Introduction

Power quality is the concept of powering and grounding sensitive electronic equipment in a manner that is suitable to the operation of that equipment. [2]

A power disturbance is any deviation from the nominal value of the input power characteristics. [2]

A power disturbance is not a power quality problem unless equipment is affected.

Voltage tolerance curves indicate the ability of equipment to ride through power disturbances.

Power quality definition includes grounding (and wiring).

Power quality is not a new concept (flicker curve from 1925).

Safety - Case Study

Situation

- A 480V transformer secondary with exposed buswork connected to the transformer secondary bushings.

PPE

- Safety glasses, Class II rubber gloves, Class II rubber sleeves, long sleeve cotton sweatshirt and hard hat.

Incident

- While attaching a CT, one side of the CT contacted a phase busbar while the other side contacted the rounded transformer enclosure.

No protective devices operated during the resulting flash.

Result

- The person making the connection experienced second degree facial burns. Safety glasses, rubber sleeves and the rubber gloves above the rubber glove protectors melted slightly. The sweatshirt charred slightly. The arc melted one end of the CT. The factory was evacuated when fire alarms went off.

- REDUCE MONITORING – CUSTOMER LOG

- DEENERGIZE WHEN POSSIBLE, USE SAFEGUARDS

- PPE AND PROPER CLOTHING PREVENT OR LIMIT INJURIES

Lessons Learned

- Before You Put on Your PPE

  - Apply common sense & look for the obvious.
  - Do the simple things first.
  - Know equipment limitations, both end use and monitoring.

- Introduction – Affect on Equipment

  - Power Disturbance is not Power Quality

    - Power Quality Problem
    - Occasionally a PQ Problem

    - Neutral to ground on outlet
    - 5ns, +/-10VpK, every ½ cycle
    - Utility capacitor switching [2]
    - 2pu: 1300Vpk on 480V system
    - ~2600 switched caps MECo and NECo
    - About 5 calls per year

- Voltage Tolerance Curves

  - CBEMA Curve
  - CBEMA Curve
  - Outdated today with modern laptops.
  - ½ cycle interruption
  - 187% = 104V on 120V
  - 187% = 100V on 115V
  - 340Vpk impulse
  - 105Vms
  - 120Vms
  - 170Vpk

- Introduction – Affect on Equipment

  - Voltage tolerance curves represent the susceptibility of electrical equipment to voltage disturbances.

    - The Computer Business Equipment Manufacturers Association agreed on tolerances computers should be designed to meet [4].
Introduction – Voltage Tolerance Curves

- Concept that tolerance to power disturbances varies from equipment to equipment, manufacturer to manufacturer, site to site and by age.
- Manufacturers either do not know or do not share voltage tolerance curves, but there is continuing research on equipment voltage tolerance.

Minimum voltage sag ride-through capability design requirements for equipment used in the semiconductor industry [2]

Introduction – Flicker Curve from 1925

- Concept that tolerance to power disturbances varies from equipment to equipment, manufacturer to manufacturer, site to site and by age.
- Manufacturers either do not know or do not share voltage tolerance curves, but there is continuing research on equipment voltage tolerance.

Transients – Nanoseconds to Cycles

- Impulsive Voltage Transient
- Additive to the waveform
- 5ns, +/-10Vpk, every 1/2 cycle
- Fast transients can not travel far

- Oscillatory Current Transient
- 10 peaks per 1/2 cycle
- 20 * 60 Hz = 1200Hz frequency
- Lasted one cycle duration
- Utility cap switching interacting with customer capacitors

Transients – ASDs and Capacitor Switching

- Control tension on wire manufacturing or on a printing press
- Slow down or speed up a pump

- The voltage and current transient will increase the DC bus voltage causing the ASD protection to operate.
- Solutions:
  - ASD vendor can change settings.
  - Customer can install line reactors or filters to reduce the impulse levels.
  - Utility can leave the capacitor on at all times or change time.
  - Utility can move the capacitor (does not always work).

- The small transient was causing the ASD drive and assembly line at a plastics plant to trip off line at 8am daily.
- Line reactors are installed on the input side of the ASD to protect the drive from utility capacitor switching transients.

