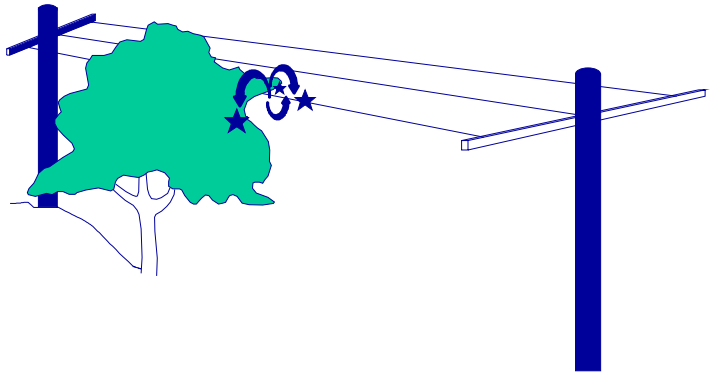
# Effects of Voltage Sags

Thomas Grebe,
Senior Consultant
Electrotek Concepts, Inc.
tgrebe@electrotek.com
www.electrotek.com

September, 2005

# Effects of Voltage Sags



- Definitions
- Causes of Voltage Sags
- Characteristics of Voltage Sags
- Voltage Sag Measurement Results
- Effect of Transformer Connections
- Effects of Voltage Sags on Sensitive Equipment
- Measures to Improve Equipment Ride-Through Capability

# Interruptions

**Interruptions -** The complete loss of ac power for at least one-half cycle.

**Momentary Interruption -** complete loss of ac power for less than 3 seconds.

**Temporary Interruption -** an interruption from 3 seconds to 1 minute in duration.

**Outage -** an interruption greater than 1 minute in duration.

# Voltage Variations

**Voltage Sag -** A reduction in the rms magnitude of voltage, of duration from **0.5 cycles to 1 minute.**

**Undervoltage** - A reduction in the rms magnitude of voltage, of duration **greater than 1 minute**.

**Voltage Swell -** An increase in the rms magnitude of voltage, of duration from **0.5 cycles to 1 minute.**

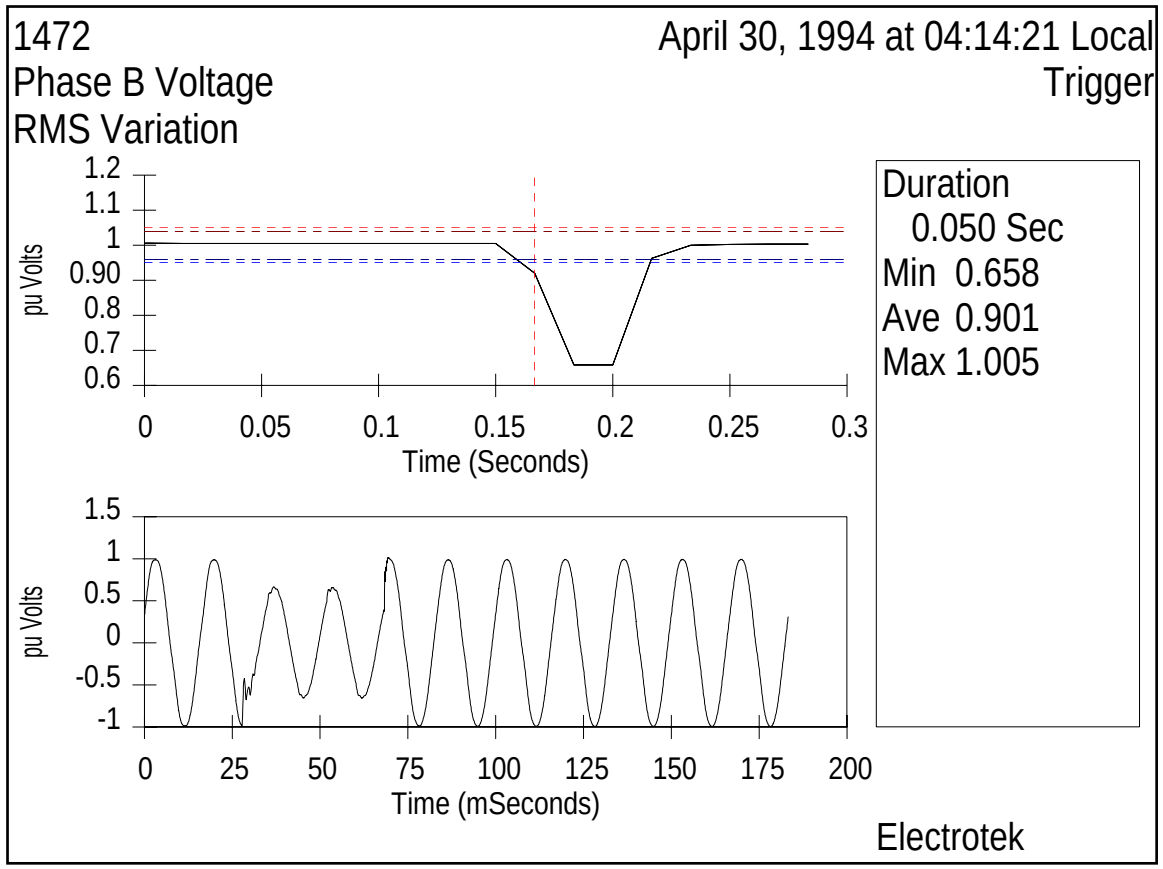
**Overvoltage -** An increase in the rms magnitude of voltage, of duration **greater than 1 minute**.

# Long Duration Variations

- Variation in the rms magnitude
- Duration greater than 1 minute
- Caused by load variations and other switching events that cause long term changes in the system voltage
- Can usually be controlled with voltage regulators

