and *tf*) in response to abrupt changes should be between 100 ms and 200 ms for resistive loads.
- The phase angle at which the voltage sag begins and ends should include a range of 0° to 360° and have a maximum resolution of 5°.
- The phase relationship of voltage sags with the power frequency should be less than ± 5%.
- Zero-crossing control of the generators should be less than ± 10°.
- The sampling rate shall be at least 10 kHz, and the data resolution should be at least 12 bits.
- The output configuration should be either wye or delta, as required by the test.
- The operating frequency of voltage should be 50 Hz or 60 Hz.

Applying the New IEEE Std. 1668

Annex C:

Certification and Test Reports

(normative)

Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 v

Presented by: Scott Bunton, CPQ, CEM

IEEE 1668 Working Group Member

April 23, 2018

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C1. Certificate Minimum Info

a) The organization issuing the certificate
b) The EUT manufacturer, manufacturer address, and manufacturer primary phone contact information
c) The EUT model number and serial number (Also consider recording Firmware Revision*.)
d) The test date
e) The test location
f) Any conditions of use for the certificate, such as voltage-range limitations, required modifications, process limitations, equipment configuration(s), and special/unusual installation requirements
g) The range of model numbers and/or serial numbers to which the certificate applies
h) The nominal voltage(s) and frequency(s) tested
i) The test equipment used, including a statement that test equipment fully complies with all requirements of this recommended practice
j) A reference to this specification, including publication date
k) The test conditions, including loading and process recipe information if applicable
l) The pass/fail decision with details related to the test levels, test procedures, or equipment specifications

** Not in IEEE 2017-2017 – FW rev note may be added in future revs.*

C2. Test Report Minimum Info

a) All information required in C.1 for a certificate.

b) The test plan.

c) The identity of the engineers who performed or participated in the testing

d) The voltage and current waveforms for all phases, including pre-sag and post-sag data, for at least a single worst-case voltage sag (worst-case being defined by the largest current drawn by the EUT, either during or after a voltage sag).

C2. Test Report Minimum Info (Cont.)

e) A complete list of all sags applied during the testing, including for each sag:

1) the phase(s) to which the sag was applied
2) the depth and duration of the sag
3) the process state of the EUT
4) the results of the sag test
5) any useful comments or observations during and after the sag

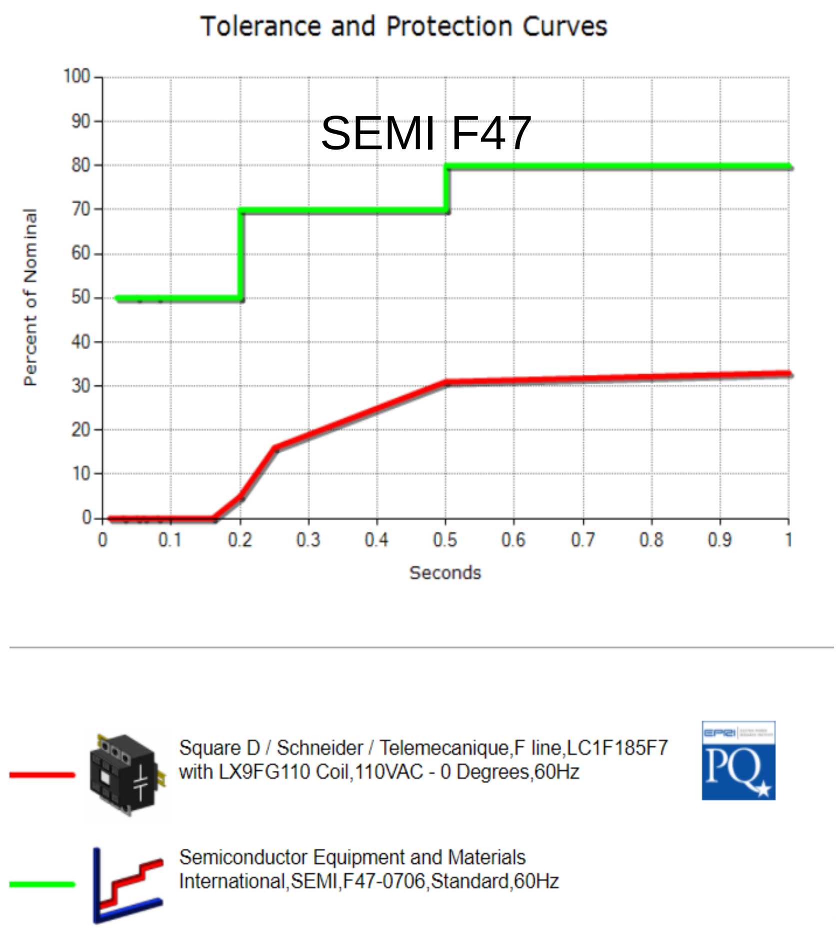
f) Photographs of the test setup, EUT, and environment.