Transients – Reactor Solution

- Utility side of reactor
- ASD side of reactor
Short Duration – Less than 1 Minute

- Momentary outages can be recloser operations.
- Sags are caused by a sudden change such as:
  - Faults on utility or customer distribution system
  - Motor starting
  - Other equipment operation (e.g., arc welders).
- Sags constitute more than 90% of problems with customer equipment.
- On average, customers could experience 12 to 16 sags in a year (pge.com ~ 20), not all of which will be either long enough or deep enough to cause equipment misoperation.

Short Duration - Voltage Sag

- Bed and Breakfast hotel supplied underground secondary.
- Flickering lights. Burden test showed good connections to the meter.
- After several weeks of monitoring finally recorded voltages 151V and 82V.
- Corroded and loose secondary neutral connection in the manhole.
- The neutral was only open during dry conditions and when truck traffic jarred the connections.

Short Duration – Flicker

- New electronic ballasted lights flicker especially during lunch break.
- Lights fed from four different non-utility substations.
- Each substation fed an energy efficient air compressors which went into energy saving mode when not in use.

Each peak is a voltage sine wave

Zoom 1% sag every third cycle

Short Duration – Flicker

1% sag every six cycles

Short Duration – Customer Log

- Importance of the customer keeping an event log.

- Bioresearch facility conducting 12 week experiments requiring continuous cooling were experiencing six chiller and air compressor shut downs per month.
- Chiller drive vendor changed trip voltage and time delay parameters.
- Air compressor auto restart was enabled.

Short Duration – Focus on the Solution

- Chip manufacturer with preferred – alternate 13.8kV outdoor metal-clad switchgear supplied off two utility feeders.
- Customer’s switchgear control system was supplied 120V via a plug into a UPS on the factory floor.
- Customer experiencing momentary interruptions.
- All utility reclosers and substation breaker placed on non-reclosing.
- Electrical contractor testing revealed no issues with the switchgear.
- Unplugging and then plugging back in the control supply into the UPS caused the preferred breaker to open and then close.
- When unplugged, breaker received signal to open but had no power, and when the control was plugged back in the system executed the open, then closed back in because the preferred source had power.
- Contractors working in the building had been using the UPS to supply drills and other construction equipment.
### Long Duration > One Minute

- Include outages, overvoltage and undervoltage
- Utilities use load tap changing transformers, regulators and capacitor banks to maintain service voltage within range.
- Range vary by state and by service voltage level. Most engineers use +/-5%.
- Voltage imbalance is limited to 3%.

### Voltage Ranges for 120V Nominal System (115V Utilization Voltage)

<table>
<thead>
<tr>
<th>Service Voltage</th>
<th>Utilization Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANSI Range A</td>
<td>126 +/-5%</td>
</tr>
<tr>
<td>ANSI Range B</td>
<td>127 +/-5.8%</td>
</tr>
<tr>
<td>MA Range A</td>
<td>126 +/-5%</td>
</tr>
<tr>
<td>MA Range B</td>
<td>127 +/-5.8%</td>
</tr>
<tr>
<td>RI</td>
<td>123 +/-2.5%</td>
</tr>
<tr>
<td>NY</td>
<td>123 +/-2.5%</td>
</tr>
<tr>
<td>ANSI A &gt;600V</td>
<td>126 +/-5%</td>
</tr>
<tr>
<td>ANSI B &gt;600V</td>
<td>127 +/-5.8%</td>
</tr>
</tbody>
</table>

### Long Duration Voltage and Voltage Sags

- Sag ride through is affected by utilization voltage.
- Service voltage of 120V (ANSI C84.1: 126V to 114V)
- Utilization voltage of equipment can be 115V
- Actual voltage in the back of the plant is 110V (-4%)
- 10V sag from a utility fault (8% sag)
- 120V – 10V = 110V at meter (Range B is 106V)
- But 110V – 10V = 100V at equipment
- Equipment might not tolerate a sag to 100V
- Sag ride through can also be affected by voltage incompatibility.
- When starting out a lower voltage there is less sag tolerance.

### Waveform Distortion

- Waveform (black) broken down into fundamental (60Hz) and 3rd (180Hz) harmonic components. [1]

### Waveform Distortion – High Neutral Current

- An electrician found high neutral current when measuring a three-phase panel prior to adding computer load.

