Power Quality and Circuit Imbalances

2015 Northwest Electric Meter School

Presented by: Chris Lindsay-Smith

McAvoy & Markham Engineering/Itron

Summary of IEEE 1159 Terms

Category	Types	Typical Duration	Common Causes
Transients	Oscillatory, Impulsive	Less than 1-cycle	Lightning, switching loads
Short duration variations	Sags, swells, imbalances	Less than 1-minute	Faults, motor starting, utility protective equipment
Long duration variations	Undervoltages, overvoltages, sustained interruptions	Over 1-minute	Poor voltage regulation, incorrect transformer tap setting, overloaded feeder, utility equipment
Voltage imbalance	-	Steady-state	Unbalanced loads, equipment failure
Waveform distortion	Harmonics, notching, noise	Steady-state	Electronic loads
Voltage fluctuations	-	Steady-state	Arcing loads, loose connections
Power frequency variations	-	Steady-state	Poor generator control

Transients

There are 2 types of transients

Oscillatory

- Voltage or current that changes polarity rapidly
- Can be categorized as low (<5kHz), medium (between 5 and 500kHz), and high frequency (>500kHz)

Impulsive

- Sudden, nonpower frequency change in the steady-state condition of the voltage, current, or both, that is unidirectional in polarity
- Can excite resonance on the power system and cause oscillatory transients

Duration of Transients

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
Impulsive Transients			
Nanosecond	5ns rise	<50ns	
Microsecond	1μs rise	50ns - 1ms	
Millisecond	0.1ms rise	>1ms	
Oscillatory Transients			
Low Frequency	<5kHz	0.3 - 50ms	0 - 4 pu
Medium Frequency	5 – 500 kHz	20μs	0 – 8 pu
High Frequency	0.5 – 5 MHz	5μs	0 – 4 pu

1 microsecond (1*μs*) = cycle time for frequency 1 x 10^6Hz (1MHz), an inverse unit
1 nanosecond (1ns) = cycle time for frequency 1 x 10^9Hz (1GHz), an inverse unit
pu = per-unit system (ex: V_{base} = 1pu)

Causes of Transients

- Impulsive
  - Lightening (direct strike or induced current)
- Oscillatory
  - Capacitor switching
  - Cable switching
  - Transformer energization
  - Ferroresonance (unstable high voltage)

Impulsive Transient

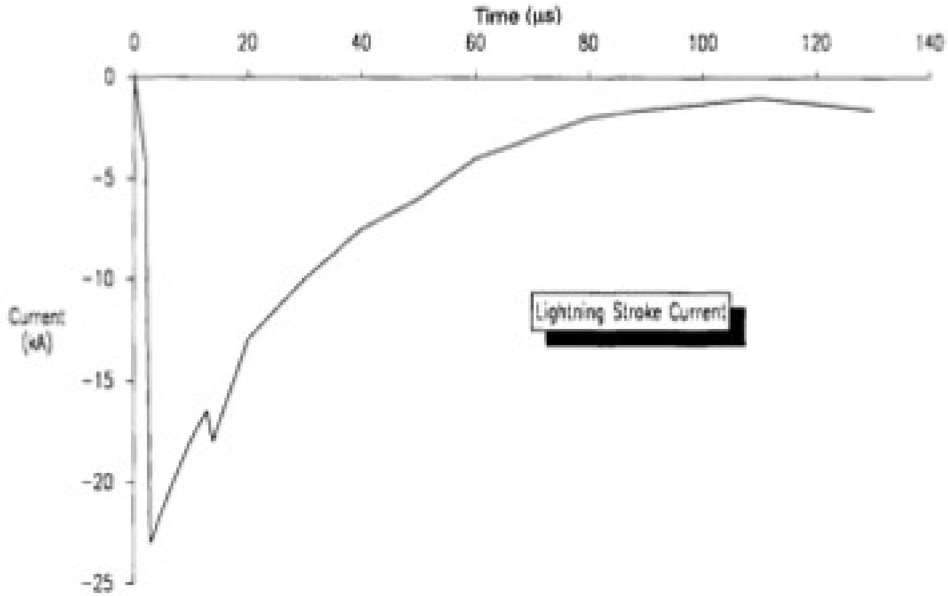


Figure 1—Lightning stroke current that can result in impulsive transients on the power system

