The Impact of Mains Impedance on Power Quality

Power Quality 2000 Conference

Boston, MA

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Line Generated Problems

- **Sources**
  - **Caused by the Utility**
  - **Caused by other *"dirty"* loads**

- **Mitigation Techniques**
  - **Separation of sensitive loads from other loads**
  - **Power conditioning devices**

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Load Generated Problems

- Types of problems
  - Voltage Sags
  - Distortion
  - Impulses
- Contributing Factors
  - Current Profile of the Load
  - Mains Impedance

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Mains Impedance

- Simple concept
  - Resistance in series with the Source
  - Voltage Drop is proportionate to the Load Current

- $V_{out} = V_{source} - (I_{load} \times Z_{source})$

- $200\ VAC = 208\ VAC - (80\ A \times 0.1\ \Omega)$

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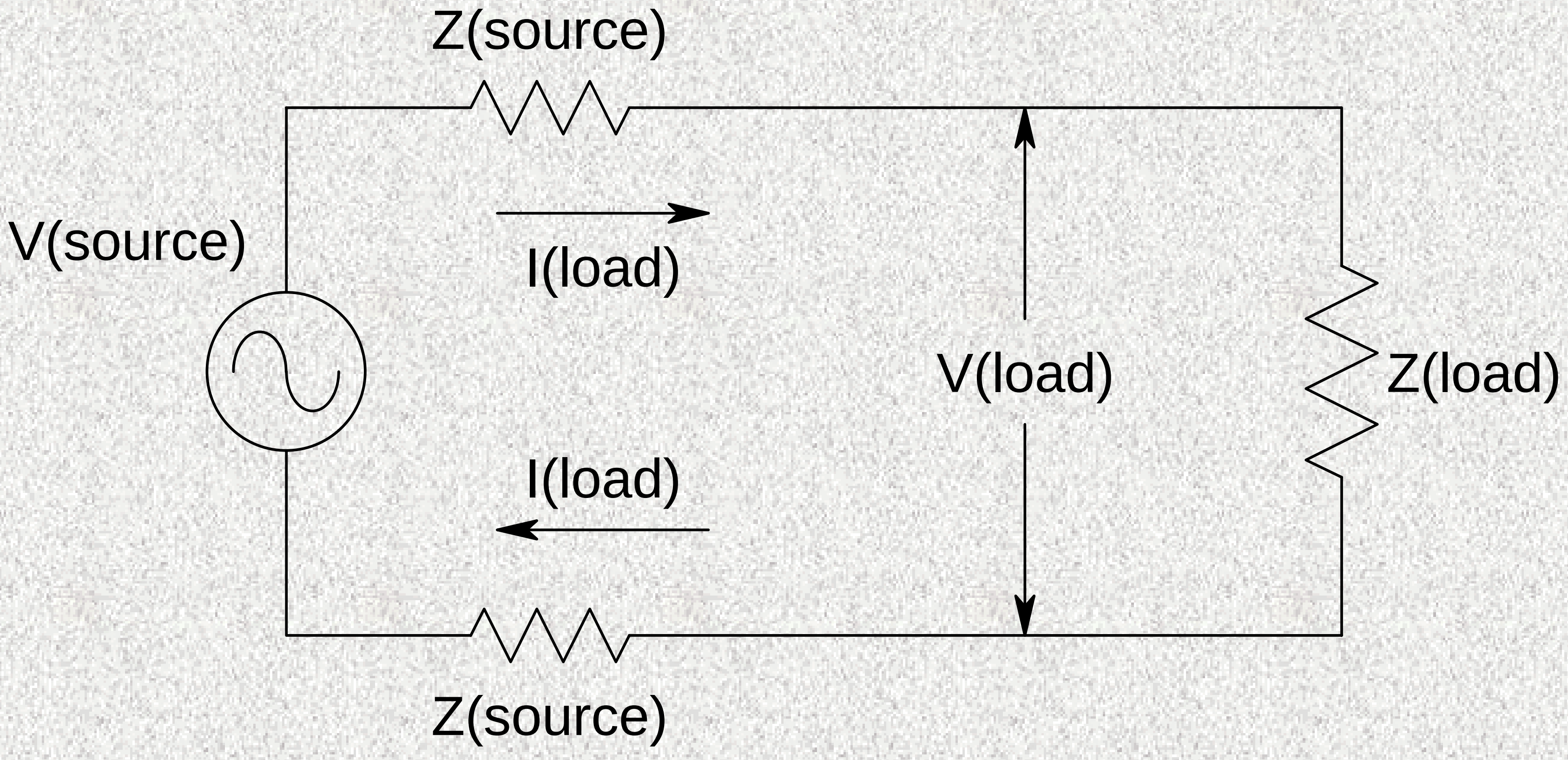
Simple Impedance Model



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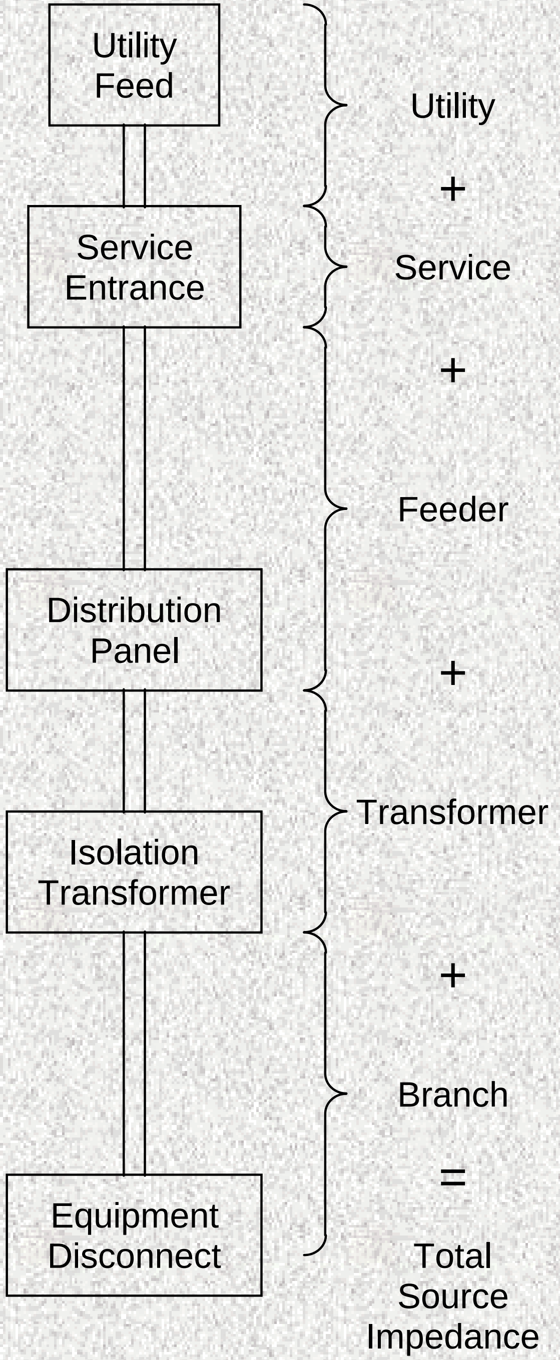
Impedance is Cumulative

- Utility Source
- Service Entrance
- Feeder Circuit
- Transformer
- Branch Circuit
- Overcurrent Protection
- Contacts
- Plug / Receptacle



Impedance Specification

- Nominal Voltage: 480 VAC
- Voltage Range: +/- 10%
- Impedance: 0.250 Ohms
  or
  5.2% @ 100 A

