Originally Presented at Power Quality 2000 (Boston, MA) on October 4, 2000

The Impact of Mains Impedance on Power Quality

By

Michael J. Russell, Consulting Electrical Engineer

PowerLines, P.O. Box 1164, Waterbury, CT 06721-1164

mrussell@powerlines.com

Abstract

Mains impedance is a critical parameter to consider when diagnosing load generated power quality problems. High impedance can contribute to voltage sags, low voltage conditions, high frequency noise, transient impulses, and harmonic voltages. These problems can be created by the critical load, or by other loads powered from the same electrical source.

This paper presents the concept of mains impedance. It starts with a simple impedance model (resistive) and the resultant effect on AC voltage at the fundamental frequency (50 / 60 Hz). A more complex model is presented, addressing inductive and capacitive components of the mains, and the impact of these on harmonic voltages and transient voltages. The concept of non-linear impedance, as often seen at the output of power conditioning devices, is introduced.

Techniques used to control impedance are presented, including selecting voltage levels, applying transformers, selecting conductors, distributing loads, and applying power conditioning equipment. Finally, case studies of impedance problems found in the field are highlighted.

1.0 Introduction

Power quality problems have historically been considered “somebody else’s problem”. Specifically, power quality problems were thought to be created at the utility level – due to switching, loading, environment, or accident. Alternately, power quality problems were found to be sourced within the facility, caused by other “dirty” loads that pollute the mains and cause problems for sensitive electronic loads.

These classic power quality problems can be described as *Line Generated.* The power quality techniques that have proven effective to combat line generated problems have fallen into two main categories:

1. Sensitive loads were separated from other loads through distance (different distribution panels, different voltages) or through electrical separation (i.e. – isolation transformers)
2. Utility or facility sourced problems were attenuated or corrected through the use of appropriate power conditioning devices.

A new trend in power quality problems is being identified. *Load Generated* power quality problems are disturbances caused by the operation of the sensitive load itself. These problems are well understood in specific industries and with certain equipment. Common problems such as waveform flat-topping, sags caused by inrush currents, and many subtractive impulses are examples of load generated disturbances. However, the continued introduction of microprocessor based controls into higher power loads and more industrial areas supports a renewed look into load generated disturbances.

Two factors contribute to the severity and frequency of load generated disturbances. The current profile of the load is critical, with the current waveform, distortion, and inrush each causing specific types of disturbances. Equally important is another factor, which to date has not been given appropriate attention – *Mains Impedance*.

2.0 Mains Impedance

Mains Impedance can be most simply represented as a source resistance inserted into the otherwise ideal AC voltage source. This resistance produces a voltage drop proportionate to the load current - the larger the current, the higher the voltage drop.

Figure 1: Mains Impedance, seen here as Z(source) distributed between two phases, causes V(load) to be less than V(source). If the source is intermittent or pulsing, V(load) will also fluctuate.

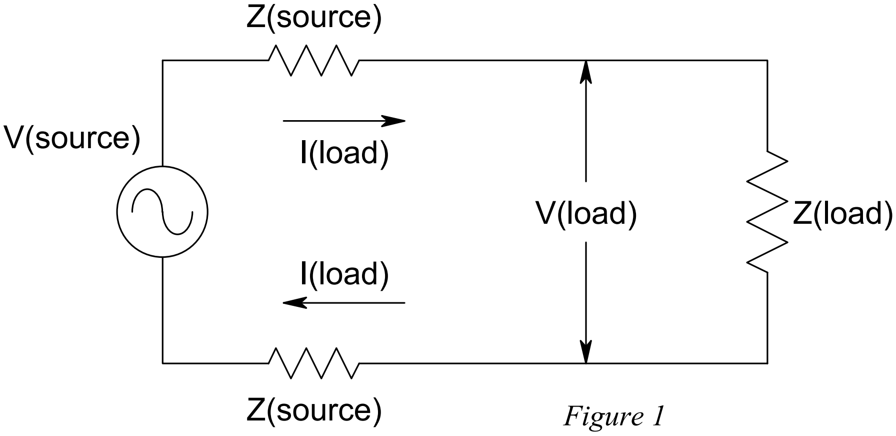


Figure 1

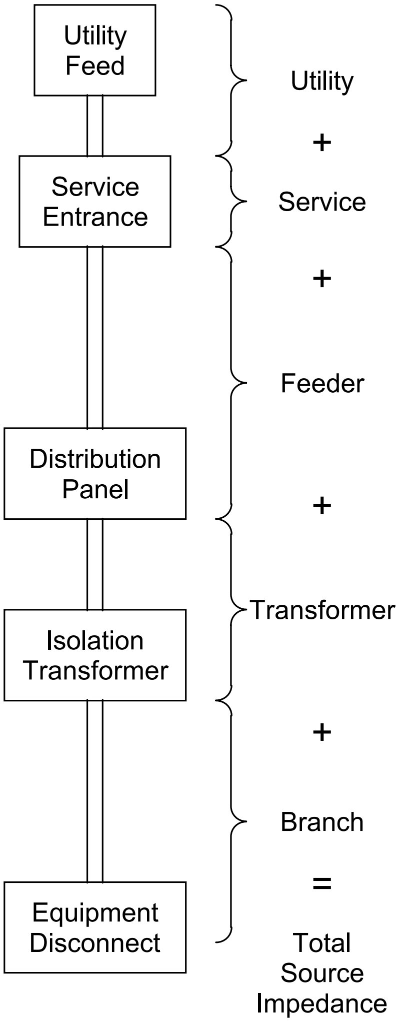


Figure 2

Mains impedance is cumulative. The effective mains impedance measured at the point of use is a sum of the impedance of every component between the utility and the point of use:

- Utility Source Impedance
- Service Entrance Impedance
- Feeder Circuit Impedance
- Transformer Impedance
- Branch Circuit Impedance
- Over-current Protection and Contact Impedance
- Connection Impedance (Plug)

Impedance can be expressed in many ways, but it is most common to express impedance as a percent voltage drop at a given load, or in ohms.