Oscillatory Transient

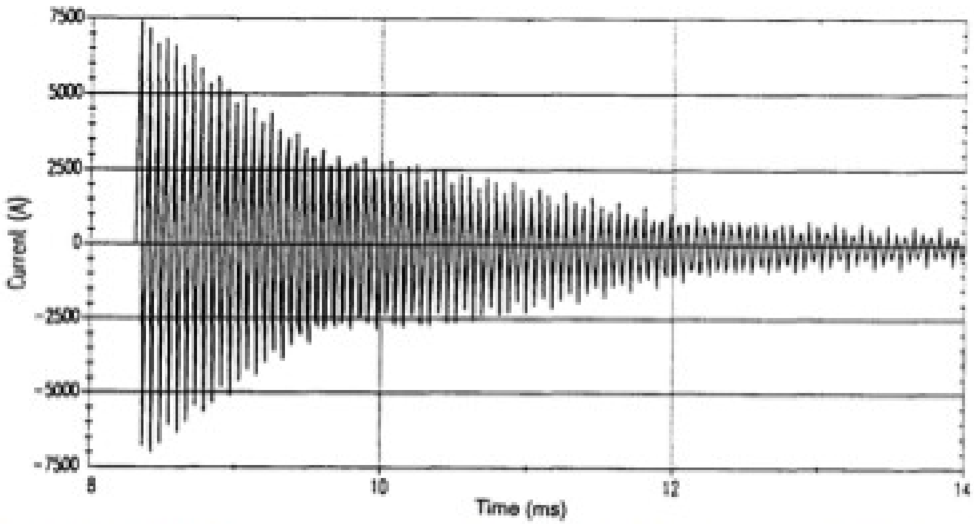


Figure 2—Oscillatory transient caused by back-to-back capacitor switching

Low Frequency Oscillatory Transient

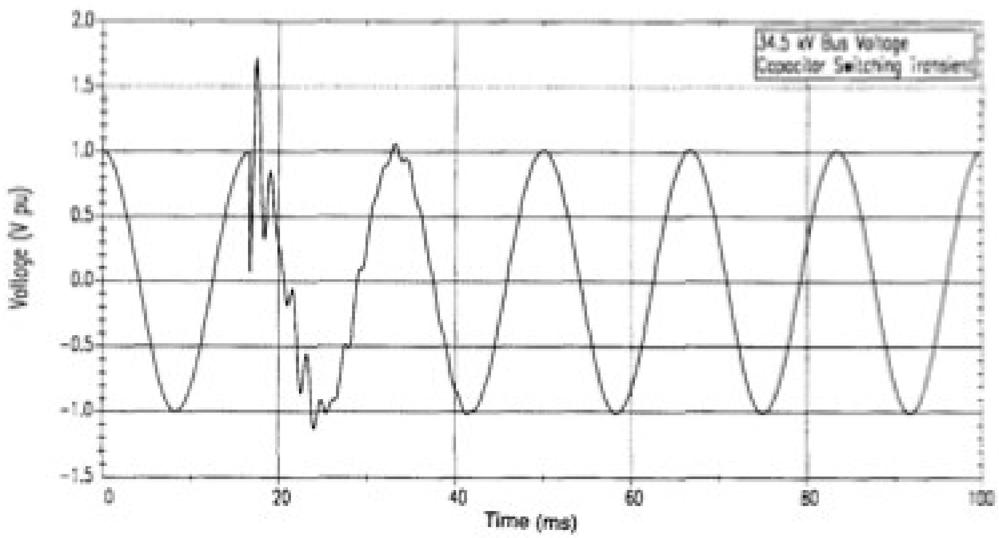
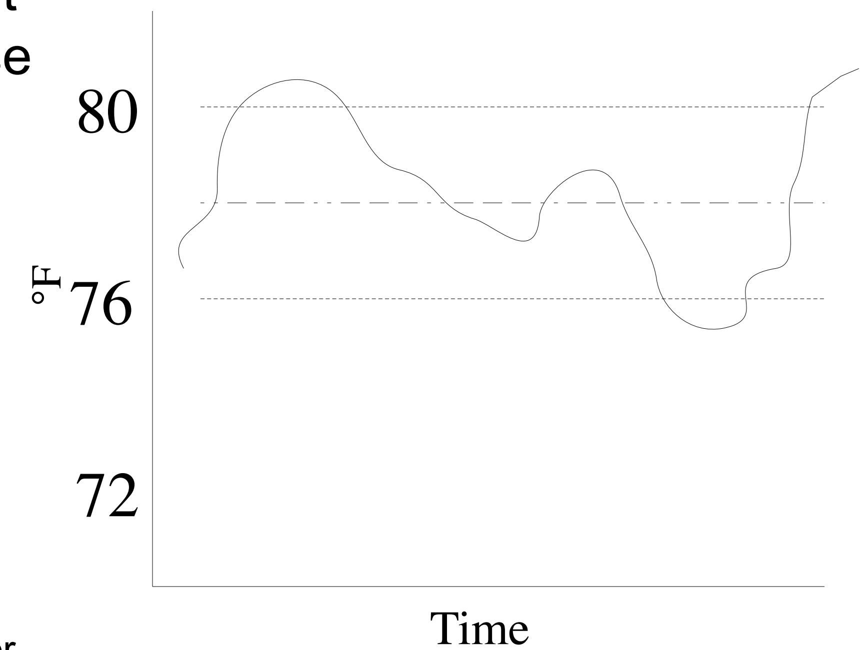


Figure 3—Low frequency oscillatory transient caused by capacitor-bank energization

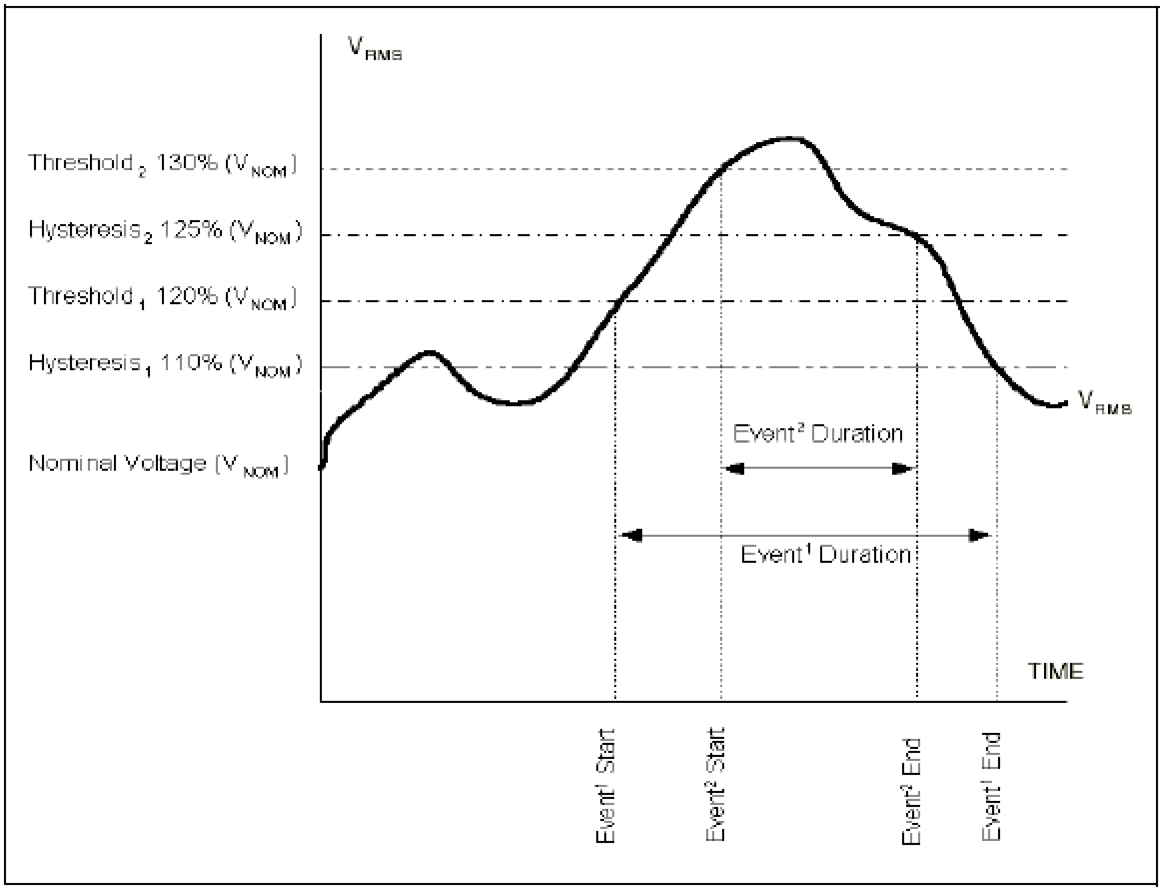
What is Hysteresis?