- 0.25Ω x 100 A = 25 VAC
- 25 VAC / 480 VAC = 5.2%

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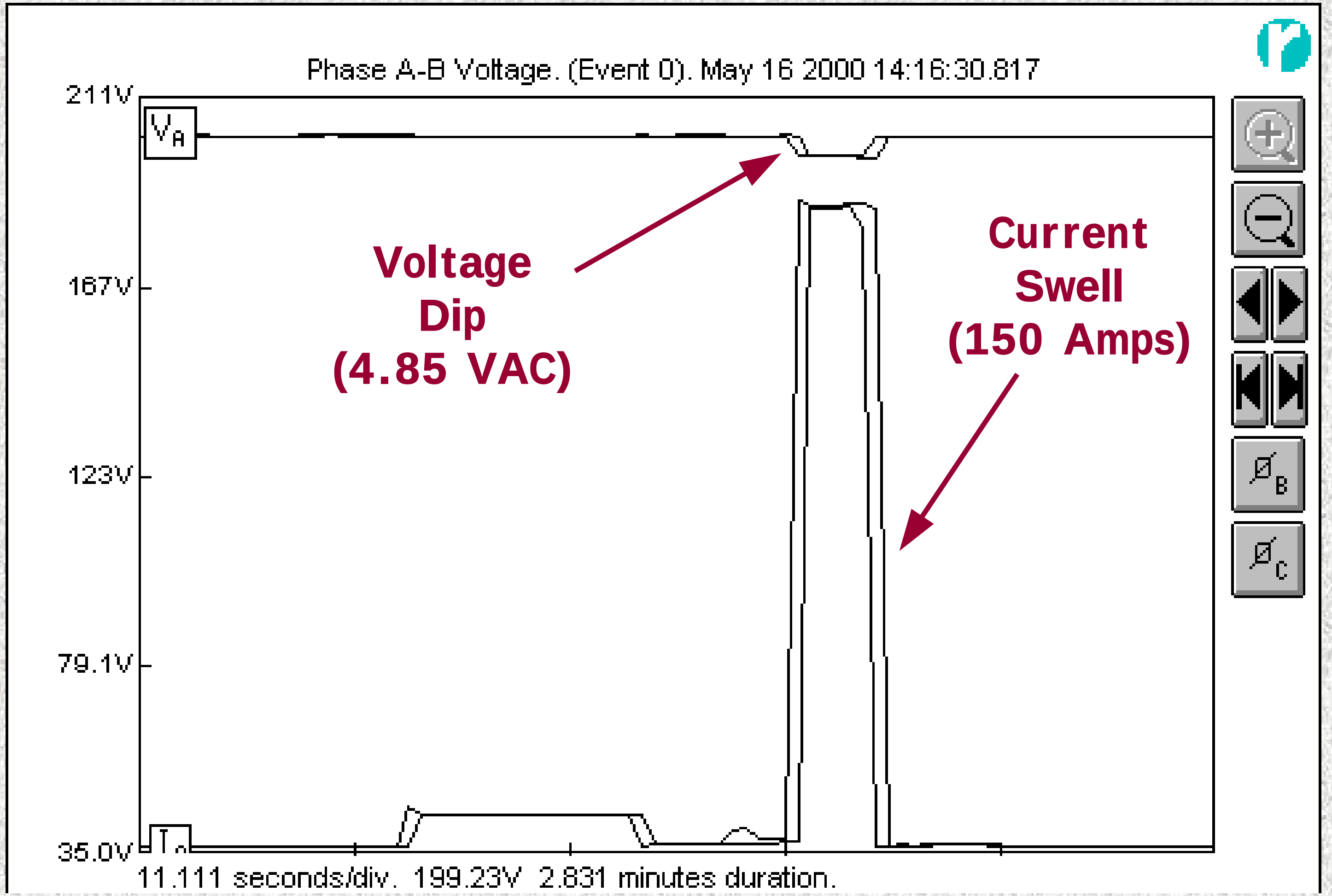
Voltage Fluctuation



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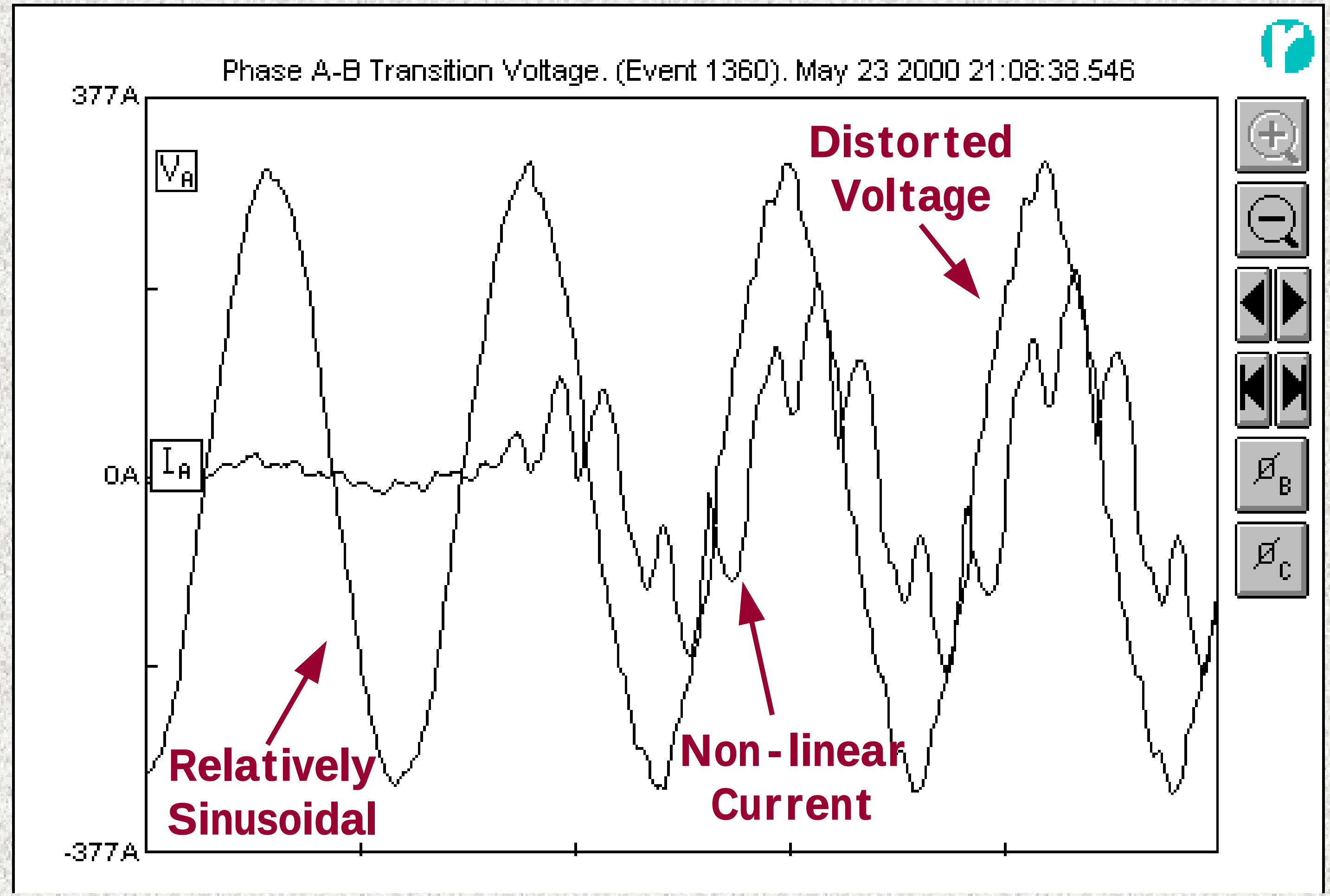
Distortion



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Transients

- Generated by Rapid Changes in Current
  - V = L x di / dt
- Primarily Subtractive
- Higher Impedance = Higher Impulses
- *Load Generated Disturbances*

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Low Impedance Problems

- Less common than Excessive Impedance
- Circuit Breaker Tripping
- AIC Rating exceeds OCP devices (safety)

- Solution: Add Impedance
  - Transformer
  - Inductor / Choke
  - Smaller Conductor Size

Complex Impedance Model

- Resistance and Inductance

- Most Common: Impedance at Fundamental Frequency
  - Short Circuit Calculations
  - Voltage Drop Calculations

- Less Common: Impedance at Higher Frequencies
  - Exacerbates distortion and transients
  - Complex Current and Complex Impedance

Non-Linear Impedance

- Normal Case: Impedance is Constant
  - Exception: Heating effects

- Magnetic Components
  - Saturation
- Power Conditioners
  - Dynamic Voltage Regulation
- Voltage Regulators
  - Tap Switch / Autotransformer
  - Address voltage drop, but not transients or voltage distortion caused by impedance

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Conductors

- Smaller Conductors = Higher Impedance
  - #12 - #2 AWG = Resistance is Dominant
  - #4/0 AWG and ⇧ = Inductance is Dominant
- Copper vs. Aluminum
  - Copper is Lower for Same Size Conductor
- Operating Temperature
  - Higher Temperature = Increased Impedance
- Conductor Orientation
  - Tightly Coupled Lowers Inductance
- Conduit Material
  - Ferrous Conduit increases Inductance

NFPA-70 (NEC)
Chapter 9 / Table 8

- DC Resistance (Ohms / 1000 ft)
- Copper and Aluminum
- 75° C
- Coated vs. Uncoated
- Stranded vs. Unstranded