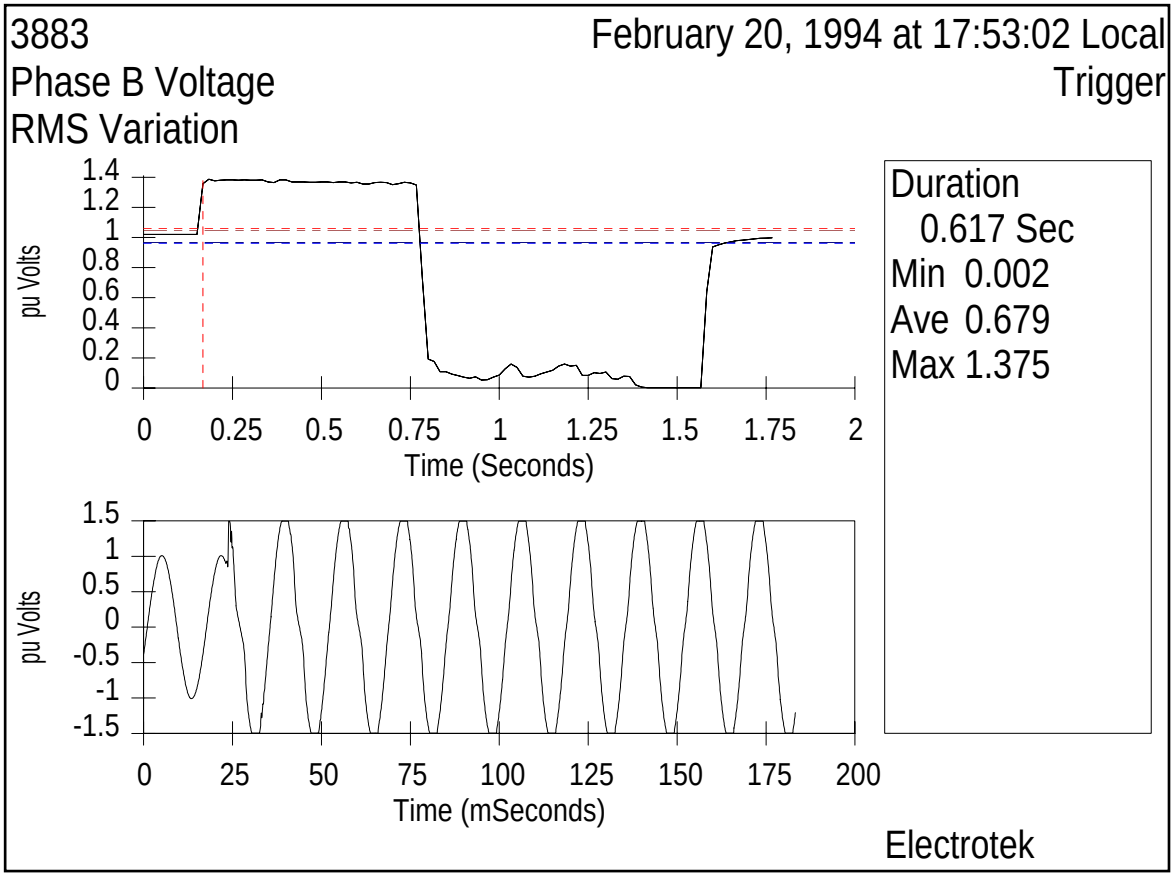
# Voltage Sag - Snapshot

- Example voltage sag caused by a remote fault



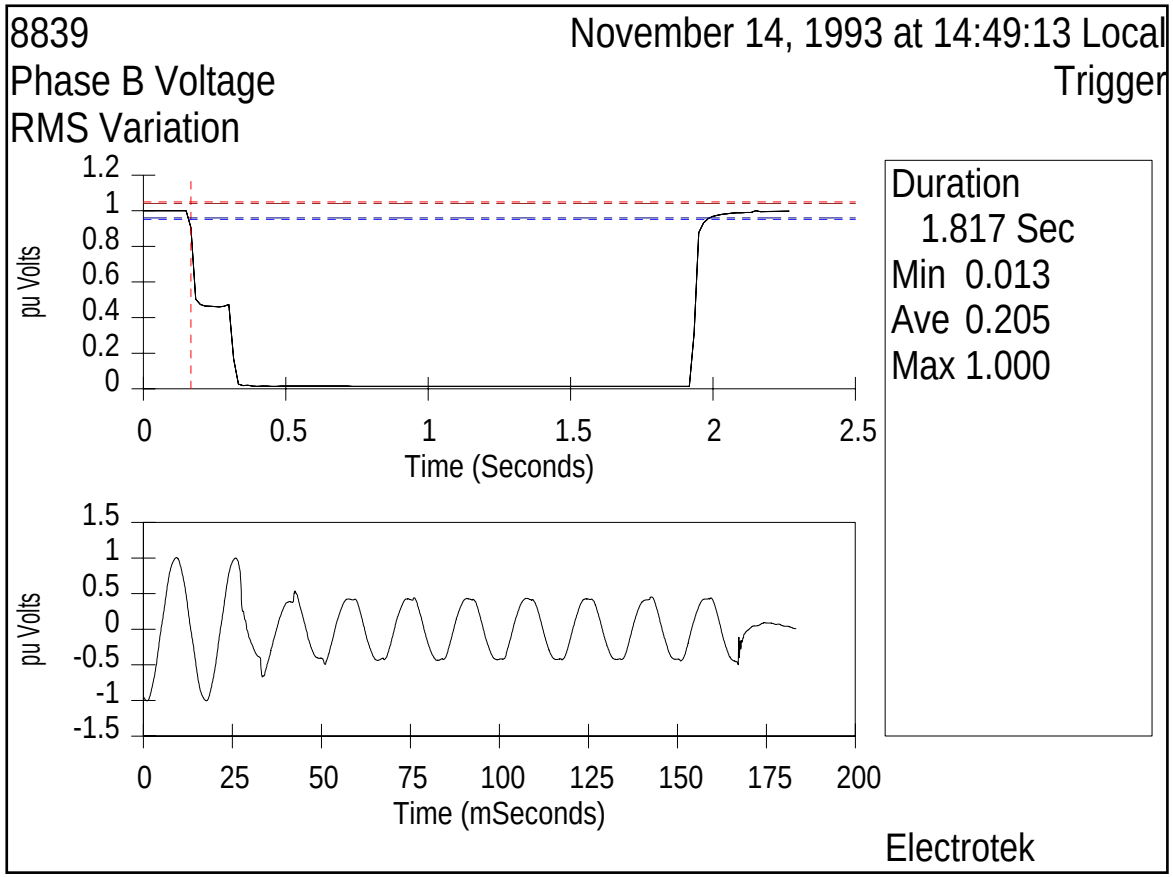
# Voltage Swell - Snapshot

- Example voltage swell during a single-phase fault



# Momentary Interruption - Snapshot

- Example momentary interruption during a temporary fault

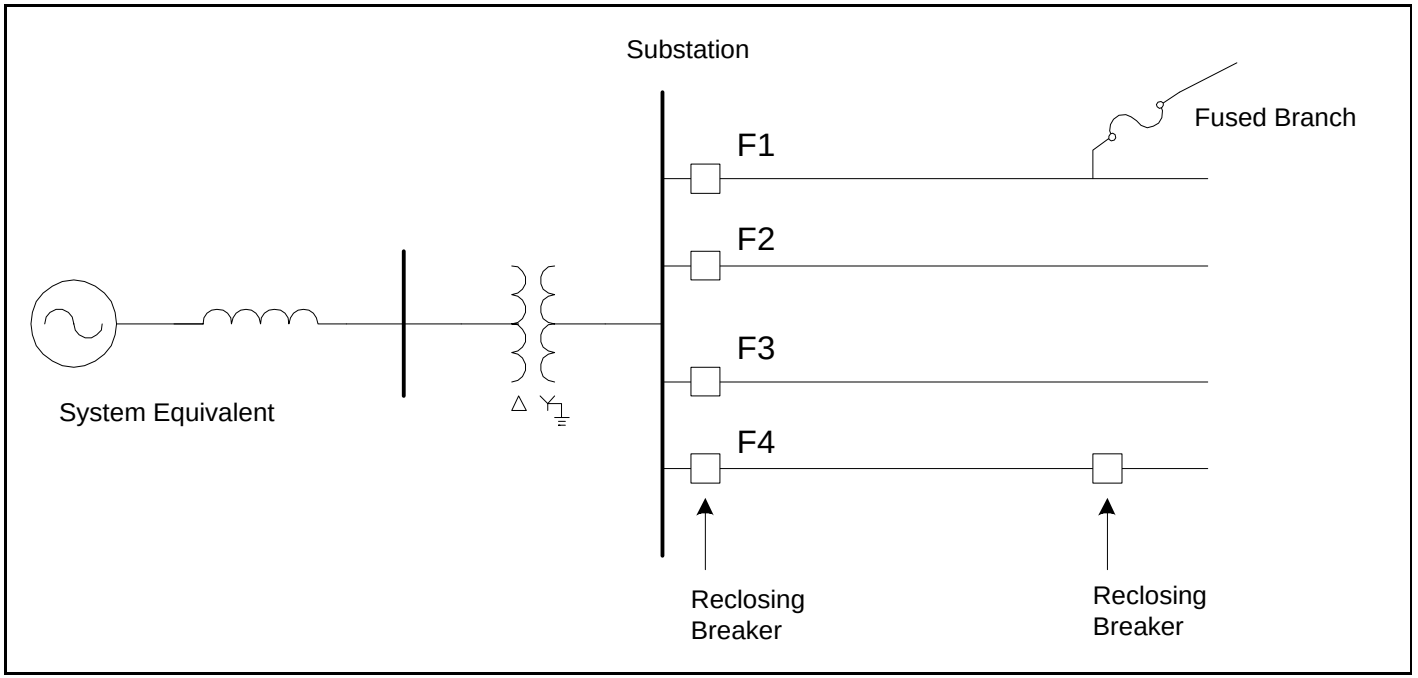


# Causes of Voltage Variations

- Voltage variations and interruptions are inevitable on the power system.
- These conditions usually occur due to faults on the transmission and distribution power systems.
- The most common voltage variation is a voltage sag resulting from a single-line-to-ground fault on the utility system.
- Single-line-to-ground faults can also result in voltage swells.
- Motor starting also results in voltage sags which are typically longer in duration than sags caused by faults.