#### Phase Current
- 31.8Arms total current
- THD: 43%
- 37% of 3rd, 18% of 5th and 11% of 7th

#### Breakdown
- 49.4Arms

- Phasor current ~ 11Arms of 3rd harmonic.
- Perfectly balanced system the 3rd harmonics from each phase sum in the neutral ~ 3*11A each = 33A of 3rd.
- Actually around 50A.
Waveform Distortion – Resonance

- Harmonic loads can be viewed as harmonic current generators. [2]
- System frequency response characteristics are dominated by the interaction between shunt capacitance and system inductances. [6]

Waveform Distortion – Resonance

- Simple calculation to determine resonance. Look for an H that is “close to” a characteristic harmonic. [6]

Waveform Distortion – Resonance

- In a six-pulse converter, the characteristic harmonics are the nontriplet odd harmonics.
- The six pulse rectifier (ASD) will have 5th, 7th, 11th, 13th, etc. harmonics.
- IEEE 519 sets recommended limits on utility voltage distortion and customer current distortion. [6]

Waveform Distortion – Resonance

- A customer recorded 8% 5th harmonic distortion at his facility between 11pm and 6am.
- The 5th harmonic was 6% overnight at the utility substation bus.
- 69/13.2kV two feeder substation with short feeders and large industrial customers.

Waveform Distortion – Resonance

- There are 8 switched capacitors on 2 feeders: (4) 1200kVAR, (3) 900kVAR, (1) 600kVAR.
- Voltage THD increases from 2% to 4% at 7pm as 2400kVAR switches off.
- Left both banks on at night.
- All caps on days
  MVAR = 4*1.2+3*0.9+1*0.6 = 8.1MVAR
  H = \sqrt{116MVAR/8.1MVAR} = 3.7
  Assume 2-1.2MVAR off at 7pm
  MVAR = 2*1.2+3*0.9+1*0.6 = 5.7MVAR
  H = \sqrt{116MVAR/5.7MVAR} = 4.5
  How close is close enough?

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Waveform Distortion – Resonance

- DC drive trips on overvoltage during start up when the customer's power factor correction caps are on steps 1, 2, 3 or 4 (7-30kVAR steps, 200hp motor).
- Parallel resonance is when amplified current oscillates back and forth between the inductance and the capacitance. Occurs when Xc = XL at a characteristic harmonic [6].
- Customer converted capacitor to a stepped filter.

Waveform Distortion – Summary

- Harmonics are useful in analyzing system impact by analyzing the impact of each harmonic.
- Harmonics related problems include:
  - Triplet harmonics summing in the neutral
  - Resonance
  - Transformer derating [7]
  - Cable derating [8]
**Wiring and Grounding**

- MRI was producing ghost images.
- Neutral to ground voltage measured 30Vrms.
- MRI panel had an isolation transformer.
- There was no bond from the transformer neutral to ground. The MRI technician installed the bond, the voltage dropped to 2Vrms, which is more typical per the technician.

**The National Electrical Code (NEC) is the minimum wiring and grounding practice required for powering sensitive equipment.**

Most power quality issues related to wiring and grounding can be resolved by conforming to the NEC.

The diagram from the NEC Handbook shows the basic points for wiring and grounding of separately derived sources [9].

**Stray Voltage**

- Neutral to Earth Voltage (VEV or NEV)
  - A voltage that results from current flowing into the earth (2-10V)
  - Not the same as Elevated Equipment Voltage
  - A voltage that occurs because a live wire came in contact with and energizes a surface that is not normally energized (20-120+ V)
  - Not the same as EMF, Stray Current, Step and Touch voltage

**Neutral to Earth Voltage**

- NEV is the voltage measured between any point on a neutral or its extension (a connected metallic pipe for example) and an isolated reference electrode placed in the earth with “zero” or “nearly zero” potential, to represent remote earth.
- NEV is a nuisance to most humans but can cause extensive harm to animals.
- The dairy industry in states such as Idaho, Michigan and Wisconsin were the primary drivers into NEV investigations.