- Method to filter signal so the output reacts more slowly than it otherwise would
- Example is thermostat:
  - Desired temperature is 78°F
    - Turns A/C on at 80°F
    - Turns A/C off at 76 °F
- The thermostat is a system; the input is the temperature, and the output is the furnace state. The furnace is either off or on, with nothing in between. If the temperature is 77 °F, it is not possible to determine whether the furnace is on or off without knowing the history of the temperature.

***From Wikipedia



Hysteresis – Voltage Swell

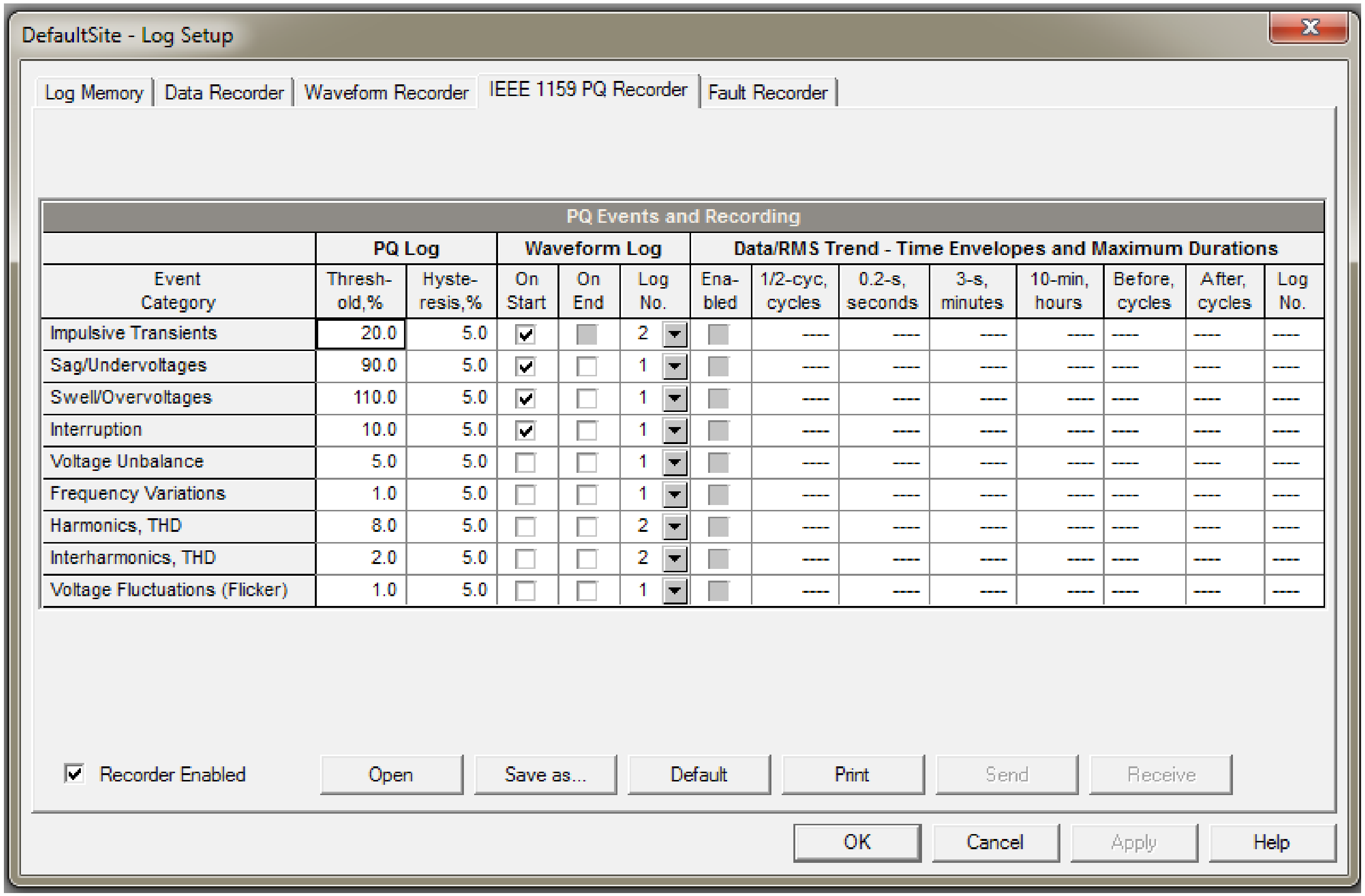


Nominal Voltage
V_{NOM}=120V

Hysteresis$_1$=132V
Threshold$_1$=144V

Hysteresis$_2$=150V
Threshold$_2$=156V

Configuring Transient



	PQ Log		Waveform Log			Data/RMS Trend - Time Envelopes and Maximum Durations							
Event Category	Thresh-old,%	Hyste-resis,%	On Start	On End	Log No.	Ena-bled	1/2-cyc, cycles	0.2-s, seconds	3-s, minutes	10-min, hours	Before, cycles	After, cycles	Log No.
Impulsive Transients	20.0	5.0	✓		2		----	----	----	----	----	----	----
Sag/Undervoltages	90.0	5.0	✓		1		----	----	----	----	----	----	----
Swell/Overvoltages	110.0	5.0	✓		1		----	----	----	----	----	----	----
Interruption	10.0	5.0	✓		1		----	----	----	----	----	----	----
Voltage Unbalance	5.0	5.0			1		----	----	----	----	----	----	----
Frequency Variations	1.0	5.0			1		----	----	----	----	----	----	----
Harmonics, THD	8.0	5.0			2		----	----	----	----	----	----	----
Interharmonics, THD	2.0	5.0			2		----	----	----	----	----	----	----
Voltage Fluctuations (Flicker)	1.0	5.0			1		----	----	----	----	----	----	----

Nominal Voltage
V_{NOM}=120V

Hysteresis=5%
$V_{Hysteresis}$=7.2V

Threshold=20%
$V_{Threshold}$=144V

Note hysteresis voltage is based on threshold, not nominal

Short Duration Events

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
Instantaneous			
Sag		0.5 – 30 cycles	0.1 – 0.9 pu
Swell		0.5 – 30 cycles	1.1 – 1.8 pu
Momentary			
Interruption		0.5 – 30 cycles	<0.1 pu
Sag		30 cycles – 3s	0.1 – 0.9 pu
Swell		30 cycles – 3s	1.1 – 1.4 pu
Temporary			
Interruption		3s – 1 min	<0.1 pu
Sag		3s – 1 min	0.1 – 0.9 pu
Swell		3s – 1 min	1.1 – 1.2 pu

pu = per-unit system (ex: V_{base} = 1pu)