# Voltage Sags vs. Interruptions vs. Outages

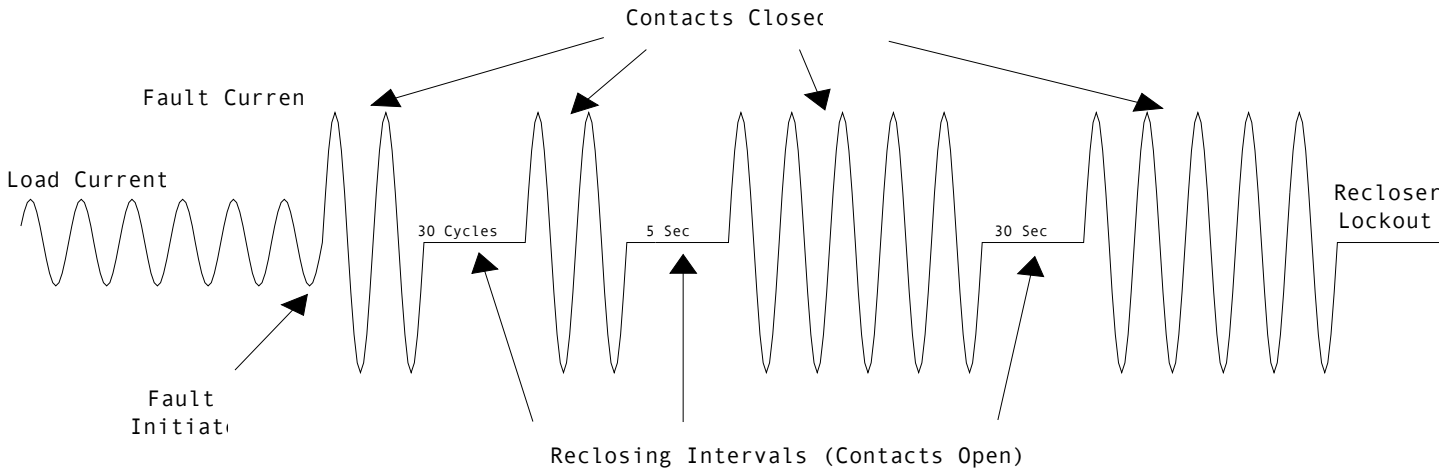
- Customers located on the faulted feeder will experience one or more interruptions.
- Customers located on parallel feeders will experience a voltage sag for the duration that the fault is left on the line.



# Fault Clearing - Two Schools of Thought

- Some utilities have reclosers with instantaneous tripping to clear faults as soon as possible and save downline fuses
  - This results in momentary interruptions for customers located downline from the recloser and short duration voltage sags for customers located on parallel feeders
- Some utilities delay opening their reclosers to allow downline equipment such as fuses to operate and clear the fault
  - This results in an outage to customers fed from the faulted line section and possible long duration voltage sags for other customers on the feeder and for customers located on parallel feeders

# Recloser Operating Sequence



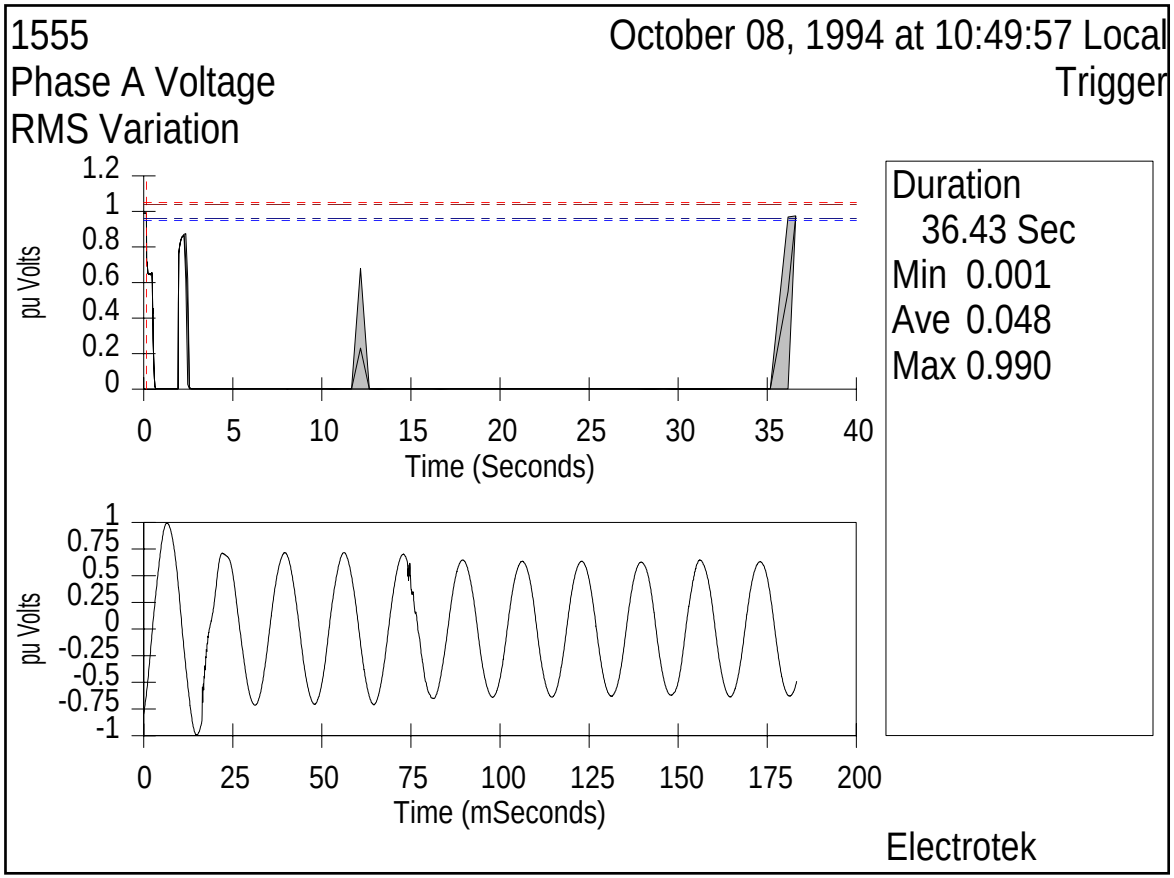

Protective systems on the utility are designed to:

[1] Protect equipment and limit damage (protection).

[2] Localize the impact to the smallest number of customers (coordination).