Table 8. Conductor Properties

Size (AWG or kcmil)	Area (Circular Mils)	Conductors – Stranding – Quantity	Conductors – Stranding – Diameter (in.)	Conductors – Overall – Diameter (in.)	Conductors – Overall – Area (in.^{2})	Direct-Current Resistance at 75°C (167°F) – Copper – Uncoated (ohm/1000 ft)	Copper – Coated (ohm/1000 ft)	Aluminum (ohm/1000 ft)
18	1620	1	—	0.040	0.001	7.77	8.08	12.8
18	1620	7	0.015	0.046	0.002	7.95	8.45	13.1
16	2580	1	—	0.051	0.002	4.89	5.08	8.05
16	2580	7	0.019	0.058	0.003	4.99	5.29	8.21
14	4110	1	—	0.064	0.003	3.07	3.19	5.06
14	4110	7	0.024	0.073	0.004	3.14	3.26	5.17
12	6530	1	—	0.081	0.005	1.93	2.01	3.18
12	6530	7	0.030	0.092	0.006	1.98	2.05	3.25
10	10380	1	—	0.102	0.008	1.21	1.26	2.00
10	10380	7	0.038	0.116	0.011	1.24	1.29	2.04
8	16510	1	—	0.128	0.013	0.764	0.786	1.26
8	16510	7	0.049	0.146	0.017	0.778	0.809	1.28
6	26240	7	0.061	0.184	0.027	0.491	0.510	0.808
4	41740	7	0.077	0.232	0.042	0.308	0.321	0.508
3	52620	7	0.087	0.260	0.053	0.245	0.254	0.403
2	66360	7	0.097	0.292	0.067	0.194	0.201	0.319
1	83690	19	0.066	0.332	0.087	0.154	0.160	0.253
1/0	105600	19	0.074	0.372	0.109	0.122	0.127	0.201
2/0	133100	19	0.084	0.418	0.137	0.0967	0.101	0.159
3/0	167800	19	0.094	0.470	0.173	0.0766	0.0797	0.126
4/0	211600	19	0.106	0.528	0.219	0.0608	0.0626	0.100
250	—	37	0.082	0.575	0.260	0.0515	0.0535	0.0847
300	—	37	0.090	0.630	0.312	0.0429	0.0446	0.0707
350	—	37	0.097	0.681	0.364	0.0367	0.0382	0.0605
400	—	37	0.104	0.728	0.416	0.0321	0.0331	0.0529
500	—	37	0.116	0.813	0.519	0.0258	0.0265	0.0424
600	—	61	0.099	0.893	0.626	0.0214	0.0223	0.0353
700	—	61	0.107	0.964	0.730	0.0184	0.0189	0.0303
750	—	61	0.111	0.998	0.782	0.0171	0.0176	0.0282
800	—	61	0.114	1.030	0.834	0.0161	0.0166	0.0265
900	—	61	0.122	1.094	0.940	0.0143	0.0147	0.0235
1000	—	61	0.128	1.152	1.042	0.0129	0.0132	0.0212
1250	—	91	0.117	1.289	1.305	0.0103	0.0106	0.0169
1500	—	91	0.128	1.412	1.566	0.00858	0.00883	0.0141
1750	—	127	0.117	1.526	1.829	0.00735	0.00756	0.0121
2000	—	127	0.126	1.632	2.092	0.00643	0.00662	0.0106

Notes:

1. These resistance values are valid **only** for the parameters as given. Using conductors having coated strands, different stranding type, and, especially, other temperatures changes the resistance.
2. Formula for temperature change: $R_2 = R_1[1 + \alpha(T_2 - 75)]$ where: $\alpha_{cu} = 0.00323$, $\alpha_{AL} = 0.00330$
3. Conductors with compact and compressed stranding have about 9 percent and 3 percent, respectively, smaller bare conductor diameters than those shown. See Table 5A for actual compact cable dimensions.
4. The IACS conductivities used: bare copper = 100%, aluminum = 61%.
5. Class B stranding is listed as well as solid for some sizes. Its overall diameter and area is that of its circumscribing circle.

FPN: The construction information is per NEMA WC8-1992. The resistance is calculated per National Bureau of Standards Handbook 100, dated 1966, and Handbook 109, dated 1972.

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NFPA-70 (NEC)

Chapter 9 / Table 9

- AC Resistance and Reactance (Ohms / 1000 ft)
- Copper and Aluminum
- 75° C
- Conduit Types
  - PVC
  - Steel
  - Aluminum

Table 9. Alternating-Current Resistance and Reactance for 600-Volt Cables, 3-Phase, 60 Hz, 75°C (167°F) — Three Single Conductors in Conduit

Size (AWG or kcmil)	Ohms to Neutral per 1000 Feet: X_L (Reactance) for All Wires: PVC, Aluminum Conduits	X_L: Steel Conduit	AC Resistance for Uncoated Copper Wires: PVC Conduit	Copper: Aluminum Conduit	Copper: Steel Conduit	AC Resistance for Aluminum Wires: PVC Conduit	Aluminum Wires: Aluminum Conduit	Aluminum Wires: Steel Conduit	Effective Z at 0.85 PF for Uncoated Copper Wires: PVC Conduit	Eff. Z Copper: Aluminum Conduit	Eff. Z Copper: Steel Conduit	Effective Z at 0.85 PF for Aluminum Wires: PVC Conduit	Eff. Z Aluminum: Aluminum Conduit	Eff. Z Aluminum: Steel Conduit	Size (AWG or kcmil)
14	0.058	0.073	3.1	3.1	3.1	—	—	—	2.7	2.7	2.7	—	—	—	14
12	0.054	0.068	2.0	2.0	2.0	3.2	3.2	3.2	1.7	1.7	1.7	2.8	2.8	2.8	12
10	0.050	0.063	1.2	1.2	1.2	2.0	2.0	2.0	1.1	1.1	1.1	1.8	1.8	1.8	10
8	0.052	0.065	0.78	0.78	0.78	1.3	1.3	1.3	0.69	0.69	0.70	1.1	1.1	1.1	8
6	0.051	0.064	0.49	0.49	0.49	0.81	0.81	0.81	0.44	0.45	0.45	0.71	0.72	0.72	6
4	0.048	0.060	0.31	0.31	0.31	0.51	0.51	0.51	0.29	0.29	0.30	0.46	0.46	0.46	4
3	0.047	0.059	0.25	0.25	0.25	0.40	0.41	0.40	0.23	0.24	0.24	0.37	0.37	0.37	3
2	0.045	0.057	0.19	0.20	0.20	0.32	0.32	0.32	0.19	0.19	0.20	0.30	0.30	0.30	2
1	0.046	0.057	0.15	0.16	0.16	0.25	0.26	0.25	0.16	0.16	0.16	0.24	0.24	0.25	1
1/0	0.044	0.055	0.12	0.13	0.12	0.20	0.21	0.20	0.13	0.13	0.13	0.19	0.20	0.20	1/0
2/0	0.043	0.054	0.10	0.10	0.10	0.16	0.16	0.16	0.11	0.11	0.11	0.16	0.16	0.16	2/0
3/0	0.042	0.052	0.077	0.082	0.079	0.13	0.13	0.13	0.088	0.092	0.094	0.13	0.13	0.14	3/0
4/0	0.041	0.051	0.062	0.067	0.063	0.10	0.11	0.10	0.074	0.078	0.080	0.11	0.11	0.11	4/0
250	0.041	0.052	0.052	0.057	0.054	0.085	0.090	0.086	0.066	0.070	0.073	0.094	0.098	0.10	250
300	0.041	0.051	0.044	0.049	0.045	0.071	0.076	0.072	0.059	0.063	0.065	0.082	0.086	0.088	300
350	0.040	0.050	0.038	0.043	0.039	0.061	0.066	0.063	0.053	0.058	0.060	0.073	0.077	0.080	350
400	0.040	0.049	0.033	0.038	0.035	0.054	0.059	0.055	0.049	0.053	0.056	0.066	0.071	0.073	400
500	0.039	0.048	0.027	0.032	0.029	0.043	0.048	0.045	0.043	0.048	0.050	0.057	0.061	0.064	500
600	0.039	0.048	0.023	0.028	0.025	0.036	0.041	0.038	0.040	0.044	0.047	0.051	0.055	0.058	600
750	0.038	0.048	0.019	0.024	0.021	0.029	0.034	0.031	0.036	0.040	0.043	0.045	0.049	0.052	750
1000	0.037	0.046	0.015	0.019	0.018	0.023	0.027	0.025	0.032	0.036	0.040	0.039	0.042	0.046	1000

Notes:

1. These values are based on the following constants: UL-type RHH wires with Class B stranding, in cradled configuration. Wire conductivities are 100 percent IACS copper and 61 percent IACS aluminum, and aluminum conduit is 45 percent IACS. Capacitive reactance is ignored, since it is negligible at these voltages.
These resistance values are valid only at 75°C (167°F) and for the parameters as given, but are representative for 600-volt wire types operating at 60 Hz.