Low Frequency Oscillatory Transient

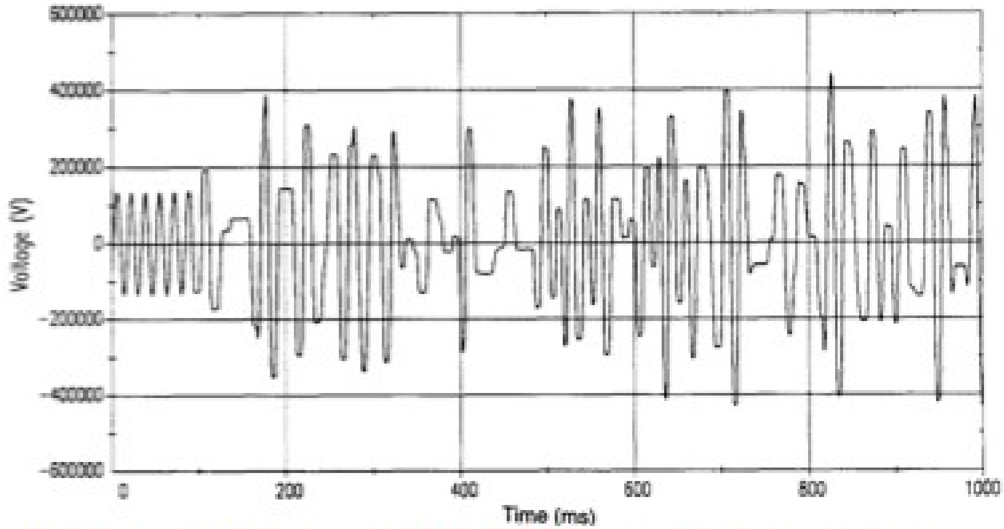


Figure 4—Low-frequency oscillatory transient caused by ferroresonance of an unloaded transformer

Short Duration Variations

There are 3 types of short duration variations

- Sags
  - Short duration voltage decrease
  - May also be described as a dip (IEC terminology)
- Swells
  - An increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min
  - Can sometimes be referred to as “momentary overvoltage”
- Interruptions
  - Occurs when the supply voltage or load current decreases to less than 0.1pu for 1 minute or less
  - May be proceeded by a sag

Short Duration Events

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
Instantaneous			
Sag		0.5 – 30 cycles	0.1 – 0.9 pu
Swell		0.5 – 30 cycles	1.1 – 1.8 pu
Momentary			
Interruption		0.5 – 30 cycles	<0.1 pu
Sag		30 cycles – 3s	0.1 – 0.9 pu
Swell		30 cycles – 3s	1.1 – 1.4 pu
Temporary			
Interruption		3s – 1 min	<0.1 pu
Sag		3s – 1 min	0.1 – 0.9 pu
Swell		3s – 1 min	1.1 – 1.2 pu

pu = per-unit system (ex: V_{base} = 1pu)