**Example:**

- Note: values are fictitious to illustrate point.
Mitigations Methods

- Detection and Restoration of Faulty or Corroded Neutral
- Grounding Improvement – Primary Side
- Equipotential Plane
- Increasing neutral wire size
- Load balancing – primary side
- Load balancing – customer side
- Increase Primary Voltage Level
- Delta system or 2 bushing transformer
- Primary to Secondary Neutral Isolation

Monitoring Equipment

- Types of Equipment
  - Multimeter
  - Clamp-on Meters
  - Data Logger
  - Power Quality Recorder
  - Power Quality Analyzer

Questions

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References

5. GE Distribution Data Book, 1990
7. Std. C57.110 – 2008, IEEE Recommended Practice for Establishing Liquid Filled and Dry Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents

Safety

 Lessons Learned
- USE THE CORRECT EQUIPMENT FOR THE JOB
- DEENERGIZE WHEN POSSIBLE OR USE SAFEGUARDS

Situation
- A three-phase, 480V junction box supplying an adjustable speed drive. A termination block jumpered the power supply conductors to various ASD circuits. The termination block connections were close together.

PPE
- Safety glasses, Class II rubber gloves, long sleeve cotton shirt and hard hat.

Incident
- While attempting to connect the monitor lead connector, the connector touched two phases on the termination block at the same time. The arc destroyed the connector and the main breaker tripped.

Result
- No injuries resulted from the flash. The carbon marks were cleaned off the termination block and power restored.

Introduction – Voltage Tolerance Curves

- Semiconductor Equipment and Materials International
- Source: PGE.COM Voltage Tolerance Boundary Paper

Introduction

- Most power related disturbances will be associated with variations in shape or magnitude of a 60 cycle per second (60Hz) sine wave.
- Two time scales: 60 Hz sine wave occurs 60 times per second.
  - 1/60 seconds = .016 seconds = 16ms = 1 cycle.
- Vpeak = Vrms * \sqrt{2}, 120Vrms * 1.414 = 170Vpk for a sine wave

- 480VL or 678Vpk

- 16ms or 1 60Hz cycle

- Flicker is a variation of input voltage sufficient in duration to allow visual observation of a change in electric light source intensity. [2]
- Not sensitive electronic equipment: eye and a light bulb.
- X Axis is time between voltage fluctuations (longer on left).
- Y Axis is percent of voltage change up or down.
- Voltage is already fluctuating 60 times per second.
- Not a new concept: 1925.

Examples
- Red dot is a 1% voltage sag occurring 10 times per second or one cycle out of every six (electronic load). This repetitive voltage sag is a flicker within the “irritation” level.
- Green dot is a 2.8% voltage increase occurring twice per day (utility capacitor switching) is on the borderline of being noticeable.
Introduction – Voltage Tolerance Curves

- 1950’s chart shows that fluorescent bulbs may have trouble starting at voltages less than 110V and may shut off at 75% (90V).

Introduction – Power Disturbances Table

- Power Disturbances Table [3].
- Transients: ns (nanoseconds) to several cycles
- Short Duration Variations: 0.5 cycles to 1 minute
  Example: Reclose attempts 5s-10s-15s
- Long Duration Variations: > 1 minute (Voltage Regulation)
- Steady State Variations: Harmonics, Noise
- Separate “voltage fluctuations” aka “flicker”

Introduction - Summary

- Power quality is the concept of powering and grounding sensitive electronic equipment in a manner that is suitable to the operation of that equipment.[2]
- A power disturbance is not a power quality problem unless equipment is affected.
- Power quality definition includes grounding (and wiring).
- Affected “equipment” does not have to be sensitive (incandescent bulb, eye, person, animal).
- Power quality is not a new concept.
- Voltage tolerance curves indicate the ability of equipment to ride through power disturbances.

Transients – Nanoseconds to Cycles

- A transient is a subcycle disturbance in the ac waveform that is evidenced by a sharp, brief discontinuity of the waveform. May be of either polarity and may be additive to, or subtractive from, the nominal waveform. [2]
- An oscillatory transient is a sudden, non-power frequency change in the steady state condition of voltage, current, or both, that includes both positive and negative polarity values. [3]
- Transient amplitudes are attenuated by the lumped inductance of the utility and customer distribution system. Attenuation is dependent on the transient rise time. Less attenuation occurs for slower (longer) transients. [2]

Transients – ASDs and Capacitor Switching

- Utility capacitors switch daily. Adjustable speed drives (ASDs) can be sensitive to the disturbance and become a power quality issue.
- For time switched capacitors, the drives will shut down at the same time every morning.