Nominal Voltage:	480 VAC
Voltage Range:	+/-10%
Impedance:	0.25 ohms *or*
	5.2% @ 100 Amps Load

In some cases, impedance specifications represent a voltage drop in addition to the permitted line fluctuations. In many cases, however, impedance is not specified. It is often assumed that the voltage range specification (here, +/- 10%) covers both line and load generated voltage changes.

2.1 Voltage Fluctuation

Impedance will cause AC line voltage to fluctuate due to changes in loading. If the load is continuous, or changes gradually, the impedance related changes will be constant or gradual. However, if the load changes quickly, impedance will cause the AC voltage to sag or drop. (Figure 3)

At right, a CT Scanner draws power in a short pulse (4.4 seconds). Here, a load change of 150 Amps causes a voltage drop of 4.85 VAC, or 2.4% of 200 VAC nominal.

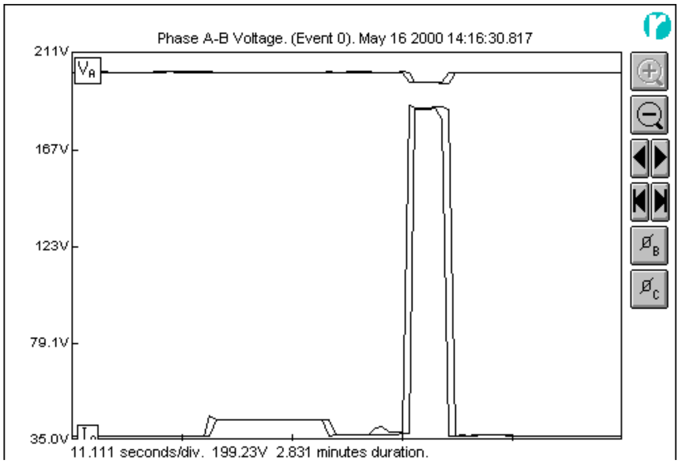


Figure 3

2.2 Distortion

Impedance will also cause voltage distortion, especially when the applied load is non-linear and contains a high level of harmonics. At right, this effect is clearly demonstrated. The voltage waveform is relatively clean when the load current is low, but as the load current increases, the voltage waveform becomes distorted. The magnitude of this effect is directly related to the mains impedance.

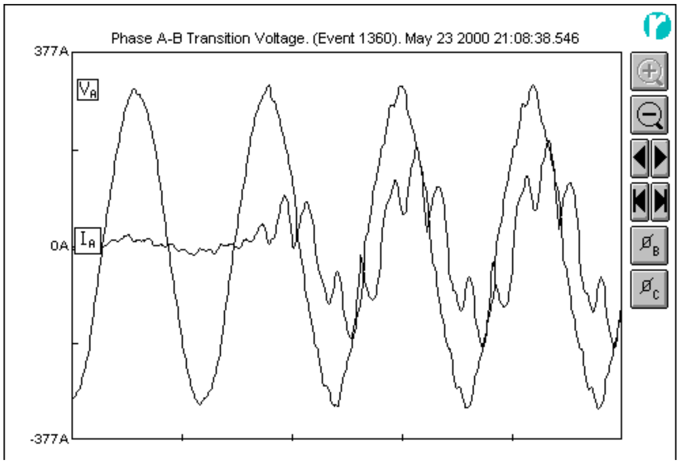


Figure 4

2.3 Transients

In addition to voltage sags and distortion, mains impedance can cause voltage transients. These are primarily due to rapid changes in current (start-up, inrush) and are most often seen as subtractive impulses.

2.4 Low Impedance Problems

It is much more common to have problems with high mains impedance than with low impedance. However, in some circumstances, low impedance can cause problems.

A low impedance source can be prone to spurious *circuit breaker tripping*. This may occur during start-up or inrush type loads, or during electrical faults. In some cases, lack of coordination between the internal protection and the external protection may result in the wrong protection operating during a fault. Case Study #3 addresses this type of problem.

Under worst case conditions, the Available Instantaneous Current (AIC) rating may exceed the ratings of the overcurrent protection device, resulting in a potential catastrophic failure if the protection attempts to interrupt a higher fault current.

Fortunately, the solution to a low impedance problem is simple. A small impedance can be easily added to the source - commonly in the form of an inductance or a transformer. This will effectively raise the impedance and limit the fault and inrush currents.

2.5 Complex Impedance Model

It is most common to express impedance as simply a resistive value (ohms) at the fundamental power frequency (50 / 60 Hz). Actual impedance consists of resistive, capacitive, and inductive components. In practice, the dominant components are resistive and inductive.

The reactive impedance elements serve to exacerbate the effects of impedance on distortion and voltage transients. Since these are caused by higher harmonics within the load current, the effect on output voltage is much worse than if the impedance was purely resistive.

Inductance in the electrical system comes from two primary sources. All *conductors* have inherent inductance, which is affected by the run length, conduit type, and distance between conductors Magnetic elements, such as transformers, filters, and chokes, also add inductance to the electrical system. In almost all cases, the impedance (resistive and inductive) of magnetic components is much higher than that added by conductors. As a result, attention to transformer specification, sizing, and design is the best way to improve impedance.