Instantaneous Voltage Sag

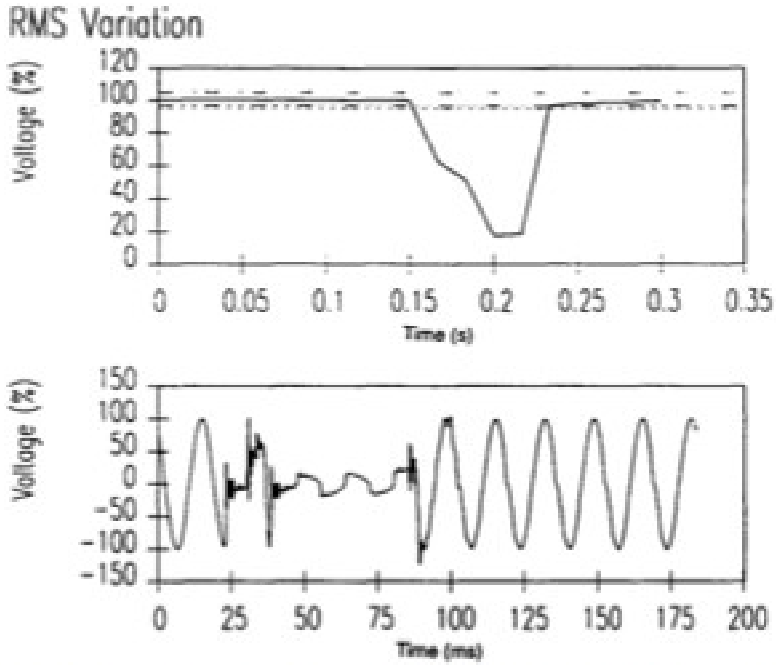


Figure 6—Instantaneous voltage sag caused by a SLG fault

SLG = single line-to-ground

Instantaneous Voltage Swell

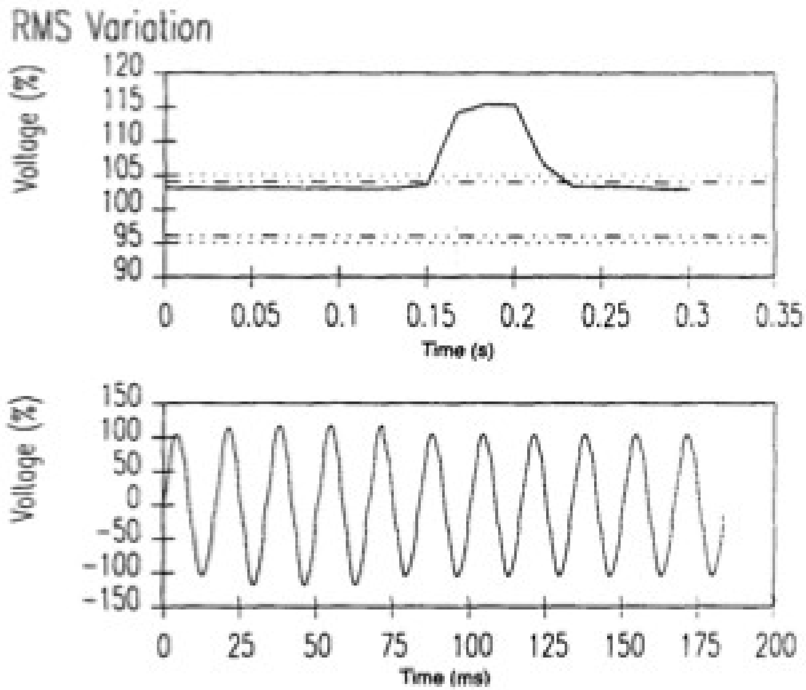


Figure 8—Instantaneous voltage swell caused by a SLG fault

Momentary Interruption

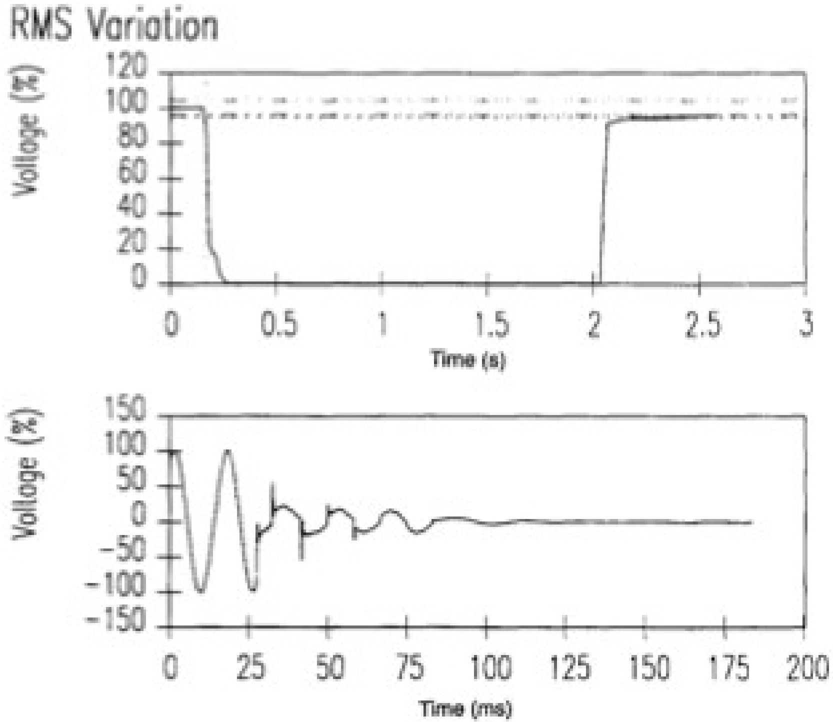


Figure 5—Momentary interruption due to a fault and subsequent recloser operation

Temporary Voltage Sag

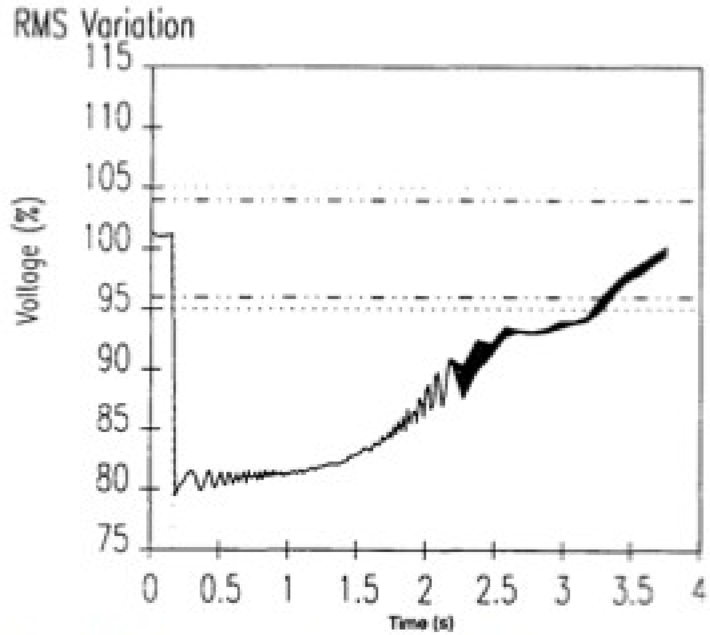


Figure 7—Temporary voltage sag caused by motor starting

Long Duration Variations

- Long duration variations are characterized by 3 different phenomena
  - Sustained interruption (not an outage)
  - Undervoltage
  - Overvoltage
- Events of this category typically last for more than 1 minute
- Typically caused by system load variations or system switching operations

Long Duration Variations and Imbalances

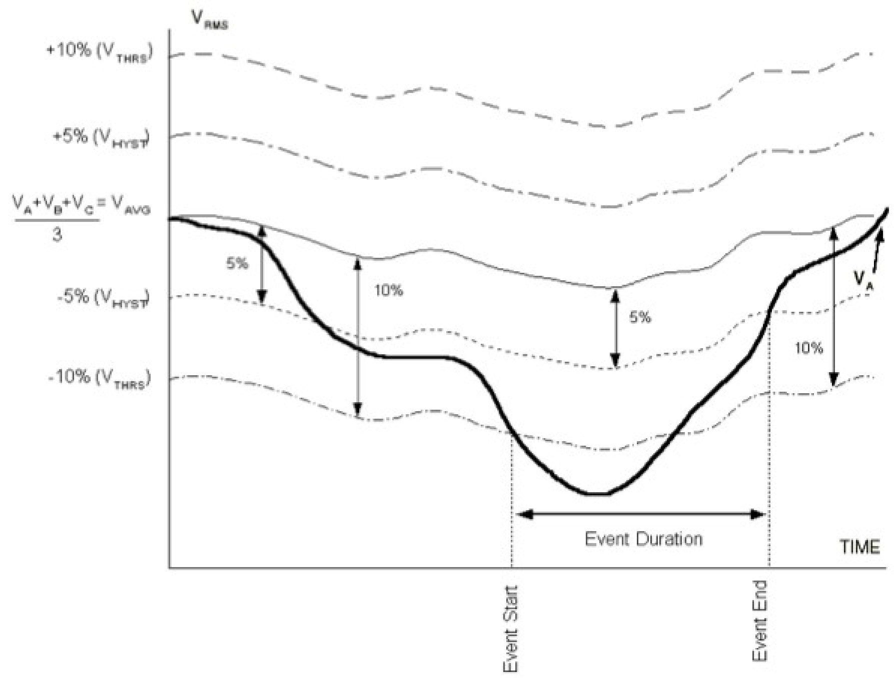
Categories	Typical spectral content	Typical duration	Typical voltage magnitude
Long Duration Variations			
Sustained interruption		>1 min	0.0 pu
Undervoltage		>1 min	0.8 – 0.9 pu
Overvoltage		>1 min	1.1 – 1.2 pu
Imbalance			
Voltage Imbalance		steady state	0.5 – 2%

pu = per-unit system (ex: V_{base} = 1pu)

Overvoltage and Undervoltage

- Causes of overvoltage
  - Switching off a large load
  - Variations in reactive compensation
    - Switching on a capacitor bank
  - Incorrect tap settings on transformers
- Causes of undervoltage
  - Switching on a large load
  - Capacitor bank switching off
  - Overloaded circuits
- Undervoltage is sometimes associated with a "brownout" - a term that is out-of-favor