2. *Effective Z* is defined as $R\cos(\theta) + X\sin(\theta)$, where θ is the power factor angle of the circuit. Multiplying current by effective impedance gives a good approximation for line-to-neutral voltage drop. Effective impedance values shown in this table are valid only at 0.85 power factor.
For another circuit power factor (*PF*), effective impedance (*Ze*) can be calculated from *R* and X_L values given in this table as follows:
$Ze = R \times PF + X_L \sin[\arccos(PF)]$.

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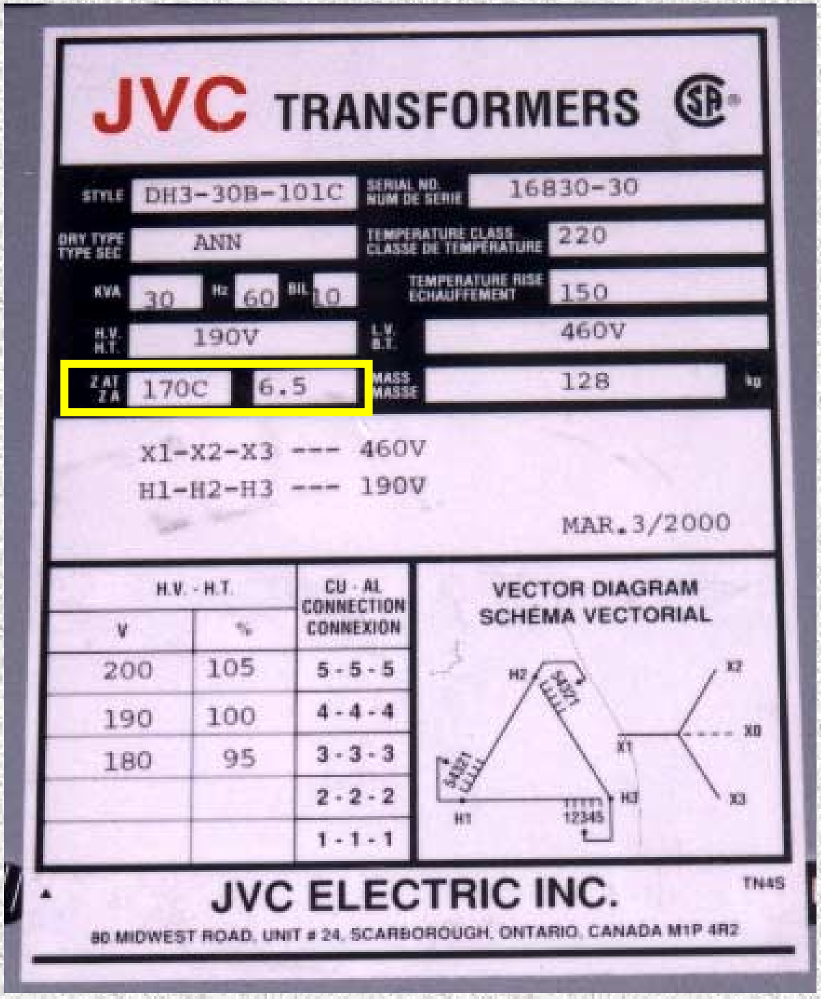
Transformers

- Typically the Highest Impedance Component / Element
- KVA is usual sizing criteria
- Impedance is often ignored
- Materials and Winding techniques are critical to impedance characteristics
- Off-the-Shelf:
  4-7% Impedance is typical

Transformer Nameplate

- Impedance is Specified at Maximum Temperature (6.5% @ 170°C)
- Real-world Impedance is usually much less (~50%)



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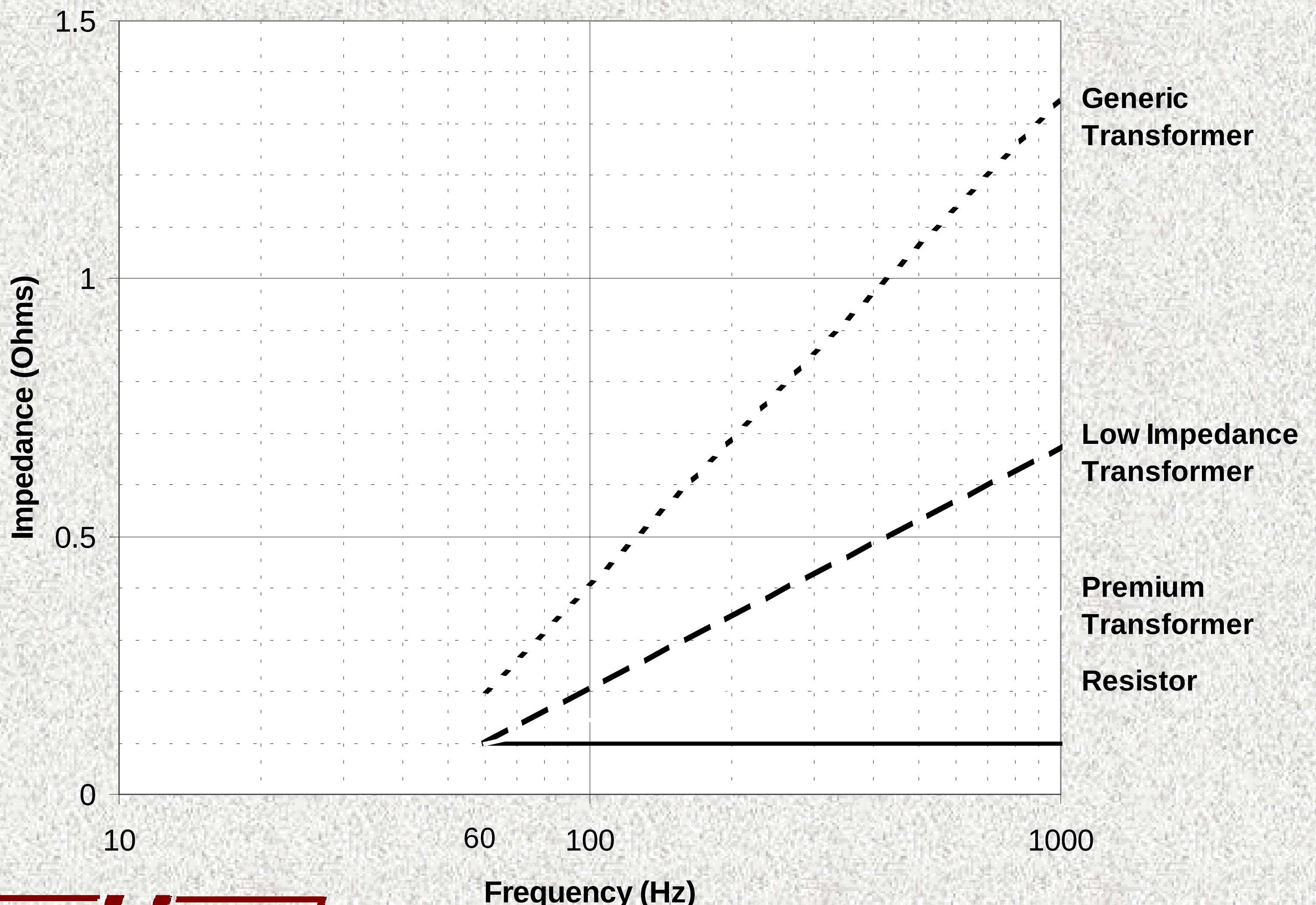
Transformer Impedance



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Connections

- ❖ Any Contact / Connection has Impedance
- ❖ Devices
  - Plugs / Receptacles
  - Fuses and Circuit Breakers
  - Contactors
  - Lugs / Butt Splices / Terminals
- ❖ Faulty Connections can Increase Resistance
  - Loose / Corroded
  - Spot Heating (Infrared Inspection)
  - Imbalance on One Phase

PowerLines

Power Conditioners

- UPS / MG Sets / Power Synthesizers / Voltage Regulators
- Active Voltage Regulation = Non-linear Impedance
- Difficult to Characterize
- Questions to Ask:
  - What is Instantaneous ΔVoltage in response to a Step-Change in Load Current?
  - How long does it take to recover?
  - What is the absolute maximum load current that can be supplied? (inrush or overload)

PowerLines

Measuring Impedance

- **Power Engineers**
  - Calculation / Theoretical Values
  - Interrupting Capacity
  - Coordinating Over-current Protection

- **Power Quality Engineers**
  - Not too concerned with impedance
  - Power Analyzers do not measure Impedance
  - Test Equipment not commonly available

- **Specialized Loads / Equipment**
  - Pulsing Loads / Intermittent Loads
  - Medical Imaging Systems (X-Ray)