Transients – Reactor Solution

- Voltage notching combined with wiring was causing office equipment lock up due to neutral to ground voltage.
- Install a reactor between the step up transformer and the drive.

Before Installation

After Installation

Voltage Notching

\[ V_{V_C} \]

\[ V_{L} \]
Short Duration – Less than 1 Minute

- Power disturbances > 1 minute are more typical utility concern (examples: Regulator 60s delay, Outages, C84.1 Regulation).
- Sag is an rms reduction in the voltage at the power frequency from 0.5 cycles to 1.0 minute. [2]
- Swell is an increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1.0 minute. [2]
- Interruption is the complete loss of voltage (<10%) on one or more phase conductors from 0.5 cycles and 1.0 minute. [2]
- Flicker is a variation of input voltage sufficient in duration to allow visual observation of a change in electric light source intensity. [2]
- Flicker may be a repetitive sag or swell.

Long Duration – Utility Capacitor Switching

- A 3% voltage change caused by a utility capacitor bank can cause irritation. If 3% is exceeded a smaller capacitor bank can be used or location can be changed to reduce system impedance.

\[
\% V_d = \frac{C_k V_{Ar} \times X}{10 \times (kV)^2}
\]

\% V_d = change in voltage
C_k V_{Ar} = kVAr of the cap bank
X = reactance of the line in ohms
kV = line to line voltage

\[
977 = 0.037 + 0.1190 \text{ ohms/1000'}
X \text{ line} = 5(0.1190) = 0.595 \text{ ohms}
\%
V_d = \frac{900 \times 0.595}{10(13.8)^2} = 2.8\% \text{ for 900kVAR switching}
\%
V_d = \frac{1200 \times 0.595}{10(13.8)^2} = 3.7\% \text{ for 1200kVAR}

Waveform Distortion

- Harmonic phase angle can vary the shape.

Waveform Distortion – Even Harmonics

- Facility where transformer and replacement transformer were noisy.
- Measurement showed one diode not firing
- Non symmetrical waveform
- Even harmonics ➔ DC current
Waveform Distortion – High Neutral Current

\[ I_{\text{thd}} = \sqrt{(\% \text{ of } 3^{\text{rd}} \text{ harmonic})^2 + (\% \text{ of fifth harmonic})^2 + \ldots} \]

\[ I_{\text{thd}} = \sqrt{(37\%)^2 + (18\%)^2 + (11\%)^2} = 0.1814 \]

\[ I_{\text{thd}} = 0.43 = 43\% \]

Waveform Distortion - Harmonics

- The total harmonic distortion (THD) is the square root of the sum of the squares of all harmonics except the first, when the magnitude of the individual harmonics are expressed as a percent of the magnitude of the fundamental. [6]

- Characteristic harmonics are those harmonics produced by semiconductor converted equipment during the course of normal operation. [6]

Waveform Distortion – Resonance

- In a six-pulse converter, the characteristic harmonics are the nontriplet odd harmonics.
  \[ h = k q +/- 1, k = \text{any integer, } q = \text{pulse number of converter} \]

- The six pulse rectifier will have 5th, 7th, 11th, 13th, etc. harmonics

Waveform Distortion – High Neutral Current

Kirchhoff’s Current Law:
At any node (neutral) in an electrical circuit, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node.
Waveform Distortion – High Neutral Current

- High neutral current on utility cap bank.
- 9th harmonic 540Hz
- Low buzz at TELCo switching station
- Removed the jumper temporarily
- TELCo typically solves the problem with grounding, shielding and filtering
- The electric utility can reevaluate the need for the bank and move or remove.