2.6 Non-linear Impedance

Most AC components have a linear impedance: the impedance is constant regardless of load current. There are two instances where impedance can be load dependent. This ***non-linear impedance*** contributes to a complex electrical system that is difficult to characterize, and often results in severe power quality disturbances.

First, magnetic components such as inductors, filters, and transformers, can be forced into *saturation* by over-current, overvoltage, or DC bias. Such a device in saturation has a very different mains impedance. In most cases, the effective impedance rises, resulting in a higher than expected voltage drop, with a similar increase in voltage transients and voltage distortion.

Second, power conditioners using active voltage regulation or double conversion technology can also produce a non-linear output impedance.

Finally, voltage regulators can address the sag or voltage drop caused by impedance. However, the regulator response time is critical - a load-generated drop in voltage will not be corrected instantaneously, but will be seen by the load for several cycles (tap switch regulator) up to several seconds (electromechanical regulator). In addition, voltage regulators do nothing to improve the voltage distortion or voltage transients caused by high impedance. Since these devices are almost always transformer based, it is very common for the regulator to make such higher frequency problems worse by increasing the total mains impedance.

Double conversion devices, such as UPS systems, rotary power conditioners, or voltage synthesizers, do correct the voltage sags, distortion, and voltage transients caused by high mains impedance. However, each of these devices has a non-linear output impedance, and must be applied with care to ensure that the output impedance of the device is compatible with the load requirements.

3.0 Impedance of Electrical Components

3.1 Conductors

Electrical conductors are the most common source of mains impedance, and the one most familiar to engineers. In general, larger conductors have lower impedance than smaller conductors do. Longer conductors have higher impedance than shorter ones. However, besides diameter and distance, other factors affect the impedance of a conductor run. In practice, the resistance is dominant for small conductors (#12 - #2 AWG) and the inductance is dominant for very large conductors (#4/0 and higher).

The most common materials for electrical conductors are copper and aluminum. Copper conductors have lower impedance than equivalently sized aluminum conductors do. As an example, a #2 AWG copper conductor has approximately the same impedance as a #1/0 AWG conductor. (NFPA-70-1999, Table 8: Conductor Properties)

The operating temperature of conductors also affects the impedance. Conductor impedance rises with temperature, and most tables of conductor resistance / impedance are based on the full-rated temperature of the conductor. A #2 AWG copper conductor, running at 30º C, has an impedance closer to a #1 AWG conductor. The conductor temperature will depend on the electrical design / derating, as well as the load characteristics (steady-state load or intermittent / low duty cycle)

Finally, the impedance of conductors depends upon how the conductors are run. Tightly coupling conductors lowers the impedance, while running the conductors loosely raises the impedance. Enclosure in steel or ferrous material results in a higher inductance value, and often higher total impedance.

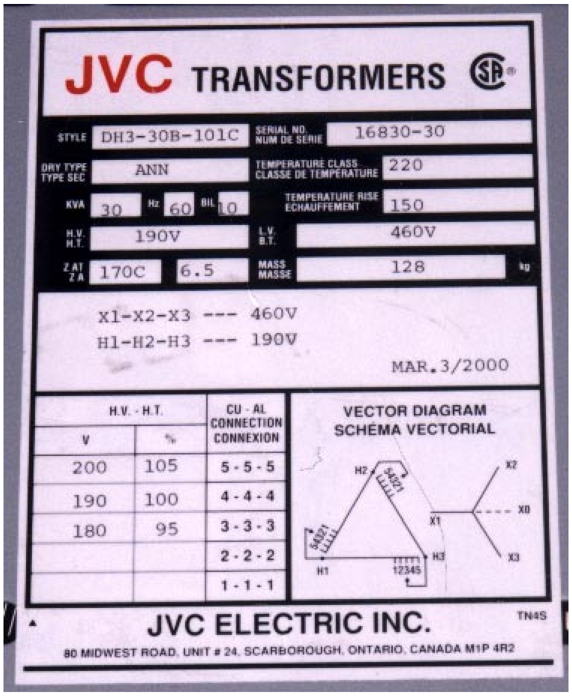
While many materials and design manuals contain tables of conductor impedance, the most readily available resources are published in the National Electric Code (NFPA-70), Tables 8 (DC Resistance) and Table 9 (AC Resistance and Reactance).

3.2 Impedance of Transformers

Transformers represent perhaps the highest percentage of impedance within a facility. As a result, the impedance of a transformer is often crucial to the performance of an electrical system with regard to load generated disturbances.

Conventional, off the shelf transformers, generally have the impedance specified on their nameplate (Figure 5) This impedance is almost always specified at a maximum operating temperature, such as 6.5% @ 170º C. (right) The actual impedance will be lower if the transformer is operated at a lower temperature.

This specified impedance is at the fundamental power frequency (50/60 Hz) and does not provide any indication of the complex impedance of the transformer, or its performance at higher frequencies.