PowerLines

Empirical Measurements

Measure ΔV

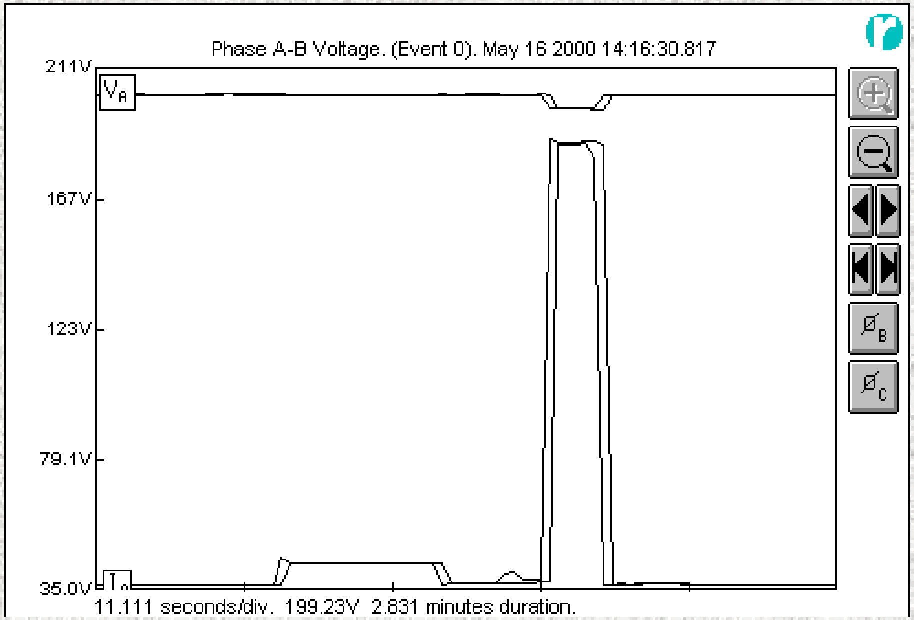
Measure ΔI

Calculate Impedance

$\Delta V / \Delta I = Z$

$4.85V / 150A = 0.032\ \Omega$

- ❖ Requires Step Load
- ❖ Power Analyzer
- ❖ Min / Max DMM



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Mains Impedance Meter

- 120 VAC / NEMA 5-15/20 Outlets

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Mains Impedance Meter

- 208 / 480 VAC – Hard-wired

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Controlling Impedance

- Standards and Guidelines
- Use Proper Voltage Levels
- Long Conductor Runs
- Transformer Specification and Application
- Load Separation
- Non-linear Sources

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Impedance Standards

- NFPA-70 / National Electrical Code
- Fine Print Note (FPN) No. 4 of 210-19(a)

"….where the maximum total voltage drop on both feeders and branch circuits to the farthest outlet does not exceed 5 percent, will provide reasonable efficiency of service."

- NFPA-70 = Safety, not Performance
- Specific Industries may have Standards
- Equipment Manufacturer
- Design Engineer

Voltage Level

- Use the Highest Possible / Voltage Level
- Three Phase vs. Single Phase
- 480 VAC vs. 208 VAC
- Goal: Reduce Load Current

RGB Display Sign

- 800 kW Demand
- 1.5 MVA Service
- Image Quality Problems (Stair-step artifact)
- 13.6 KV Feeder
- 208Y/120 VAC Secondary

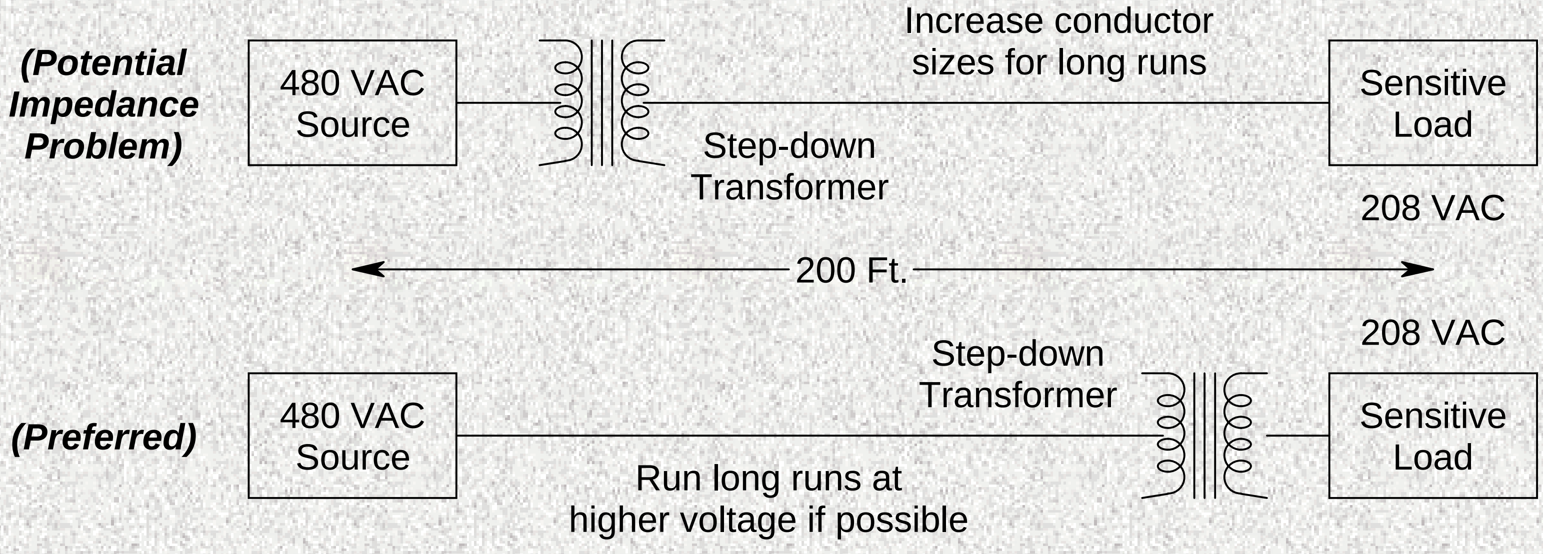
PowerLines

- **Load Generated Distortion (Phase Controlled SCR)**
- **Excessive Transformer Impedance**
- **Excessive Secondary Conductor Impedance (208 VAC Bus Bar)**

PowerLines

Long Conductor Runs

- Consider impedance / voltage drop, not just thermal performance
- Increase conductor size to reduce impedance / voltage drop
- Long conductor runs at highest voltage possible



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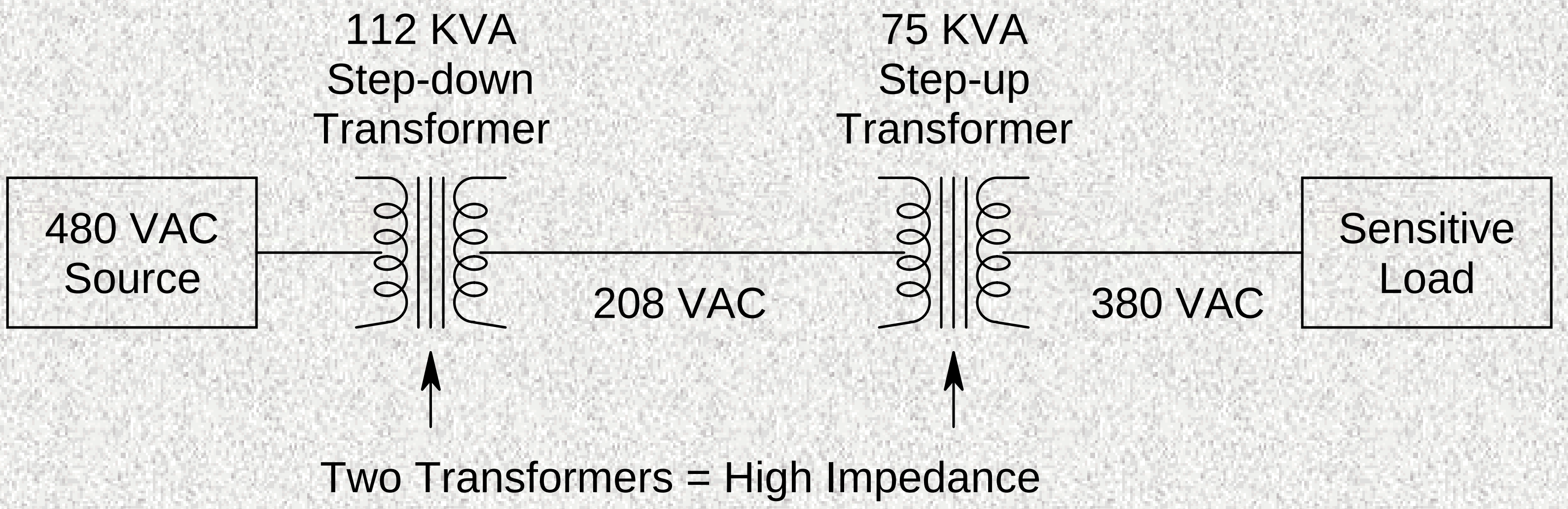
Transformers