<table>
<thead>
<tr>
<th></th>
<th>HN</th>
<th>RH</th>
<th>H</th>
<th>LH</th>
<th>Jumper 27A of 9th harmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Neutral</td>
<td>17.4A normal</td>
<td>11.4A no jumper</td>
<td>12.3A with jumper</td>
<td>9.6A no jumper</td>
<td></td>
</tr>
<tr>
<td>Ground</td>
<td>8A with jumper</td>
<td>1.2A no jumper</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Wiring and Grounding

- Doctor's Office
  - Examination equipment was damaged. Retrofitted older home.
  - New outlet in office grounded to water pipe. Loose bond at main panel.
  - Neutral to ground measured 92Vrms and 500Vpk.
  - NEC allows exceptions for branch circuit wiring, but in this case the equipment was not suited for the environment.

Wiring and Grounding

- Clean Room Manufacturing Facility
  - Clean room equipment supplied off an equipment distribution center/controller.
  - Robotic arm would occasionally throw product around the room.
  - A fault on the extruder machine caused voltage potential.
  - Five volts measured from distribution center to nearby water pipes and air handling equipment.
  - There was no ground. The distribution center was supplied via a PVC conduit from a cable tray with no ground conductor run with the circuit.
  - Without a ground reference, the signals between various equipment can become garbled.

Wiring and Grounding

- Below is a table that includes some wiring problems, their associated power disturbance and some affects of the disturbance on equipment.

<table>
<thead>
<tr>
<th>Wiring Problem</th>
<th>Power Disturbance</th>
<th>Equipment Affects</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Questions

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Possible Reasons for NEV

- Improper wiring or grounding at customer premises.
- Faulty electrical equipment at the customer premises e.g. well pumps, swimming pools.
- Improper wiring or grounding at a neighbor’s premises
- Faulty distribution equipment serving an area e.g. underground cable
- Other utilities in the area e.g. CATV, telephone, railroads
- Load imbalance on the conductors
- High triplen harmonic current especially the odd harmonics
- Poorly balanced distribution feeders
- Long single phase side taps with heavy loads at the end
- High return current in the grounded neutral system
- High resistance earth resistance (ledge, very dry soil, etc.)

Example:

Medium length, moderately loaded, single phase side tap, poorly installed grounds, plastic water system, high impedance splices.

High Impedance Neutral?

Note: values are fictitious to illustrate point.
Factors Affecting NEV

- Soil conditions
- Magnitude of load imbalance
- Length and size of conductors serving the loads
- Grounding systems
- Integrity of the neutral conductor

Safety, Safety and more Safety

Neutral to Earth Voltage

- NESC requires multi-grounded system; National Grid and electric utilities in the US follow the NESC standard
- When current flows in earth a potential difference is created between earth and any electrically grounded structure
- Low voltage NEV may be present at many locations on an electric delivery system
- NEV can result in unpleasant sensations (voltage threshold varies among different individuals)
- NEV is normally considered a nuisance, especially to humans.

Monitoring Equipment

<table>
<thead>
<tr>
<th>Types of Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multimeter</td>
</tr>
<tr>
<td>Clamp-on Meters</td>
</tr>
<tr>
<td>Data Logger</td>
</tr>
<tr>
<td>Power Quality Recorder</td>
</tr>
<tr>
<td>Power Quality Analyzer</td>
</tr>
</tbody>
</table>

Stray Voltage Example

Shower

- A person can complete a path from an improperly grounded water system to a better ground.
- 6V were measured between the water and to sewer pipes, with a frequency measurement of 180Hz.
- The electrical system was bonded to the water pipe system. There were no ground rods. The water pipe connection to the well was recently changed to PVC. The septic pipes are metal out to the back yard septic tank. The septic pipe was at an earth potential, while the electrical system ground was at 6V coming from the telephone line ground.
- Completely disconnecting the power service drop had no affect.
- Removing one of the two telephone lines dropped the voltage down to less than 2V (opening the other line had no effect).
- The home owner had that telephone line disconnected, then hired an electrician to bond his electrical system to his septic pipe as well as the water pipe and the ground rod.
Neutral to Earth Voltage Investigative Approach

- There are many possible causes or sources for N to E voltage which make it difficult to track and resolve.
- Assessment and areal mapping
- First, most likely probable causes are investigated.
- Second, investigation of the surrounding area is conducted.
- Third, investigation continues in the larger and larger areas until the problem is resolved.