JVC TRANSFORMERS

STYLE DH3-30B-101C
SERIAL NO. / NUM DE SERIE 16830-30
DRY TYPE / TYPE SEC ANN
TEMPERATURE CLASS / CLASSE DE TEMPERATURE 220
KVA 30 Hz 60 BIL 10
TEMPERATURE RISE / ECHAUFFEMENT 150
H.V. / H.T. 190V
L.V. / B.T. 460V
Z AT / Z A 170C 6.5
MASS / MASSE 128 kg

X1-X2-X3 --- 460V
H1-H2-H3 --- 190V
MAR.3/2000

H.V. - H.T.		CU - AL CONNECTION CONNEXION
V	%	
200	105	5 - 5 - 5
190	100	4 - 4 - 4
180	95	3 - 3 - 3
		2 - 2 - 2
		1 - 1 - 1

VECTOR DIAGRAM
SCHÉMA VECTORIAL

JVC ELECTRIC INC.
80 MIDWEST ROAD, UNIT # 24, SCARBOROUGH, ONTARIO, CANADA M1P 4R2

Figure 5

Transformer construction and winding techniques greatly affect the transformer impedance at both the fundamental frequency as well as at higher harmonics.

Figure 6: Transformer Impedance

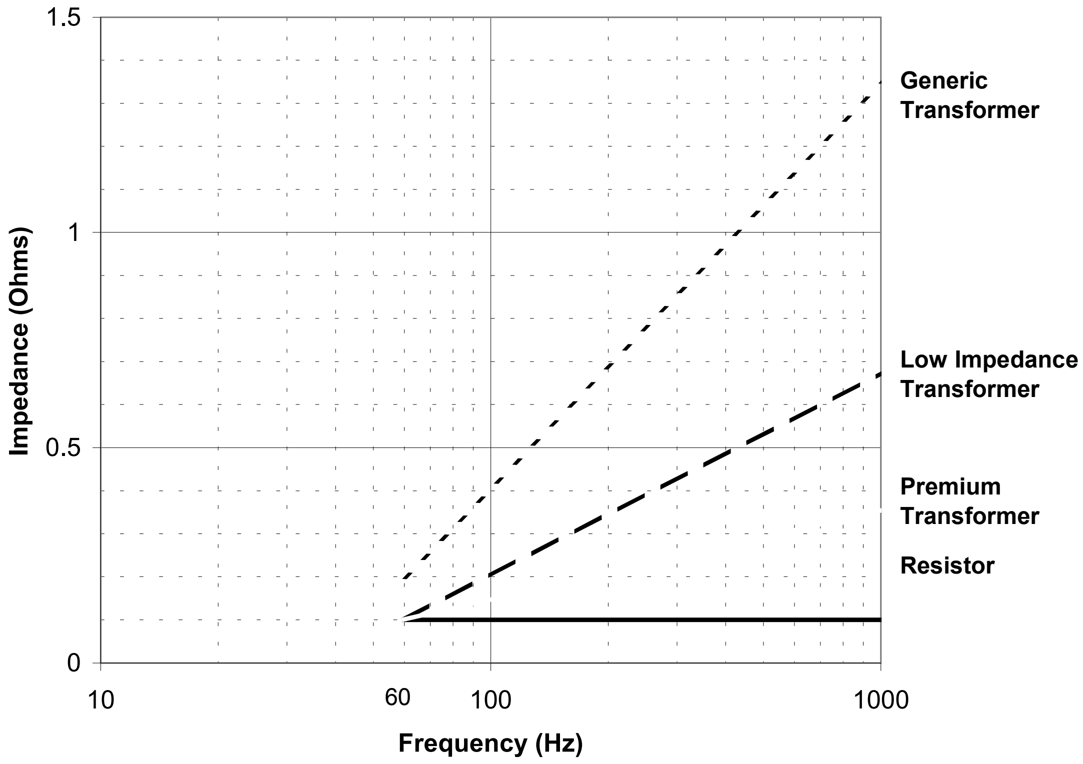


Figure 6 illustrates the difference in impedance for various transformers.

A **Resistor** is shown for comparison. Impedance is not dependent upon frequency, and so is flat from 60 Hz to 1000 Hz

A **Generic Transformer**, using conventional winding techniques and generally cost-optimized, has a specific impedance at 60 Hz (here, 0.2 ohms). As frequency increases, the impedance increases substantially.

A **Low Impedance Transformer**, using the same conventional winding techniques as a generic transformer, but designed with more steel and copper to reduce impedance, has a lower impedance at the fundamental frequency, and a proportionately lower impedance at higher frequencies.

Finally, a **Premium Transformer**, using higher quality copper and steel, and better quality winding techniques, has a lower impedance at both the fundamental power frequency as well as at higher frequencies.

Even though a Low Impedance Transformer and a Premium Transformer have similar impedance at the fundamental power frequency, the impedance of the transformer at higher frequencies are often quite different.

3.3 Impedance of Connections

Electrical connection points such as contacts, plugs and receptacles, circuit breakers, fuses, and terminals each have a small amount of contact resistance or impedance. While these values are generally much smaller than the impedance of conductors and transformers, they can add up over the course of a complex electrical circuit.

Faulty connections at these points can cause a high impedance on one phase, resulting in unbalanced load sharing and higher numbers of power problems on the affected phase. Such faulty connections (loose wiring, corrosion) can be detected through infrared imaging if the electrical system is loaded - the faulty connection point will generate higher heat. However, if the electrical system is unloaded or lightly loaded, it is unlikely that thermal imaging will find a problem. Secondary effects (drop-outs, impulses, etc) will point to the loose or corroded connection. Case Study #2 documents this type of problem.

3.4 Impedance of Power Conditioning Devices

Any power conditioning device that incorporates active voltage regulation or creates its own sine wave will have a non-linear impedance. The impedance of such devices cannot be easily characterized or measured as can that of a normal electrical source.