g) The rationale for the pass/fail decision, including detailed performance criteria.

h) Any recommendations and/or conclusions that resulted from the testing

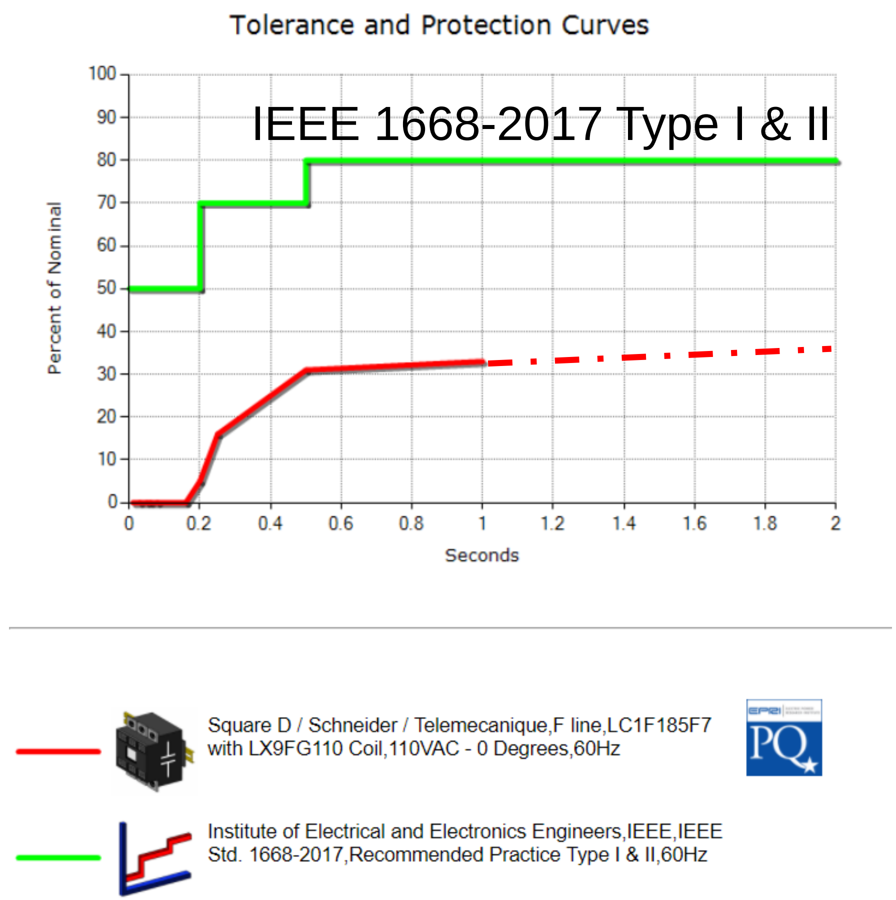
Jump Starting Compliant Components via SEMI F47

- IEEE 1668-2017 Requirements for Single-Phase Equipment is very similar to SEMI F47
- Only difference is one test point
  - SEMI F47 – 80%, 1 second
  - IEEE 1668 – 80%, 2 seconds



SEMI F47 Test Result Review for Component IEEE 1668 Certification

- Many compliant single-phase SEMI F47 devices can be reviewed for compliance to IEEE 1668-2017 by compliance testing companies.
- Review previous test results
- Apply understanding how specific loads will react to the 2 second test point vs. 1 second.
  - Relays, contactors, and motor starters should easily transfer
  - Power Supplies may require more review or sample testing.



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Closing Remarks

Bill Howe, PE, CEM

IEEE PES SCC-22 Chair

Workshop Recap

- Welcome and Kick-Off, Bill Howe, Chair PES SCC-22
- Scope, Purpose, and Normative References, Alden Wright, 1668 WG
- Laying the Groundwork, Jim Rossman, 1668 WG
- Primer on Voltage Sags, John Mentzer, 1668 WG
- Recommended Test Requirements, Mark Stephens, 1668 WG
- Test Procedures and Guidelines, Mark Stephens, 1668 WG
- Test Equipment Requirements, Scott Bunton
- Certification and Test Reports, Scott Bunton
- Closing Remarks, Bill Howe, Chair PES SCC-22