- Specify transformers by KVA *and* Impedance
- Do not "gang" similarly sized transformers
- Consider low impedance / premium designed transformers



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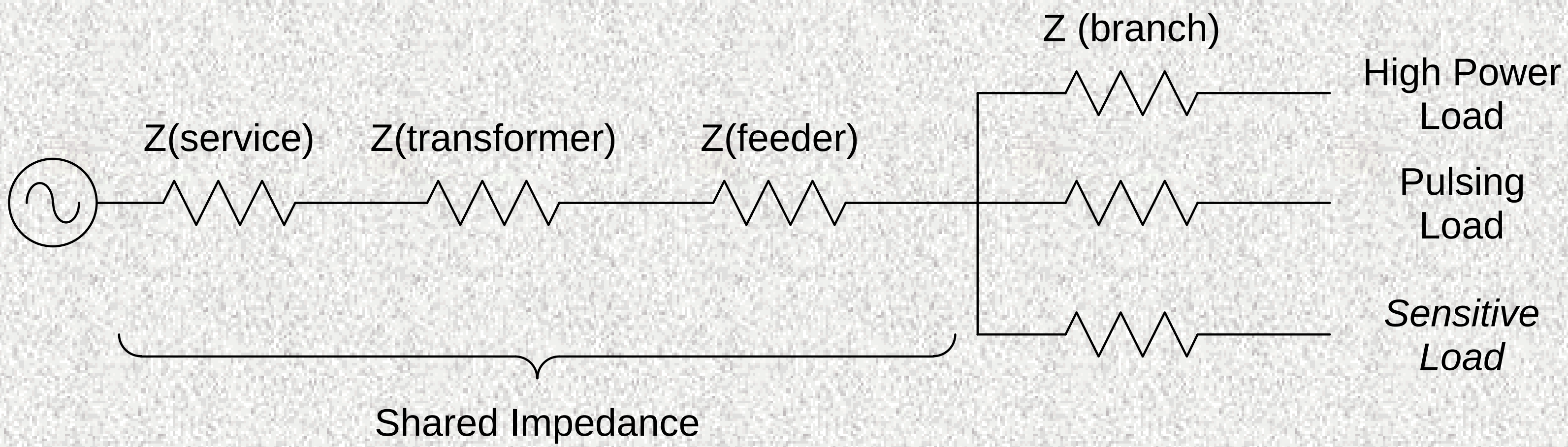
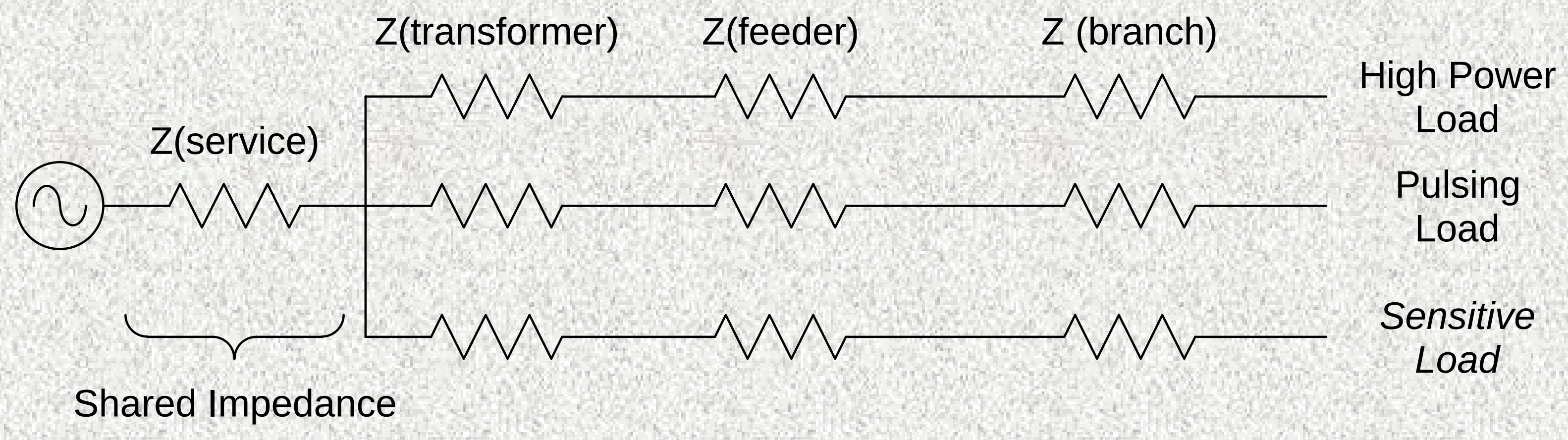
Load Separation

- ❖ **What does it mean to "Separate" loads?**
  - **What is "dirty" power?**
  - **What is a "good ground"?**
- ❖ **Minimize "shared impedance"**



Load Separation

- Individual isolation transformers and feeder / branch circuits
- Make shared impedance as low as practical
  - Increase Service Size and Conductor Sizes
  - Low Impedance Transformers



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Non-Linear Sources

- Is device approved for specific type of load?
  Ask the manufacturer!
- Conventional Loads
  - Computers / Data Processing
- Special Loads
  - Pulsing Loads
  - Motorized Loads
  - Industrial Loads
  - Medical Imaging

Case Study #1

- Cancer Treatment Center
- Linear Accelerator
  - Radiation Therapy
- Calibration Issues
  - Reduced Throughput
  - Concern about patient dose

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Linear Accelerator

PowerLines

Impedance Measurements

Phase	Voltage	Impedance
Red-Neutral	121.4 VAC	0.115 Ω
Blue-Neutral	121.7 VAC	0.054 Ω
Black-Neutral	121.5 VAC	0.059 Ω

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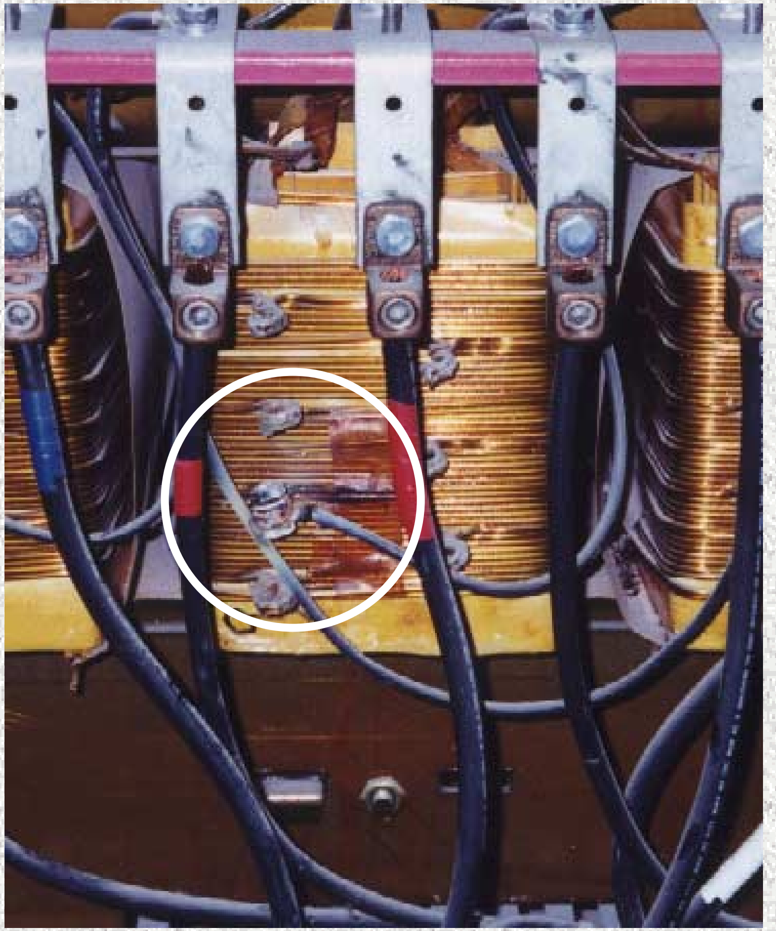
Transformer Tap



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Case Study #2

- Sheet Metal Manufacturer
- Precision Metal Punch
  - Hydraulic System / Large Motor
- Circuit Breaker Tripping on Start-up
  - Motor Stalling
  - Excessive Voltage Drop