When evaluating such devices with regard to output impedance, consider the following:

- What is the instantaneous change in voltage (first cycle) in response to a 0 - 100% change in output current. Some devices can not handle such a large step in load current. What are the load requirements?
- How long does the device take to regulate the voltage after such a step load? (cycles)
- What is the absolute maximum load current that can be supplied. The normal electrical source can supply a large inrush or overload - the typical UPS or other form of power conditioner cannot.

4.0 Measuring Impedance

Impedance has historically been the realm of calculation and theory. Hands-on measurement and evaluation of impedance was uncommon. Only equipment manufacturers with experience in pulsing, low duty cycle, or high power loads knew enough to specify mains impedance. Engineers were primarily concerned with impedance to ensure proper Interrupting Ratings of protective devices, and to coordinate overcurrent protection.

Most power quality engineers do not measure impedance as part of their normal site evaluations. There are few pieces of test equipment capable of measuring mains impedance.

4.1 Empirical Measurements

Simple voltage and current measurements (loaded vs. unloaded) can provide the basis for an impedance calculation. Such a calculation is rudimentary - simply $Z = \Delta V / \Delta I$ - but it can provide valuable information. Care must be taken in making such measurements since the ΔV is often very small, and the voltage can change due to other factors not related to the load current. However, this sort of a measurement and calculation is well within the range of contemporary digital multi-meters and power analyzers.

If the existing load does not provide a good range of current, it is possible to add a temporary resistive load to create a measurable change in voltage.

4.2 Mains Impedance Meters

Several devices are available that measure mains impedance on electrical systems. Small hand-held devices that are suitable for measuring the mains impedance of 120 VAC / 20 Amp circuits can be purchased for $300 - $800 US dollars. These are usually integrated into devices that check voltage level, grounding, etc. Larger devices that can measure mains impedance up to 480 VAC, on circuits of almost any capacity, can be found for $2,000 - $6,000 (USD). To date, all impedance measuring devices measure at the fundamental power frequency only.

In the future, power quality analyzers may have the hardware and software built in to evaluate mains impedance. With the computational power built-in to such devices, complex mains impedance at the fundamental as well as higher frequencies should be measurable.

5.0 Controlling Impedance

Design engineers can control impedance, and prevent high impedance conditions, by following a number of guidelines with regard to specifying and designing electrical systems.

5.1 Standards and Requirements

There are no general standards or requirements with regard to impedance. The National Electric Code (NFPA-70-1999) addresses voltage drop (impedance) through a 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 operation."* This Fine Print Note is a recommendation, and not a requirement.

The NFPA-70 document is primarily concerned with safety - not with electrical performance. As a result, designing an electrical based entirely on minimum values as found in this document most often results in an electrical design that is properly rated from a thermal and an overcurrent protection perspective, but one which may be rife with impedance related power quality problems.

Specific industries may have standards or electrical guidelines that provide recommendations on mains impedance.

Electrical design engineers must consider impedance in the facility, and the impact of facility impedance on equipment design. Lacking other design criteria, a 5% impedance specification is reasonable.

5.1 Voltage Level

Careful consideration of AC voltage level can be effective when designing to control impedance. If mains impedance is an issue, and a low impedance source is desired, electrical feeds should be run at the highest voltage possible. Similarly, high power equipment should be designed to operate from as high a mains voltage as practical.

As an example, the author once consulted on a large decorative message board sign that drew 800 kW of power, and was designed to operate from a 208Y/120 VAC source. Power quality problems seen at the sign were actually impedance problems, caused in part by distortion and transients generated on the 208Y/120 VAC bus-bar feeding power to the sign from a 1.5 MW dedicated service. The sign power could have been much more easily delivered if the sign had been designed to operate from 480 VAC.

5.2 Long Conductor Runs

Unfortunately, too many branch and feeder circuits are sized based on the NFPA-70 minimum values for ampacity, based on the overcurrent protection and thermal ratings alone. Rarely is impedance considered in these designs.

If AC conductor runs are long (> 50 feet) consider increasing the conductor sizes. Manufacturers in some industries publish recommended conductor sizes vs. run length for their equipment.

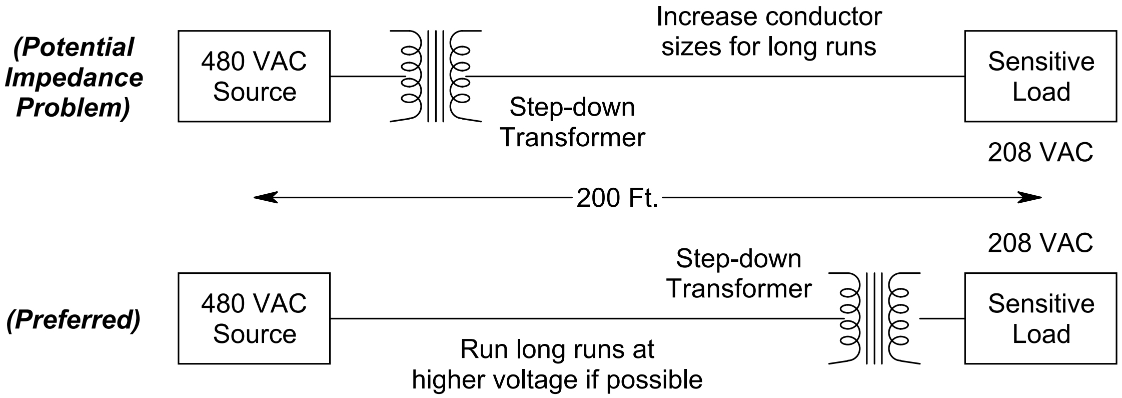


Figure 7

If a long conductor run is unavoidable, try to make this run at the highest possible voltage level, to reduce the need for large conductors and to minimize the voltage drop.