# Reclosing Sequence - Snapshot

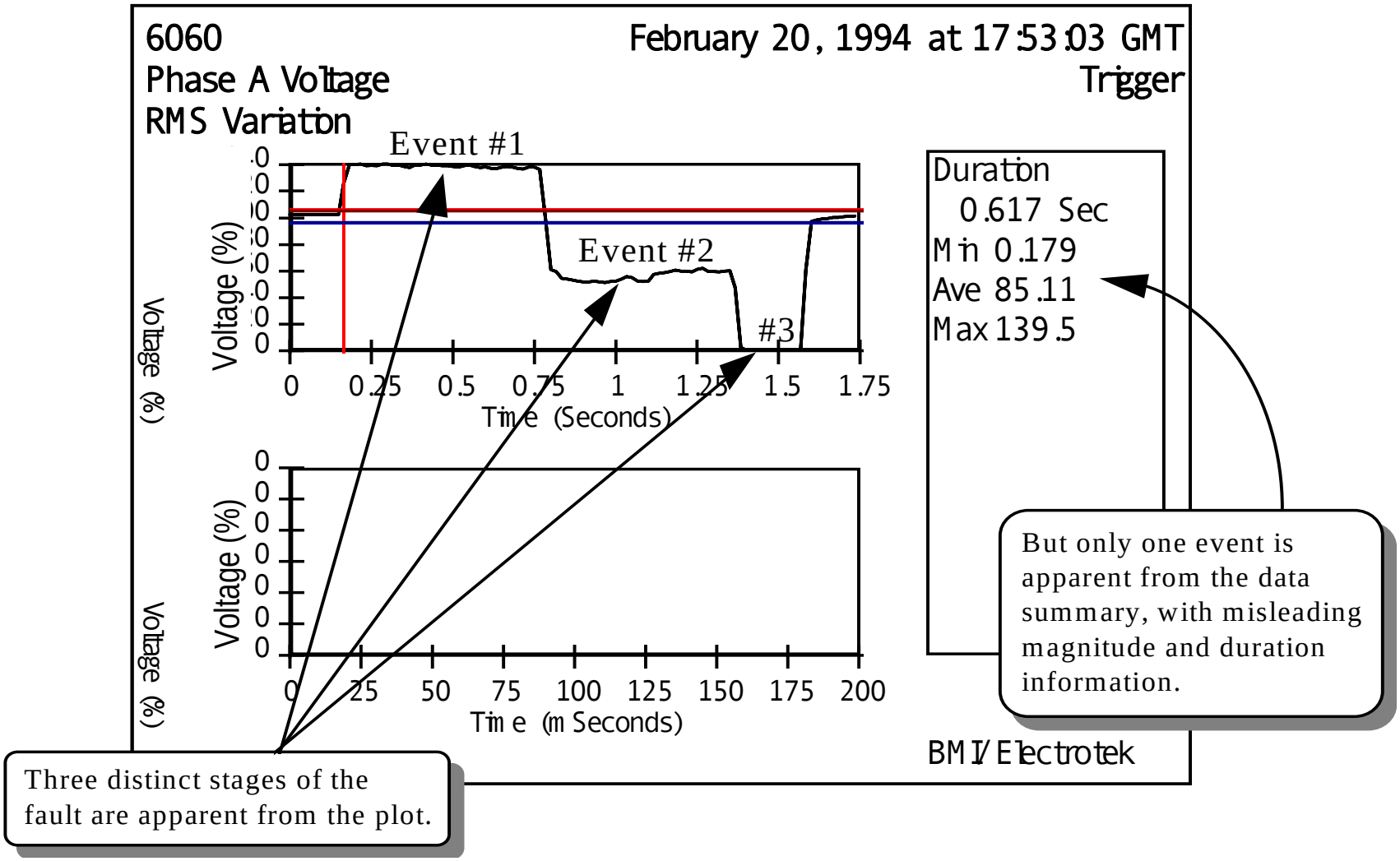
- Example temporary interruption and reclosing process



# Voltage Sag Characteristics

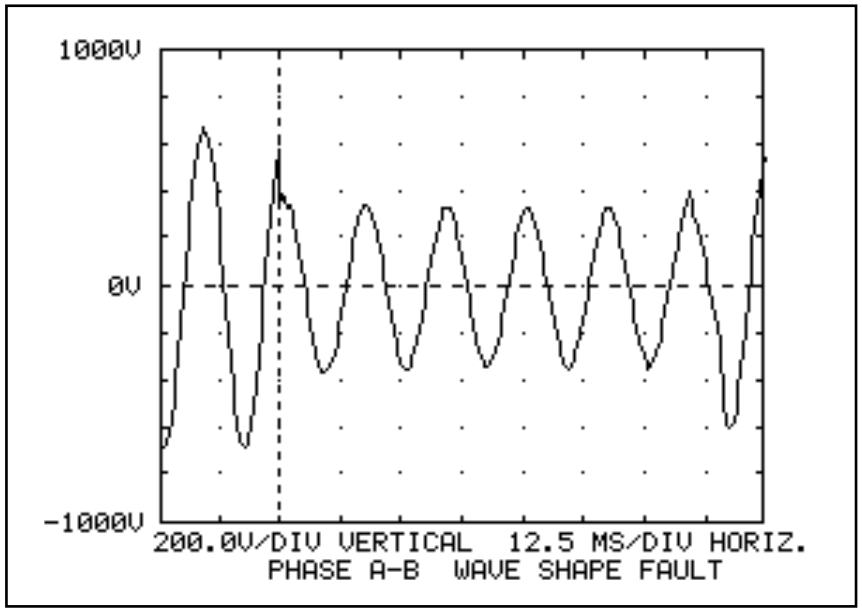
- Transmission system voltage sags are usually more consistent in duration than distribution system voltage sags.
- The further the fault is from the substation, the less impact it will have on the substation voltage (and the customers being serviced from that substation.
- Most voltage sags tend to be less than 1 second in duration and 30% or less in magnitude
- Plant transformer and load connections can be important when determining voltage sag severity.
- Motor starting voltage sags can last several seconds.

# Characterizing Voltage Sag Events

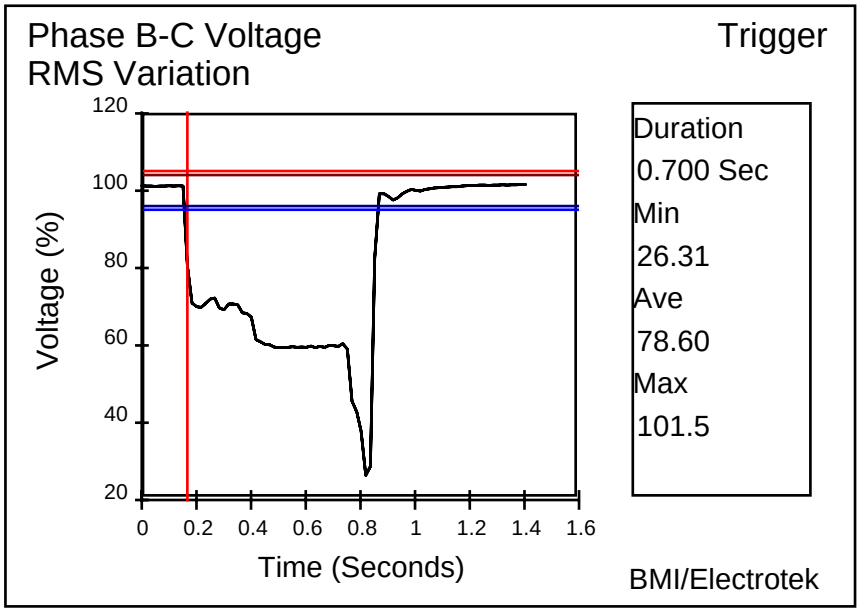


# Transmission vs. Distribution Voltage Sags

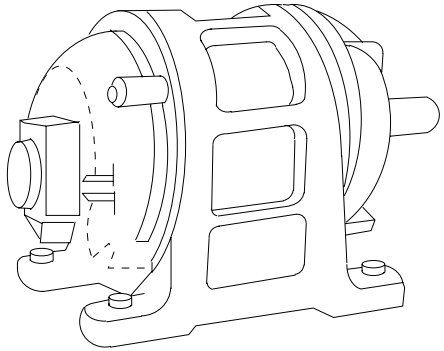
This voltage sag lasted for **6 cycles** before the fault was cleared and is an example of a **transmission system fault**:



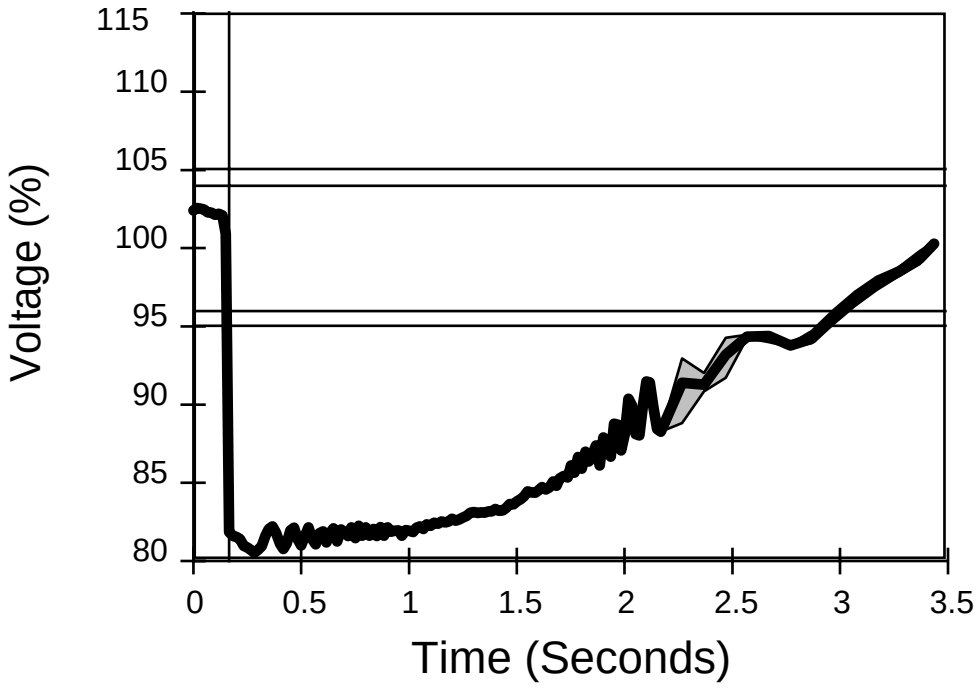

This voltage sag lasted for almost a **second** before the fault was cleared by an automatic throw-over switch and is an example of a **distribution system fault**:



# Motor Starting Sags



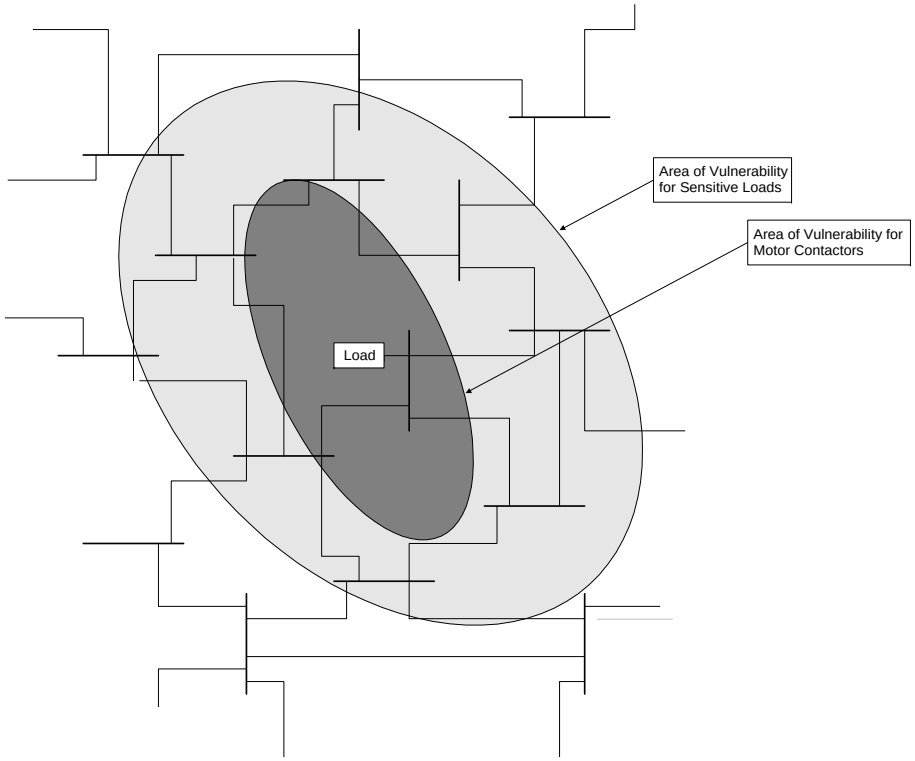
**RMS Variation**



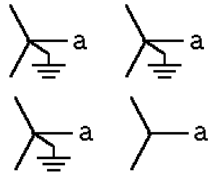
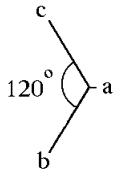
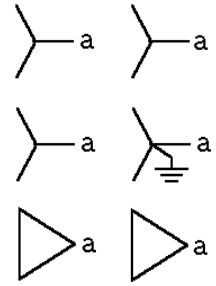
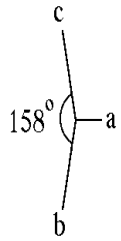
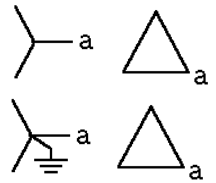
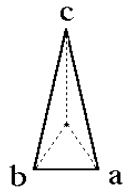
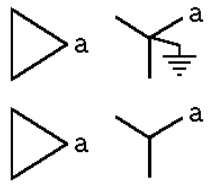
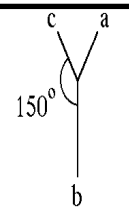

**Duration**
**2.800 Sec**
**Min**
**80.55**
**Ave**
**88.13**
**Max**
**102.5**

# Concept of Area of Vulnerability

- The higher sensitivity of certain loads will cause these loads to be affected by faults further away on the power network.
- If the area of vulnerability can be determined (through computer calculations), then the enclosed line sections can be analyzed for their expected lightning performance.
- The lightning performance analysis can determine the expected number of lightning induced faults per year per mile of line.
- An expected number of voltage sags per year that cause the particular equipment to stop can be determined.

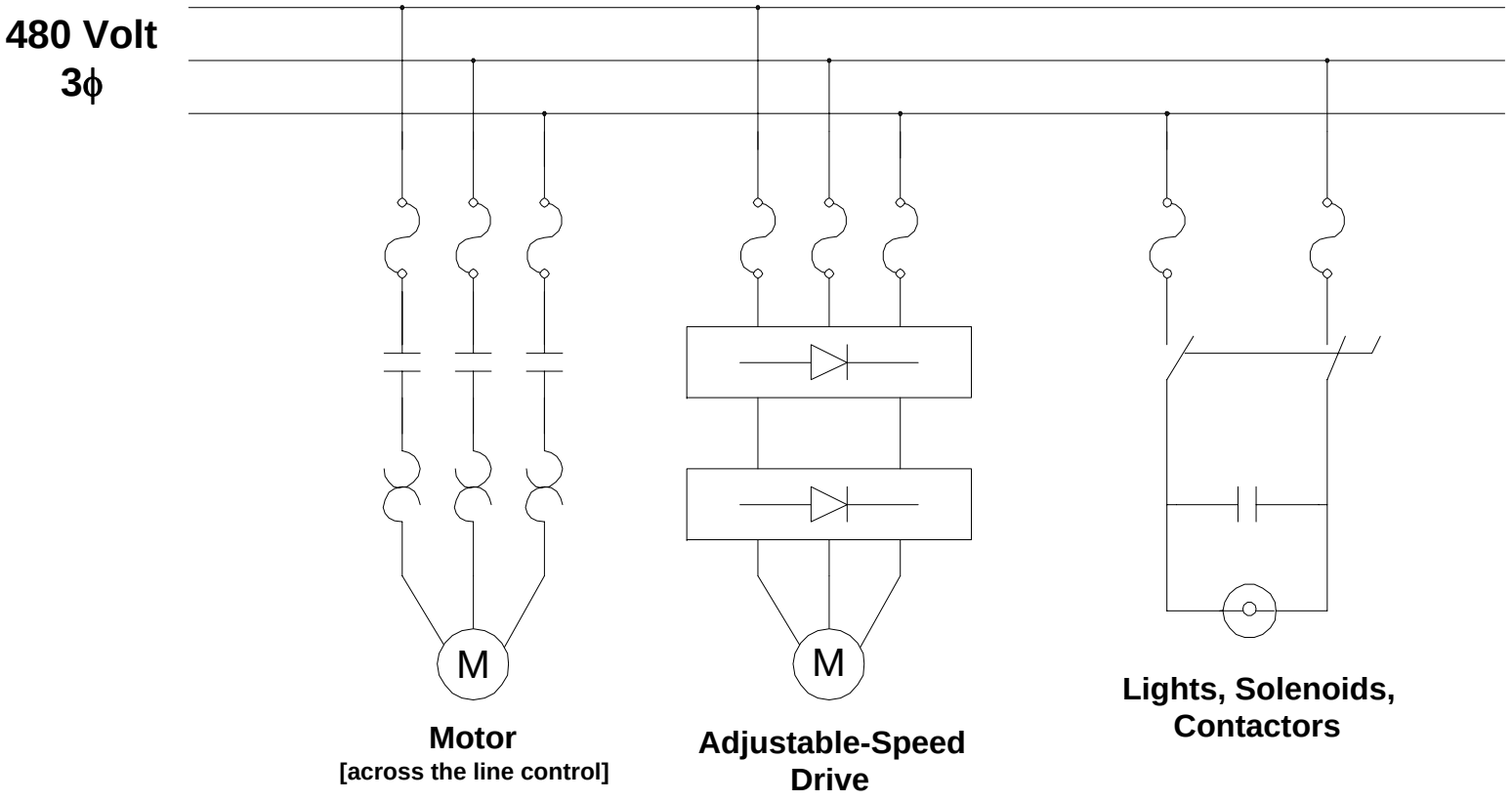


# Effect of Transformer Connections

| Transformer Connection | Phase-to-Phase Vab | Vbc | Vca | Phase-to-Neutral Va | Vb | Vc | Phasor Diagram |
|---|---|---|---|---|---|---|---|
|  | 0.58 | 1.00 | 0.58 | 0.00 | 1.00 | 1.00 |  |
|  | 0.58 | 1.00 | 0.58 | 0.33 | 0.88 | 0.88 |  |
|  | 0.33 | 0.88 | 0.88 | --- | --- | --- |  |
|  | 0.88 | 0.88 | 0.33 | 0.58 | 1.00 | 0.58 |  |