Voltage Imbalance



Determining Voltage Imbalance

- Voltage imbalance can be calculate from the phase-to-phase voltage
- $V_{imbalance}(\%) = 100 \times (\text{max deviation from } V_{avg})/V_{avg}$

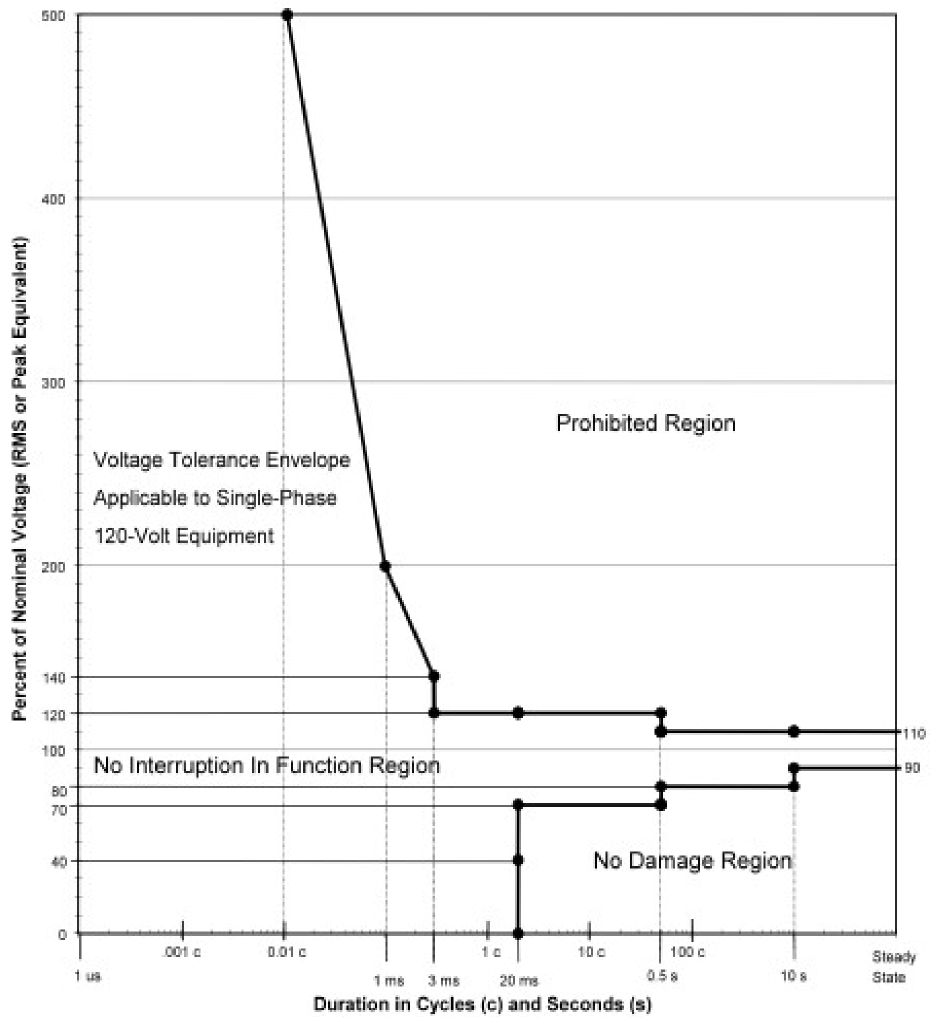
Example:

Phase-to-phase V = 228, 232, and 230; $V_{avg} = 230$

$V_{imbalance} = 100 \times (2)/230$

$V_{imbalance} = 0.87\%$

ITI (CBEMA) Curve

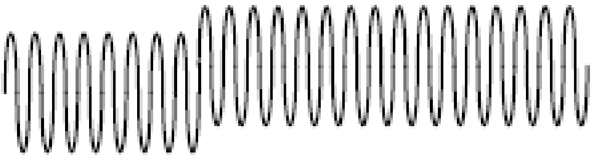


Waveform Distortion

- Five primary types of waveform distortion
  - DC offset
  - Harmonics
  - Interharmonics
  - Notching
  - Noise

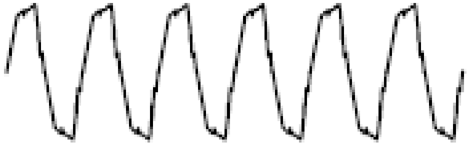
DC Offset

- Results from DC induced on the AC power system
  - Heats up transformer
  - Transformer cannot deliver the rated amount of current
  - Example of DC offset waveform:



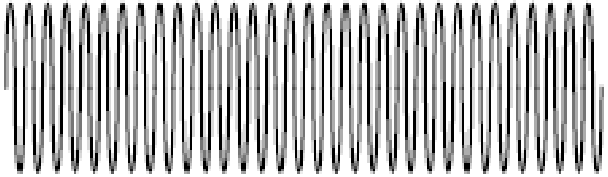
Harmonics

- Harmonics are the manipulation of the fundamental sine wave at frequencies that are multiples of the fundamental
  - Example
    - 300Hz is the 5^{th} harmonic of a 60Hz fundamental frequency
  - Example waveform:



Interharmonics

- Interharmonics cause the supply voltage to change by imposing waveform distortion
- Certain industrial processes using cycloconverters (mines, cement plants, steel mills) transform the supply voltage into an AC voltage of higher or lower frequency than what the utility provides
- Waveform example:

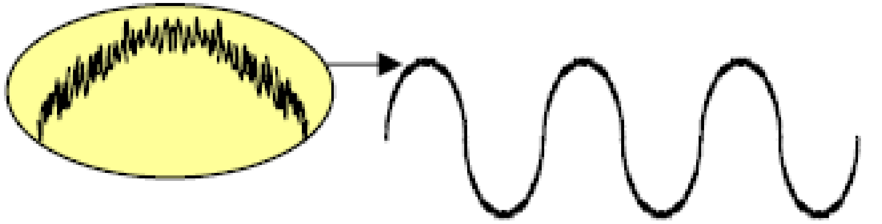


Notching

- Notching is a periodic voltage disturbance that typically occurs over each ½ cycle
- Caused by arc welders, VSD, and dimmers
- Waveform example:

Noise

- Noise is unwanted voltage or current superimposed on the voltage or current waveform
- Sources: Radio transmitters, power electronics, arc welder, etc.
  - Poor grounding makes a system more susceptible
- Waveform example:



Effects on Equipment

- Transients
  - Degradation or immediate failure of all types of equipment
  - Insulation breakdown
  - Component failure in electronic equipment’s power supply
  - Nuisance tripping on VSD