5.3 Transformers

Transformers are typically the highest impedance elements in an electrical design. Many electrical designs do not bother to specify impedance - relying on boilerplate specifications and the KVA rating of the transformer. However, the impedance of common transformers varies widely, and should be a consideration in the specification and selection of a transformer manufacturer and design.

In general, higher volume transformer manufacturers have the design tools and volume to justify engineering the excess capacity out of their designs. As a result, such transformers often have a higher impedance than similar KVA designs from smaller manufacturers.

Premium quality transformers often have a lower impedance. They use a higher grade and larger quantities of copper and steel, and manufacturing techniques designed to minimize impedance. These improve the transformer impedance at both the fundamental frequency as well as the higher frequencies associated with harmonics and transients, albeit at a higher cost per KVA.

Do not gang similarly sized transformers to step voltages up and down. Instead, use one single transformer with the correct input and output voltages to match the source voltage and the equipment requirements.

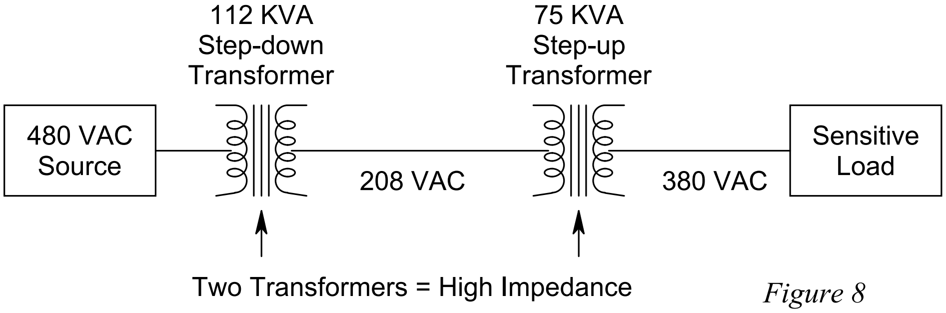


Figure 8

5.4 Load Separation

It has become an axiom that to maximize power quality, high power and pulsing loads should be separated from sensitive loads. In most cases this involves powering these loads from different transformers or electrical panels. However, there is little in the way of specific guidelines with regard to how much separation is adequate for reliable operation.

An alternate way to view this separation is to minimize the “shared impedance” between high power loads and sensitive loads. The high power loads will cause load-related disturbances - but these will be very minor if the point of common connection with the sensitive loads is a large distribution panel near the service entrance. The lower the impedance at this point of common connection, the better. By using a numerical value such as impedance, specific recommendations and guidelines can be developed.

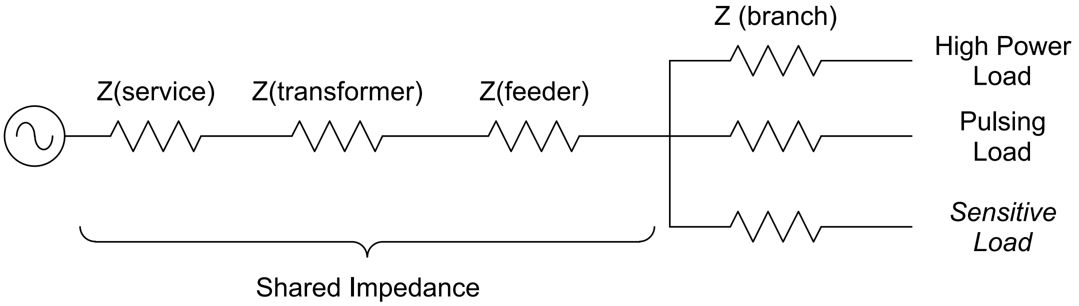
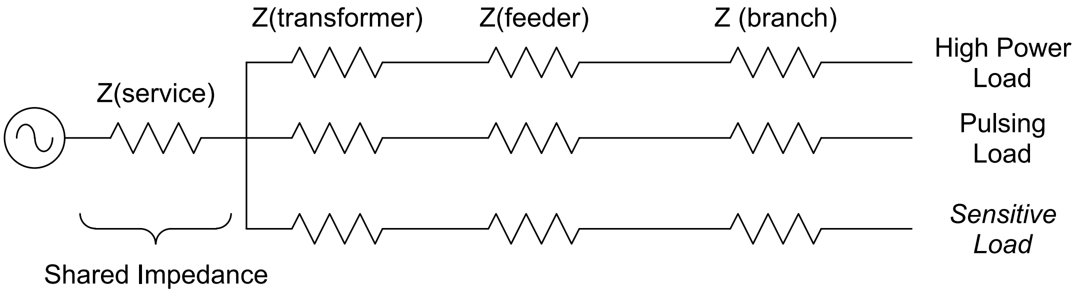


Figure 9a (above) - With the service entrance, transformer, and feeder circuit impedances in common, power problems are more likely

Figure 9b(below) - Using a separate transformer and feeding circuit for separate loads can reduce the shared impedance, and minimize load to load interference.



5.5 Non-linear Sources

Whenever a non-linear source is specified or applied, ensure that the manufacturer of this device is aware of the nature of the load. Non-linear sources include UPS systems, voltage regulators, rotary power conditioners, emergency generators, inverters, voltage synthesizers, etc.

Conventional loads such as computers, servers, lights, and office equipment should not be a problem for these devices. But high power devices such as medical imaging equipment, factory automation, industrial controls, etc. can have unique and disruptive current profiles. The non-linear source may not be able to supply these currents without substantial derating or design modifications.