# Connection to the Power System

Typical industrial single phase and three-phase loads:



# Determining Reliability: Present

- System Average Interruption Frequency Index (Sustained Interruptions >5 minutes)

$$\text{SAIFI} = \frac{\text{Total Number of Customer Interruptions}}{\text{Total Number of Customers Served}}$$

*Source: IEEE Standard 1366*

# Determining Reliability - Future

- System Average RMS (Variation) Frequency Index $_{\text{Voltage Threshold}}$ -- $\text{SARFI}_{\%V}$
- Number of specified short-duration rms variation per system customer
- Voltage threshold allows assessment of compatibility for voltage-sensitive devices
- 60 second aggregation

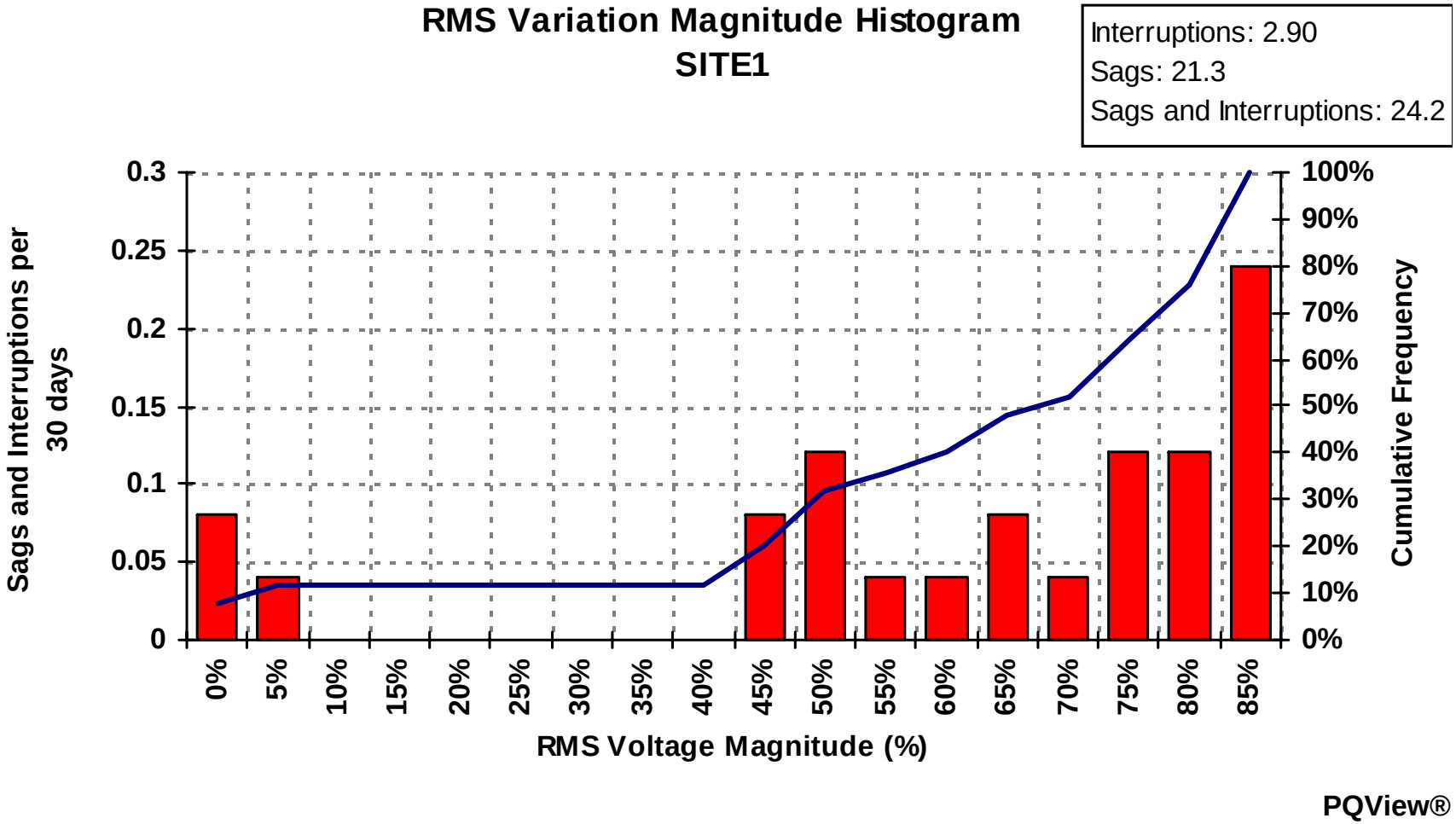
$$SARFI_{\%V} = \frac{\sum N_i}{N_T}$$

$\%V \equiv$ rms voltage threshold
140, 120, 110, 90, 80, 70, 50, 10

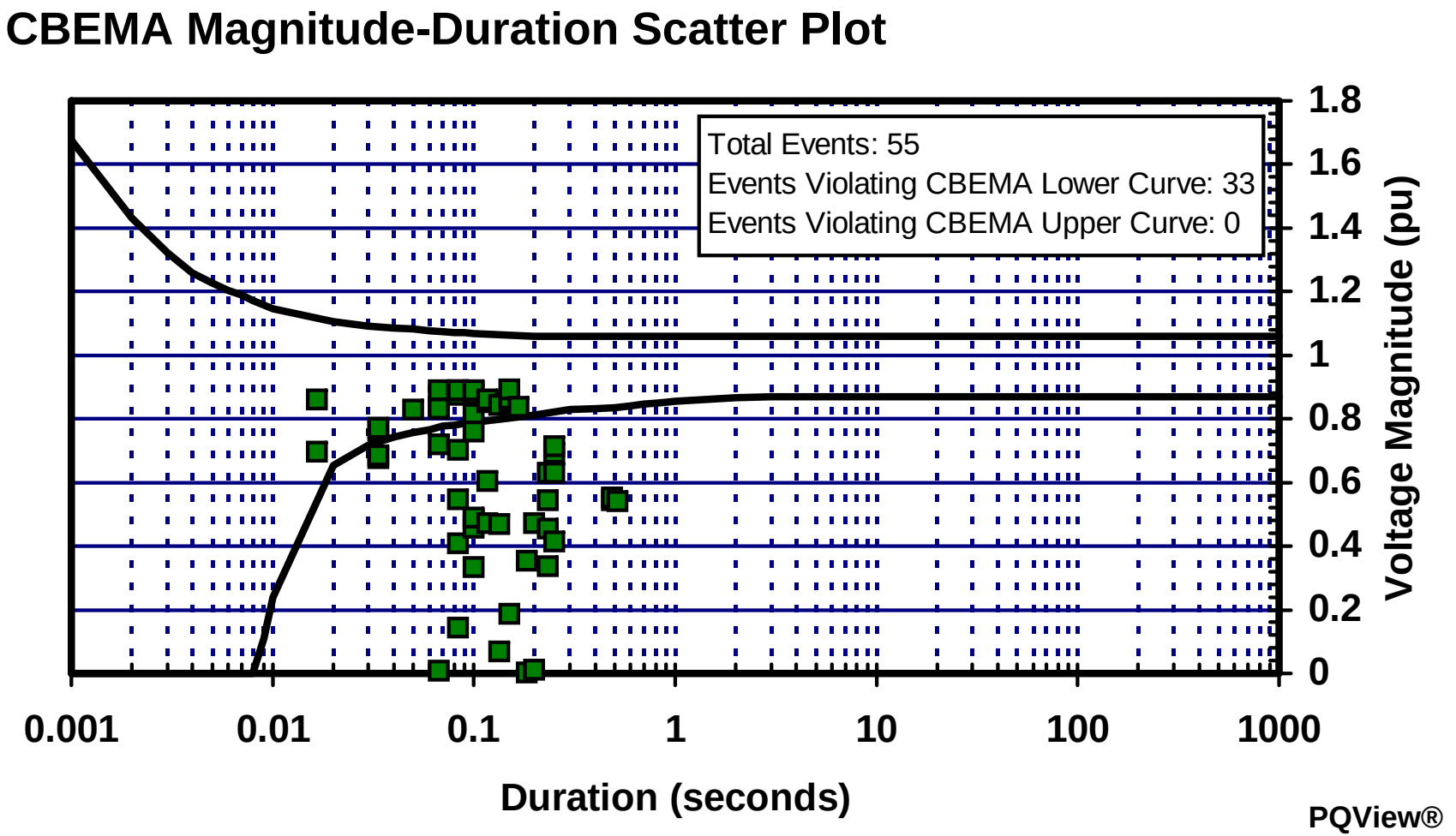
$N_i \equiv$ # customers experiencing rms < $\%V$ for variation $i$ (rms > $\%V$ for $\%V$ >100)