Effects on Equipment

- Short Duration Variations
  - Interruptions
    - Equipment shutdown
      - $$$ for utility
  - Sags
    - Process disruption initiated by electronic process controllers
  - Swells
    - Reduced equipment life
    - Immediate failure of electronic devices

Effects on Equipment

- Long Duration Variations
  - Sustained interruptions
    - Equipment shutdown
  - Undervoltages
    - Motor controllers can drop out (70-80% of nominal V)
    - Excess heating on induction motors (higher current)
    - Lower VAR output from capacitor banks (square of V)
  - Overvoltages
    - Equipment failure
    - Excess VAR output from capacitor banks (square of V)

Effects on Equipment

- Voltage Imbalance
  - Typically present in the customer's load
  - 1% or less is desirable
    - Minimizes heating effects on utility equipment
  - An imbalance of 2-5% can be caused by a blown fuse on one fuse of a 3-phase cap bank
  - An imbalance of 5% or more are typically caused by a single-phasing condition

Methods of Recording

- There are various ways to monitor voltage and other electrical parameters
  - Utility service entrance
    - Meter or portable recorder
  - Equipment subpanel
  - Weatherhead
  - Vault
  - Wall outlet

Styles of Recorders

Socket-type

Service entrance-type

Meter
(customer-owned or utility-owned)