6.0 Case Studies / Impedance Problems

The following case studies are taken from real world power quality consulting performed by *PowerLines* for its medical and industrial clients.

6.1 Case Study Number 1: Loose Connection Affects System Performance

Location: A cancer treatment center affiliated with a small hospital in the northeast United States.

A radiation therapy linear accelerator, used for cancer treatment, was experiencing calibration problems. The radiation dose to the patient, which must be stable and consistent to ensure proper treatment, was fluctuating throughout the workday, requiring frequent recalibration and reducing patient throughput. Power monitoring had detected normal voltage levels and moderate voltage fluctuations - not outside of equipment specifications.

Measurement of the mains impedance at the equipment terminal found a large imbalance.

Phase	**Voltage**	**Impedance**	**I(short-circuit)**
Red-Neutral	121.4 VAC	0.115 Ω	1.00 kA
Blue-Neutral	121.7 VAC	0.054 Ω	2.09 kA
Black-Neutral	121.5 VAC	0.059 Ω	1.95 kA

Similar measurements at the source found impedance to be balanced. Measuring the impedance at various points along the electrical system led to the identification of a loose transformer tap connection on the 480 VAC primary of the 30 KVA transformer feeding the equipment.

The arrow points to the transformer tap itself. The copper coil and connection wire in the vicinity of the tap also show signs of heating (conducted from the tap), resulting in a blackening of the transformer tape and a degradation of the wire insulation.

More dangerous - the adjacent conductor (parallel to the white lines) is a different 480 VAC phase. This wire is touching the overheated tap, and shows signs of insulation degradation and heating. A short circuit from this wire to the tap would cause a circuit breaker trip (best case) resulting in short term loss of equipment use.

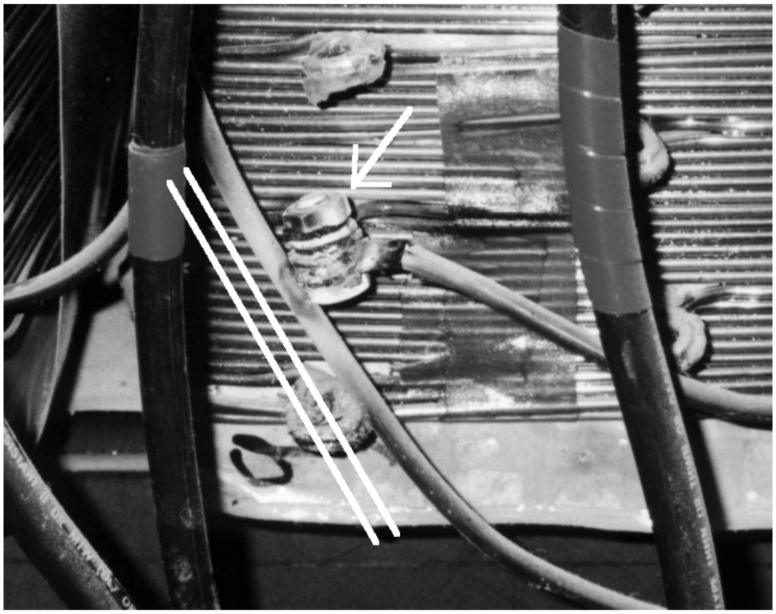


Figure 10

Worst case, this short circuit could cause an arcing fault that could damage or destroy the transformer, and possibly start an electrical fire.

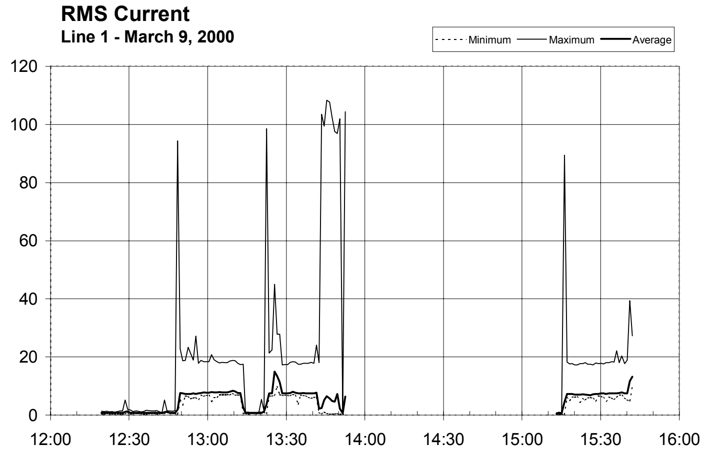
While infrared / thermal imaging would have detected this problem during preventative / planned maintenance, this was impractical and expensive to use for troubleshooting. Measuring the mains impedance permitted rapid identification and localization of the problem.

.

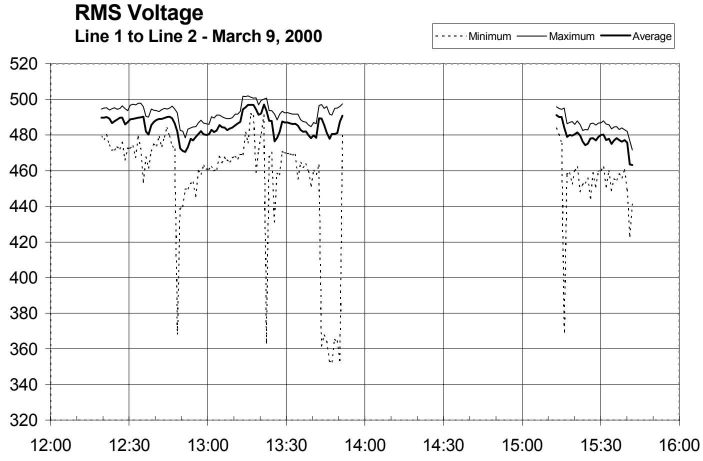
6.2 Case Study Number 2: High Impedance Causes Breaker Tripping

Location: A sheet metal manufacturing facility located in a small, urban industrial building in the greater New York City area.