$N_T \equiv$ total # system customers

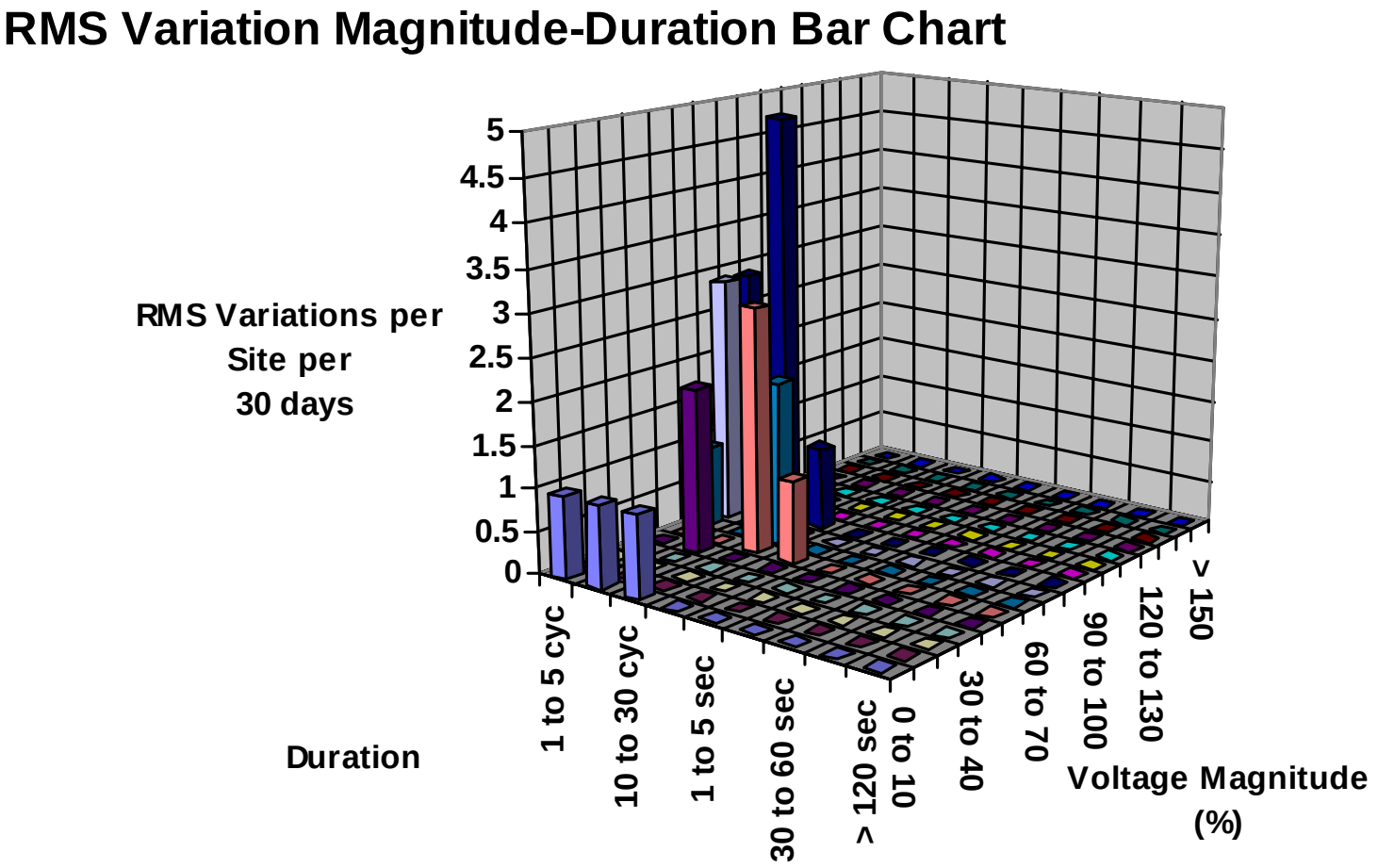
# Voltage Sag Analysis - Histograms



# Voltage Sag Analysis – Scatter Plots



# Voltage Sag Analysis – Mag/Dur Bar Chart



# Solutions to Voltage Sag Problems

- Utility Solutions
  - Prevent Faults
  - Modify Fault Clearing Practices
- Customer Solutions
  - Power Conditioning
- Equipment Solutions
  - Modification of Electronic Controls
  - Equipment Procurement Specifications

# Utility Solutions to Voltage Sags

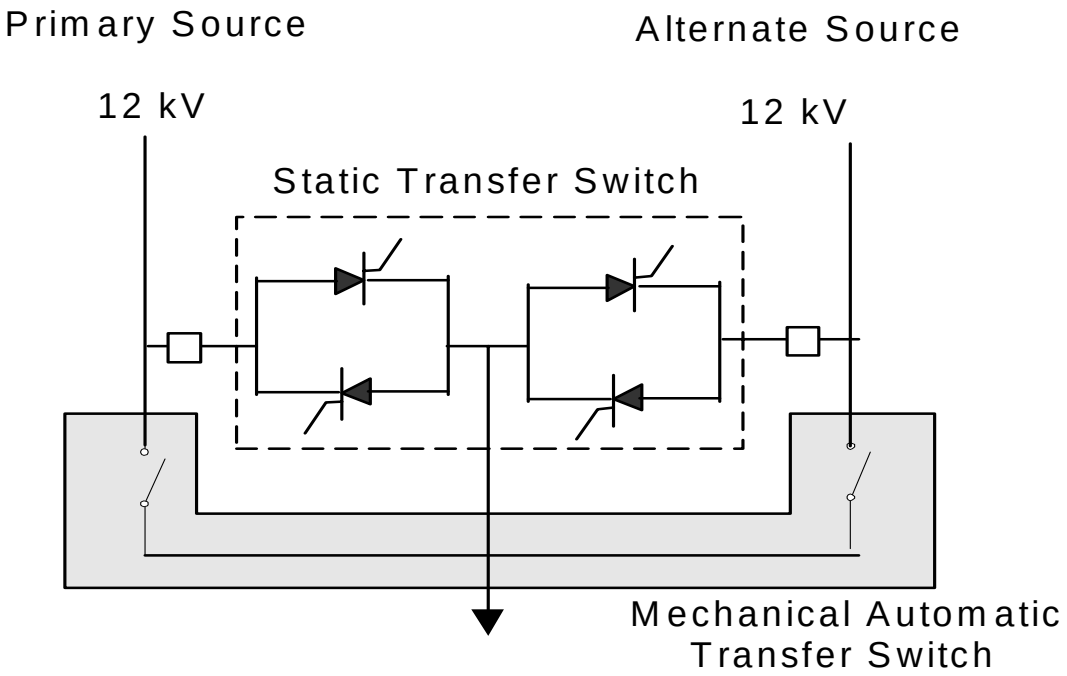
- Utility should maintain log that records system faults along with their probable cause
- Any transmission line that shows a trend toward lightning induced faults should be investigated
- Utilities have two basic options to reduce or prevent voltage sags
  - Prevent faults
  - Modify fault clearing practices