PowerLines

Manufacturer Requirements

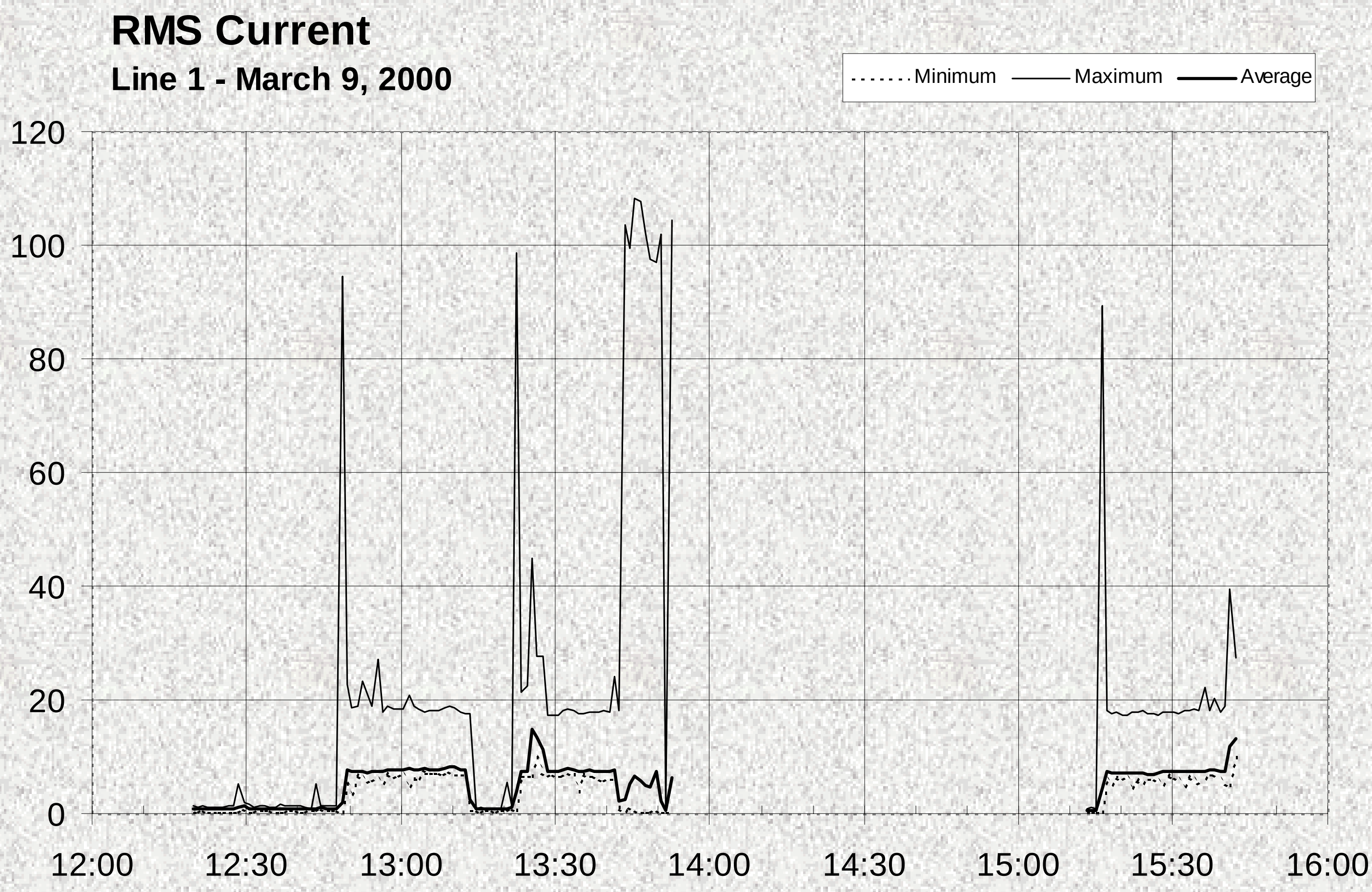
- Voltage: 480 VAC
- Power: 18 KVA
- Current: 22 Amps

Installed Power:

- Circuit Breaker: 70 Amps (tripping)
- Transformer: 15 KVA (#1)
17 KVA (#2)
30 KVA (#3)

PowerLines

Current Graph



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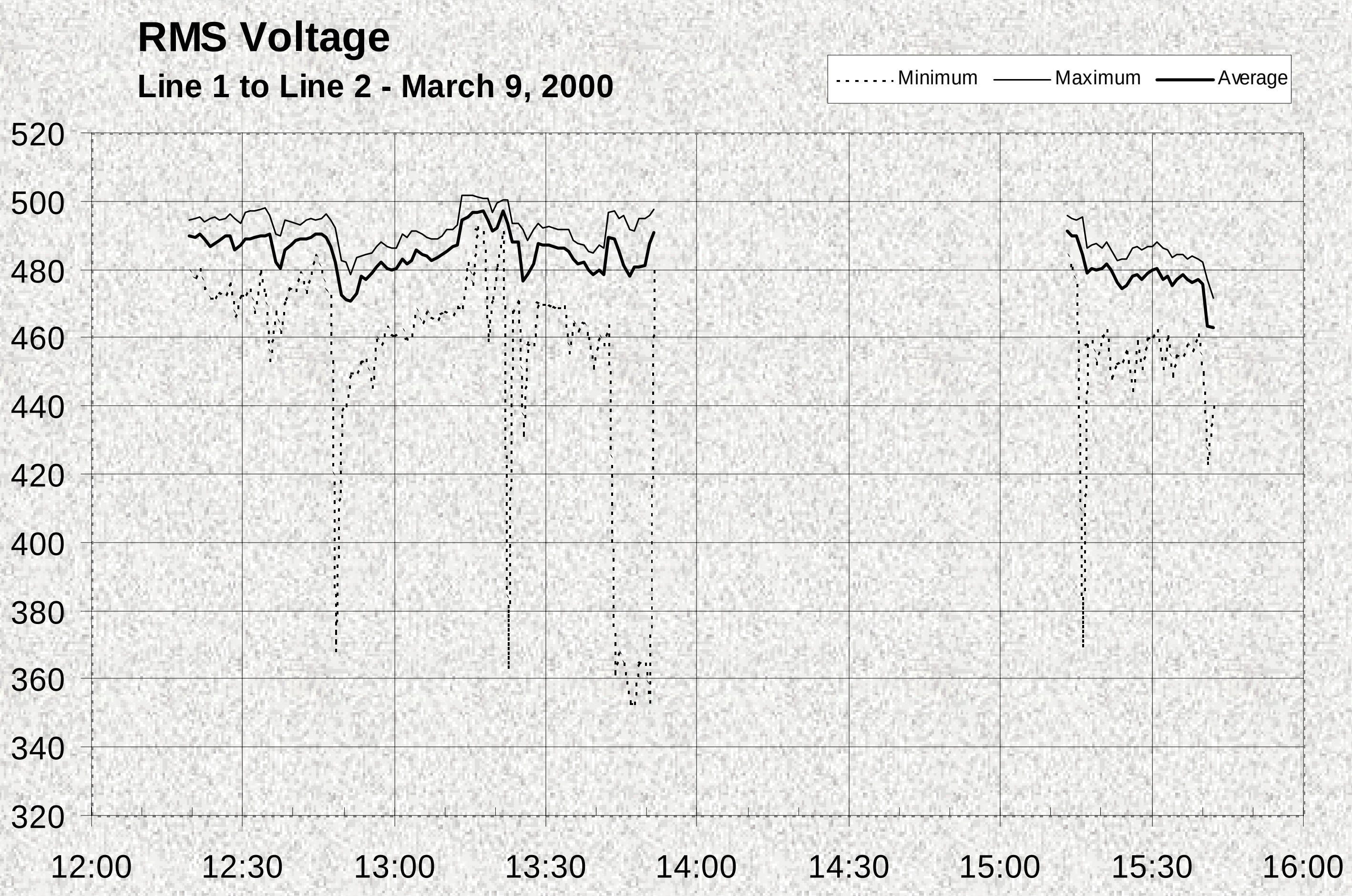
Voltage Graph



PowerLines

Analysis

- Normal Inrush Current was not an issue
- Under some load and line conditions, motor stalled (excessive voltage drop)
- When Motor Stalled, high current caused circuit breaker tripping

Solution:

Reduce Mains Impedance!