A precision metal punch relied on a hydraulic system, powered by a large three-phase motor. The punch consisted of a master computer (Unix-based), PLC type machine controllers, and the hydraulic motor. During initial power-on, the PLC-controllers and the master computer went through a start-up and initialization cycle. When this was completed, and a punch program loaded, the hydraulic system was energized. The manufacturer specification for the equipment was for a 480 VAC source rated for 18 KVA (22 Amps).



Figures 11a (above) and 11b (below)



Occasionally, a 70 Amp circuit breaker feeding the system would trip when the hydraulic system was energized.. This resulted in loss of the punch program, a need to reboot and re-initialize the system and occasionally a crash of the master control computer. When the computer crashed, the manufacturer's service engineer had to be called to the site to reload software, resulting in a 4-8 hour downtime for the equipment.

Power monitoring at the site found that the starting-current of the machine could rise as high as 100 Amps for several cycles. This alone did not appear to be a problem, as repeated starting of the motor produced no circuit breaker tripping.

However, monitoring of the AC mains feeding the system found voltage sags during start-up to as low as 360 VAC.

Excessive mains impedance of the source consisting of a 208 VAC utility supply and a small (30 KVA) step-up transformer provided a very high source impedance.

The solution: reduce the mains impedance by pulling a new feeder from a higher capacity electrical source, and replacing the 30 KVA transformer with a lower impedance device. A small UPS used to power the system computer would have prevented the software loading issues.

An interesting side note: The manufacturer, in attempting to correct this problem, had replaced an 18 KVA transformer at the site with a 30 KVA transformer. While this approach was technically and intuitively sound, they in fact replaced a low impedance 18 KVA transformer (3.9% @ 170º C) with a higher impedance 30 KVA transformer (6.5% @ 170º C), *In doing so, they actually increased the mains impedance, making the problem worse!*

6.3 Case Study Number 3: Low Impedance Causes Noisy Conductors

Location: A medium sized wire and cable manufacturer in northern New England

A large inductive preheating unit, powered from 480 VAC single phase, was experiencing a mysterious problem during initial power on. Specifically, the power conductors feeding the device jumped or moved in the conduit, causing a loud "slapping" or vibration that was disconcerting to operators as well as potentially damaging due to conductor mechanical stresses.

This problem did not occur with the preheat unit at a different location, powered from the facility 208 VAC source via a step-up transformer. A similar unit, moved to the same spot, experienced the same type of problems, eliminating a device malfunction or service issue. Equipment performance was not affected.

The Inductive Pre-heat unit design was fairly simple – with a large inductive coil, a few simple control boards (analog) and a switching Thyristor or SCR module.

The cable slapping was found to be caused by large inrush currents. These currents were a residual of the pre-heater design (lack of soft-start or hold-off circuitry) and/or misadjustment. When the device was initially switched on, the Thyristor fired (either deliberately or accidentally) and the resulting inrush into the de-energized coil was huge. (1000's of Amps)

The reason that the device did not experience such a problem in the previous location was that the 208 VAC source and the step-up transformer provided adequate impedance to limit the inrush current to a lower value, such that cable movement did not occur. The much stiffer source provided at the new location (480 VAC bus bar) had a much lower impedance that did not limit the current.

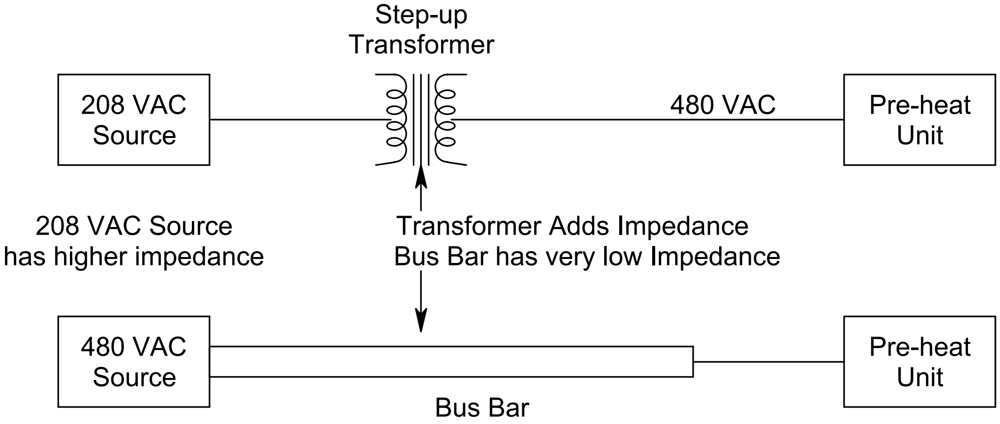


Figure 12

To resolve this problem, the facility purchased line reactors to add impedance and limit inrush currents. Other techniques that would have increased impedance include creating a softer (higher impedance) source (longer run length, smaller conductors) or inserting an isolation transformer (480 VAC to 480 VAC)

Acknowledgements

The author would like to thank Randy Redding, of Teal Electronics for an eight-year education in the fine art of transformer impedance.