# Utility Solutions - cont.

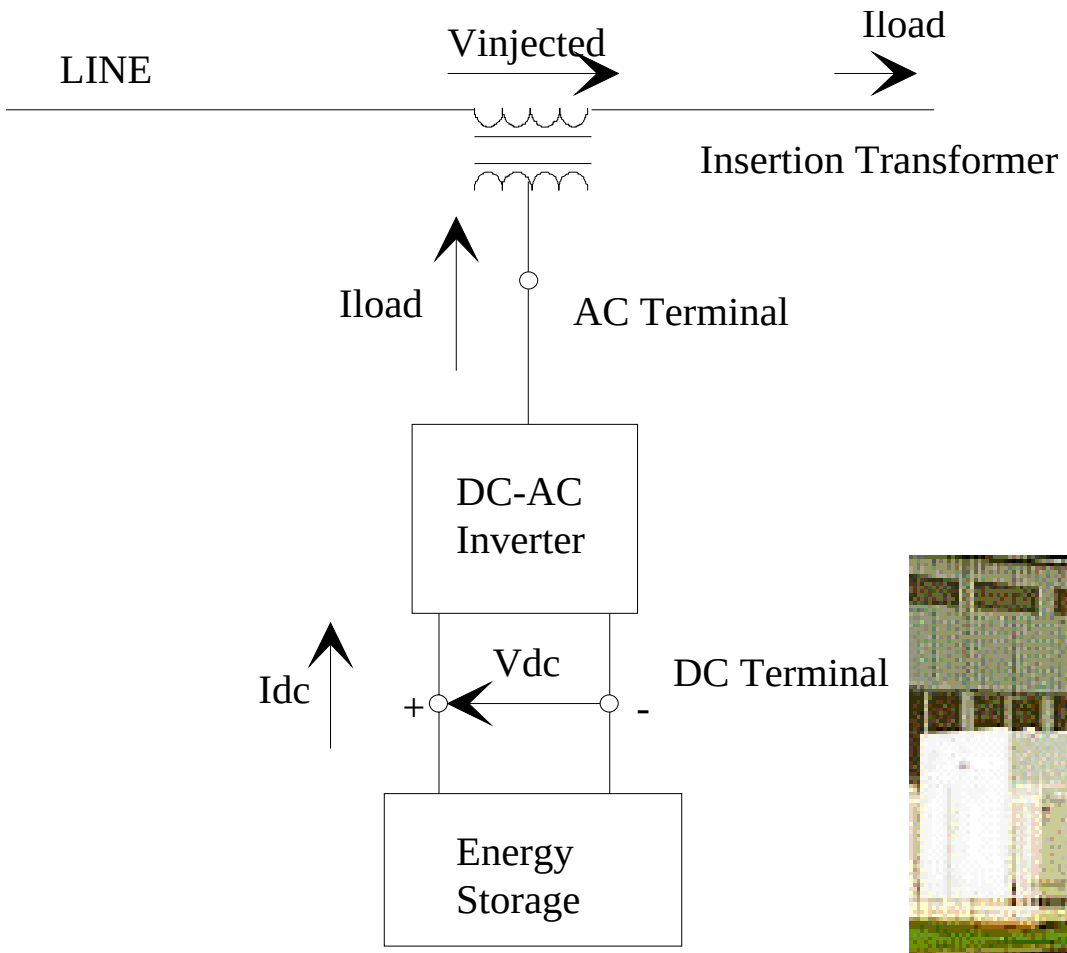
- Fault prevention
  - Tree trimming
  - Add line arresters
  - Insulator washing
  - Animal guards
- Modify fault clearing practices
  - Add line reclosers and reactors
  - Loop schemes
  - Modified feeder design

# Solid-State Switches with Dual Feeders

- Solid-state switches can be used to switch load from one feeder (normal) to the emergency backup feeder in less than a quarter-cycle which is fast enough to prevent load interruptions

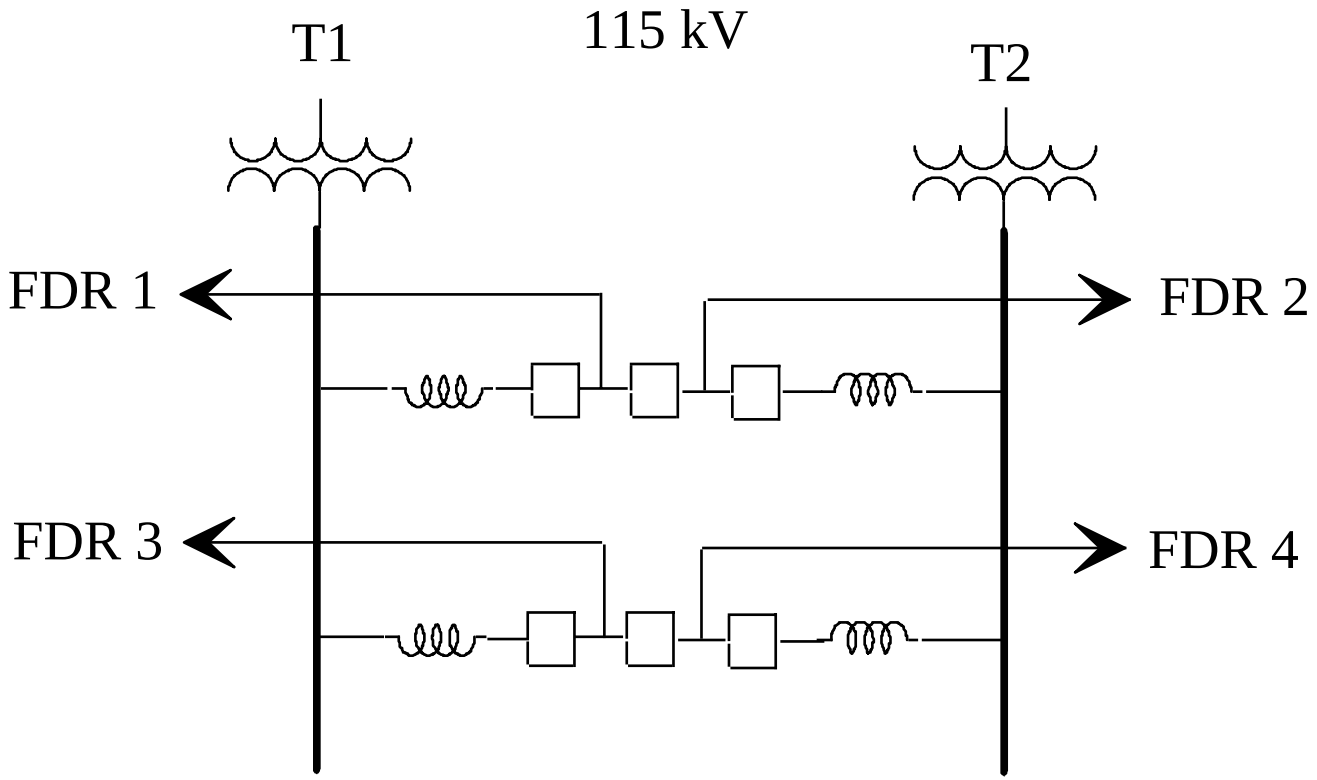


# Dynamic Voltage Restorer (DVR)




# Feeder Reactors can Limit Voltage Sags

- Feeder reactors and low impedance substation transformers can be used to limit voltage sags to 80% for faults on parallel feeders



# Economics for Voltage Sag Solutions