PowerLines

Transformer Comparison

Original Transformer → 15 KVA, 6.5% Impedance → 1.730 Ω @ 480 VAC

First Replacement Transformer → 17 KVA, 3.9% Impedance → 0.916 Ω @ 480 VAC

Second Replacement Transformer → 30 KVA, 6.5% Impedance → 0.864 Ω @ 480 VAC

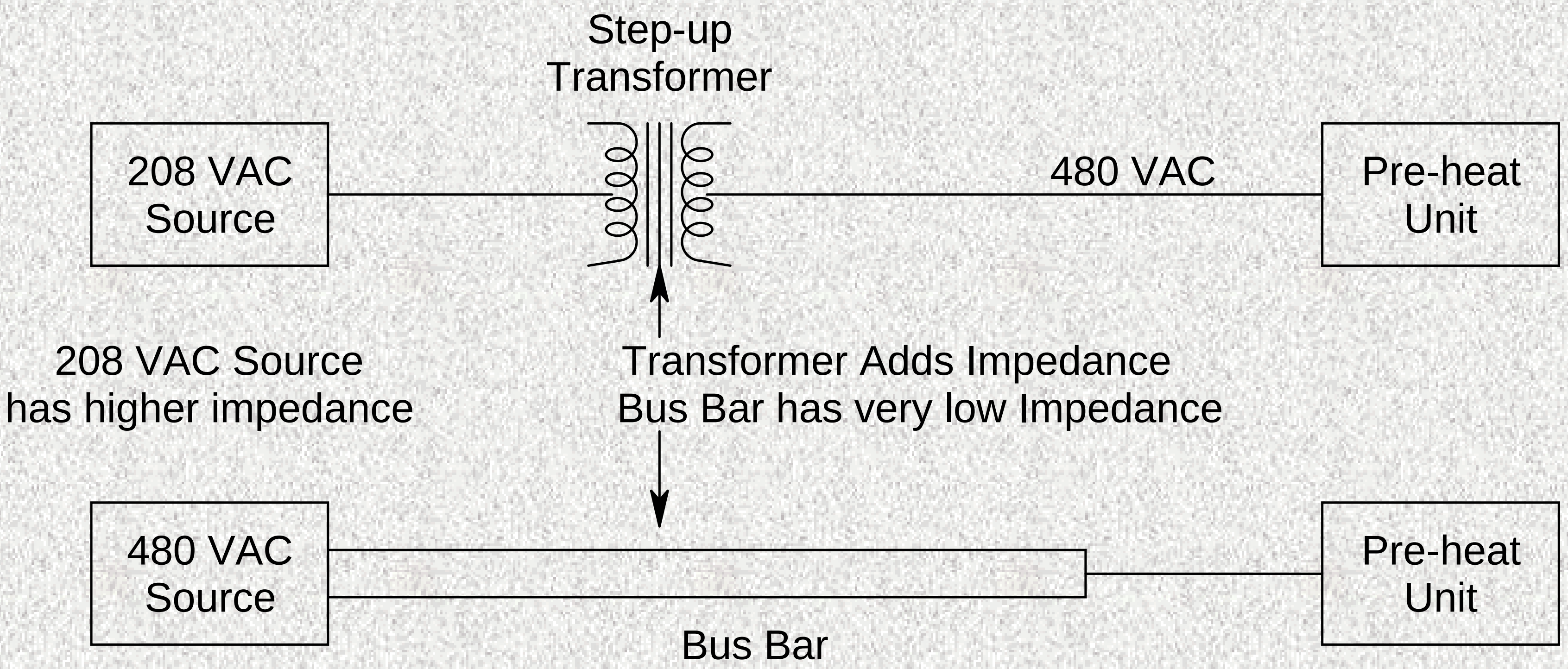
PowerLines

Case Study #3

- Wire and Cable Manufacturer
- Inductive Pre-heating Unit
- 480 VAC / Single Phase
- Recently moved from 208 VAC power to 480 VAC power
- Symptom:
  Cable “slapping” during operation

PowerLines

Old Power vs. New Power



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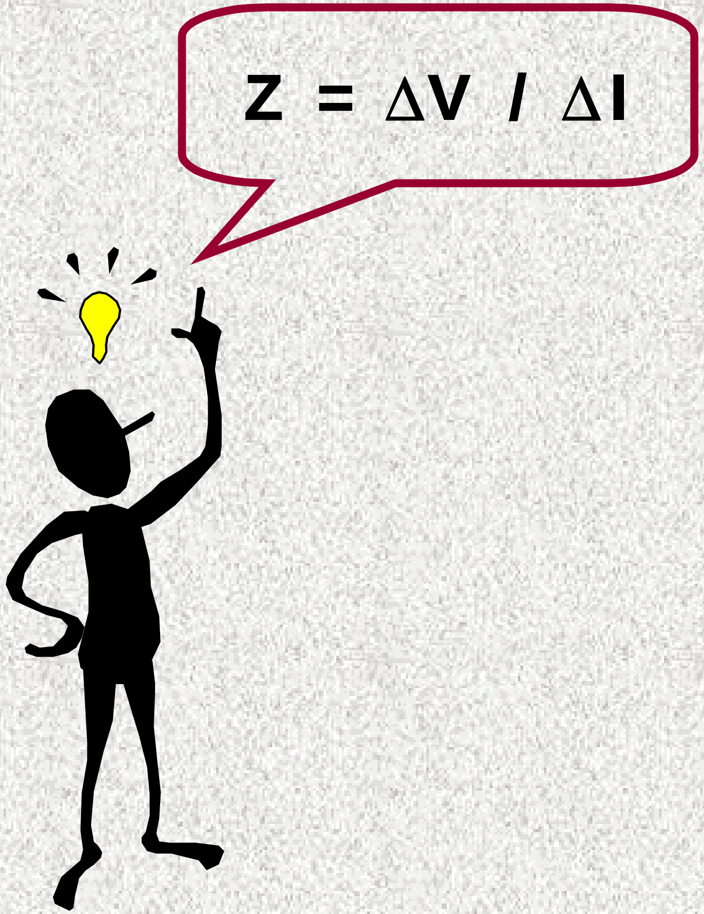
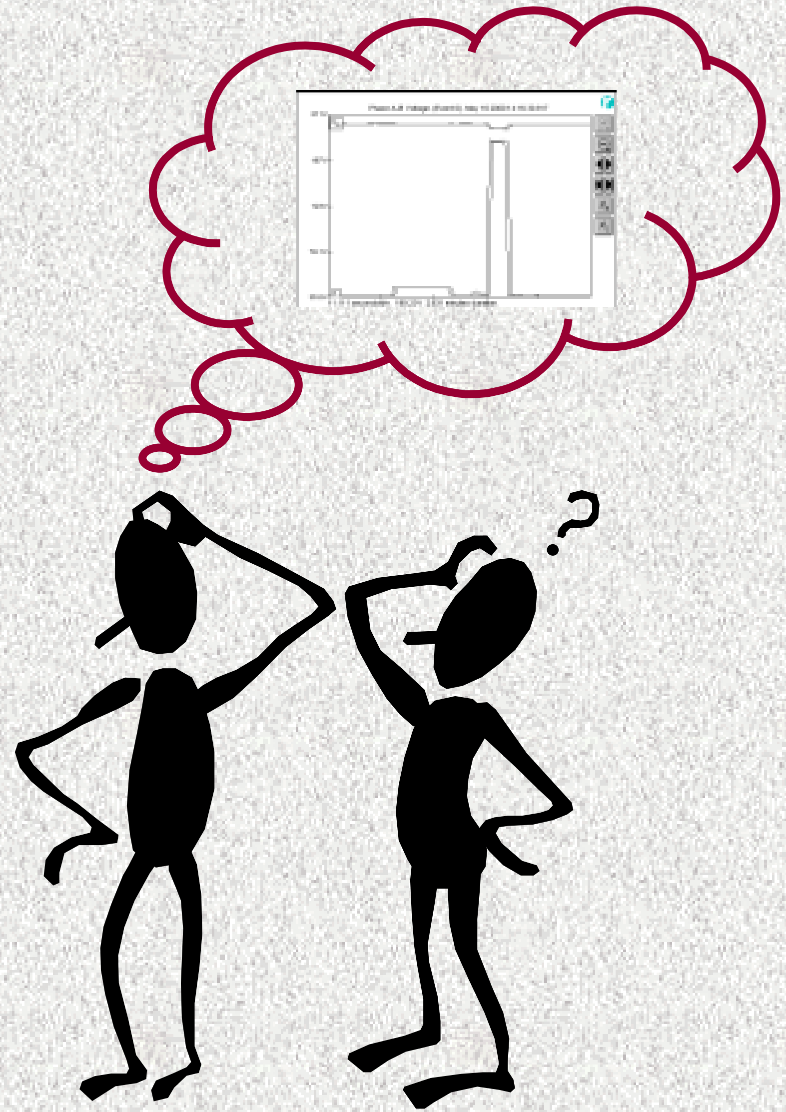
Question & Answer





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