Wall outlet-type

Flexible current transformers

Monitoring Locations

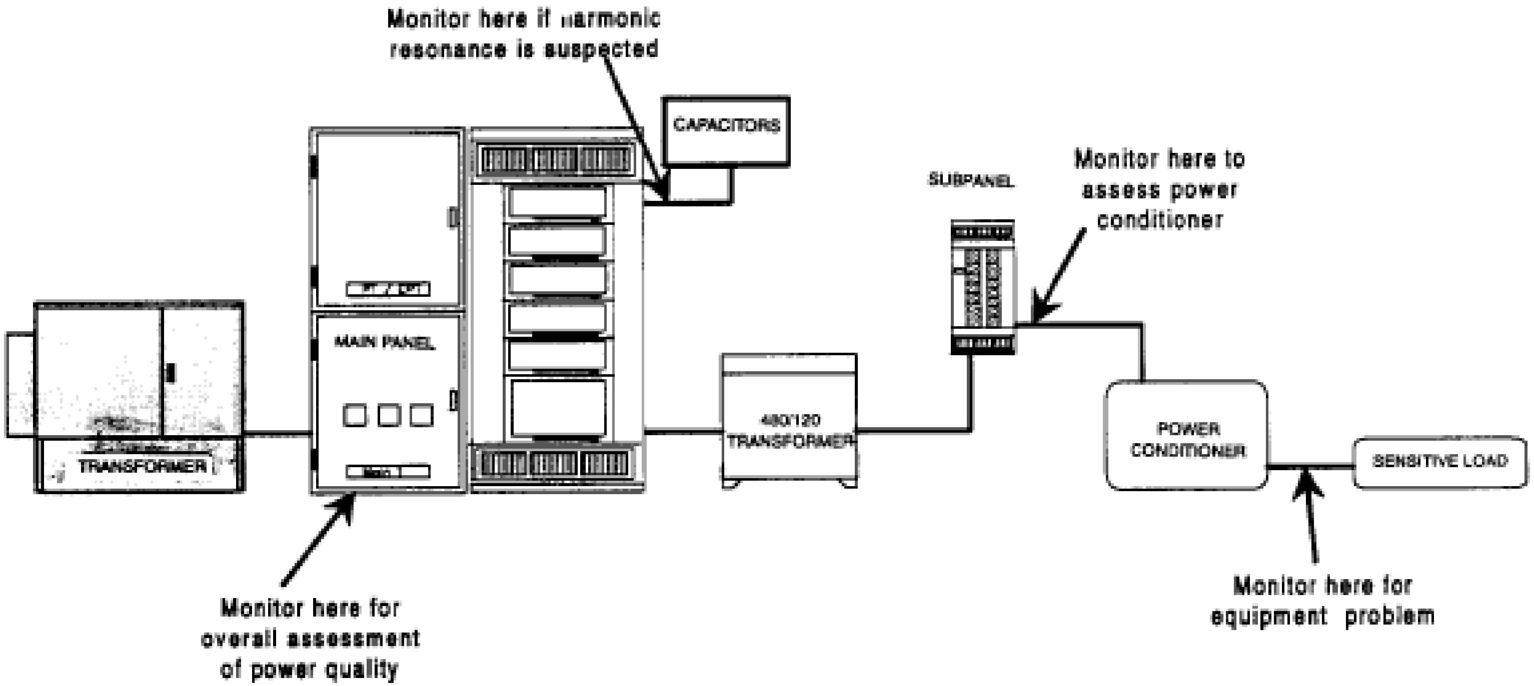


Figure 15—Suggested monitoring locations on a typical low voltage system

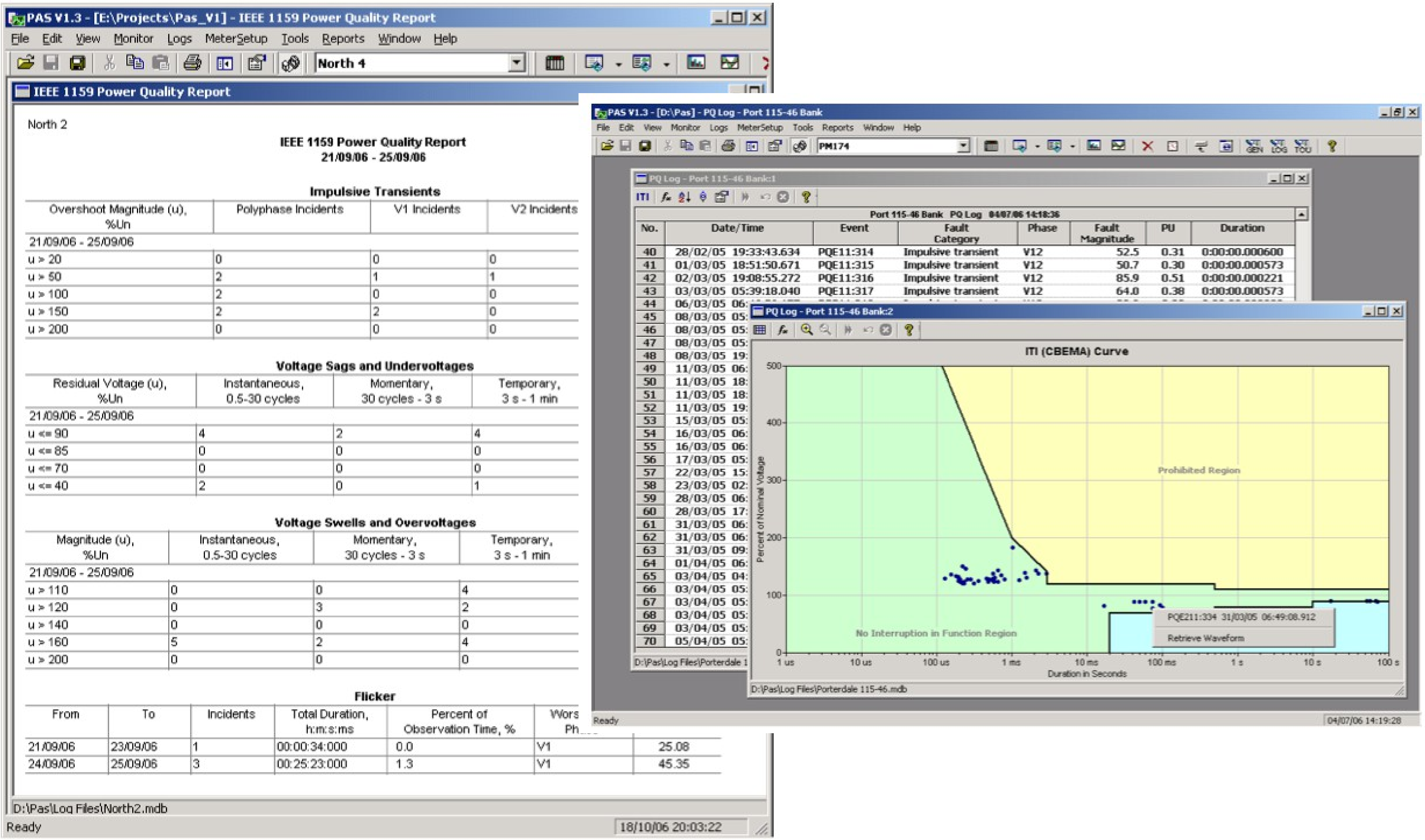
Problem Analysis - IEEE 1159

Typical Problem	Disturbance Type	Possible Causes
Overheated neutral Intermittent lock-ups Frequency deviations	Steady-state	Shared neutrals Improper or inadequate wiring High source impedance Notching Harmonics
Interruption Garbled data Random increases in harmonic levels		Utility faults Inrush currents Inadequate wiring
Intermittent lockups Lights flicker	Sag/swell	Source voltage variations Inrush/surge currents Inadequate wiring
Component failure Dielectric breakdown Lock-ups Garbled data/Wavy CRTs	Impulses/EMI or RFI	Lightning Load switching Capacitor switching Static discharge Hand-held radios Loose wiring/arcing
Overheated transformers Voltage distortion Current distortion Overheated motors	Harmonics	Electronic loads SCR/rectifier
Problems occur at the same time Problems occur at regular intervals	All	Timed loads Cyclical loads

Pattern Recognition

Patterns	Possible Causes
Time of day	Power factor correction capacitors being turned on automatically Parking lot lights turning on and off automatically or with photoelectric switches HVAC/Lighting systems on automatic control
Duration of disturbance	Cyclical loads such as pumps and motors Laser printing heating elements cycling on for only 10-30s Timing controls on process or manufacturing equipment
Frequency of occurrence	Continuous cycling of heating element in laser printer and/or copier Transients from SCR controlled devices occurring every cycle Vending machine compressor motor creating transients at turn on

Analysis Using Meter Data



North 2

IEEE 1159 Power Quality Report
21/09/06 - 25/09/06

Impulsive Transients

Overshoot Magnitude (u), %Un	Polyphase Incidents	V1 Incidents	V2 Incidents
21/09/06 - 25/09/06			
u > 20	0	0	0
u > 50	2	1	1
u > 100	2	0	0
u > 150	2	2	0
u > 200	0	0	0

Voltage Sags and Undervoltages

Residual Voltage (u), %Un	Instantaneous, 0.5-30 cycles	Momentary, 30 cycles - 3 s	Temporary, 3 s - 1 min
21/09/06 - 25/09/06			
u <= 90	4	2	4
u <= 85	0	0	0
u <= 70	0	0	0
u <= 40	2	0	1

Voltage Swells and Overvoltages

Magnitude (u), %Un	Instantaneous, 0.5-30 cycles	Momentary, 30 cycles - 3 s	Temporary, 3 s - 1 min
21/09/06 - 25/09/06			
u > 110	0	0	4
u > 120	0	3	2
u > 140	0	0	0
u > 160	5	2	4
u > 200	0	0	0

Flicker

From	To	Incidents	Total Duration, h:m:s:ms	Percent of Observation Time, %	Wors... Ph...	
21/09/06	23/09/06	1	00:00:34:000	0.0	V1	25.08
24/09/06	25/09/06	3	00:25:23:000	1.3	V1	45.35

Port 115-46 Bank PQ Log 04/07/06 14:18:36

No.	Date/Time	Event	Fault Category	Phase	Fault Magnitude	PU	Duration
40	28/02/05 19:33:43.634	PQE11:314	Impulsive transient	V12	52.5	0.31	0:00:00.000600
41	01/03/05 18:51:50.671	PQE11:315	Impulsive transient	V12	50.7	0.30	0:00:00.000573
42	02/03/05 19:08:55.272	PQE11:316	Impulsive transient	V12	85.9	0.51	0:00:00.000221
43	03/03/05 05:39:18.040	PQE11:317	Impulsive transient	V12	64.0	0.38	0:00:00.000573
44	06/03/05 06:						
45	08/03/05 05:						
46	08/03/05 05:						
47	08/03/05 05:						
48	08/03/05 19:						
49	11/03/05 06:						
50	11/03/05 18:						
51	11/03/05 18:						
52	11/03/05 19:						
53	15/03/05 05:						
54	16/03/05 06:						
55	16/03/05 06:						
56	17/03/05 05:						
57	22/03/05 15:						
58	23/03/05 02:						
59	28/03/05 06:						
60	28/03/05 17:						
61	31/03/05 06:						
62	31/03/05 06:						
63	31/03/05 09:						
64	01/04/05 06:						
65	03/04/05 04:						
66	03/04/05 05:						
67	03/04/05 05:						
68	03/04/05 05:						
69	03/04/05 05:						
70	05/04/05 05:						

More Information

- Online resources
  - IEEE standards
    - In particular, IEEE 1159
  - Wikipedia
  - Manufacturer's publications
    - Understanding scanner records, instruction manuals, etc.
- Seminars
  - IEEE classes
  - Western Power Institute PQ training

Thank you for being attentive

Any questions before concluding?