

OPTIMIZING MAINS IMPEDANCE: REAL WORLD EXAMPLES

by

Judith M. Russell
Consulting Electrical Engineer
PowerLines

Introduction

Power Quality has historically been quantified in terms of voltage. Metering equipment measures RMS voltage level, voltage sags and swells, voltage harmonics, or voltage transients. Current, if measured, becomes a secondary parameter – useful in diagnosing problems (line generated vs. load generated, or assessing the impact of voltage disturbances on a particular load) or sizing solutions. While current is usually not the first thing reviewed, it has become standard to measure both voltage and current when investigating power quality. Impedance, however, is rarely measured directly, and only occasionally assessed indirectly, in the diagnosis and resolution of power quality issues.

Impedance is an important issue for almost any piece of sensitive electronic equipment, but it is of particular importance in the following cases:

- There is an intermittent, cycling, or pulsing characteristic to the load
- There is a high inrush current to the sensitive load or a sub-system of the sensitive load
- The sensitive equipment requires high power / high current, or an allied or connected piece of equipment requires high power
- The load current is non-sinusoidal – perhaps a single-phase rectified load, or a three-phase power converter with minimal input filtering. These loads, drawing current with relatively high harmonic currents, often team up with high impedance to cause significant voltage problems.

While considering, measuring, and understanding impedance are often important factors in resolving power quality problems, the concept is not well understood outside of power quality engineering. One problem is that impedance is not something that can be easily marketed or sold. Few pieces of test equipment consider impedance – either directly or indirectly. A handful of manufacturers have marketed impedance-optimized devices (usually isolation transformers) over the years, but often at a premium price that limits their appeal. The copper industry has a power quality group that spends a lot of time talking about impedance - admittedly, to promote the use of copper.

For the most part, however, impedance is a poor cousin to more exciting products such as transient suppressors or uninterruptible power supplies, or more dramatic power quality topics such as grounding, voltage sags, or harmonics.

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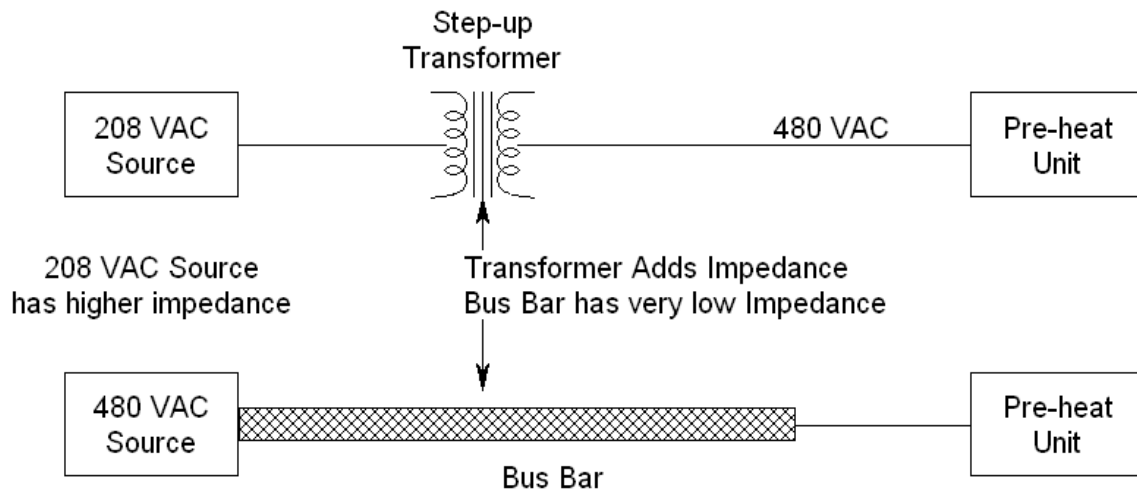
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Optimizing vs. Minimizing

Readers will note that I have used the word *optimizing* in the title of this paper, as opposed to the word *minimizing*. While the majority of impedance related power quality issues are indeed related to excessive impedance, occasionally the reverse is true. The tools and techniques discussed herein to measure and to correct impedance problems are equally valid.

Three cases of real world “low impedance” problems are brought to mind:

1. A wire manufacturing facility, where a 480 VAC inductive pre-heating unit experienced serious cable “slapping” at switch-on, related to high inrush currents. This was both disconcerting to the user, as well as potentially damaging to the cable and conduit. The device had recently been moved from a soft source (high impedance, 208 VAC, via a small step up transformer) to a low impedance source (480 VAC bus).



The solution: *add some impedance to limit the inrush currents.*

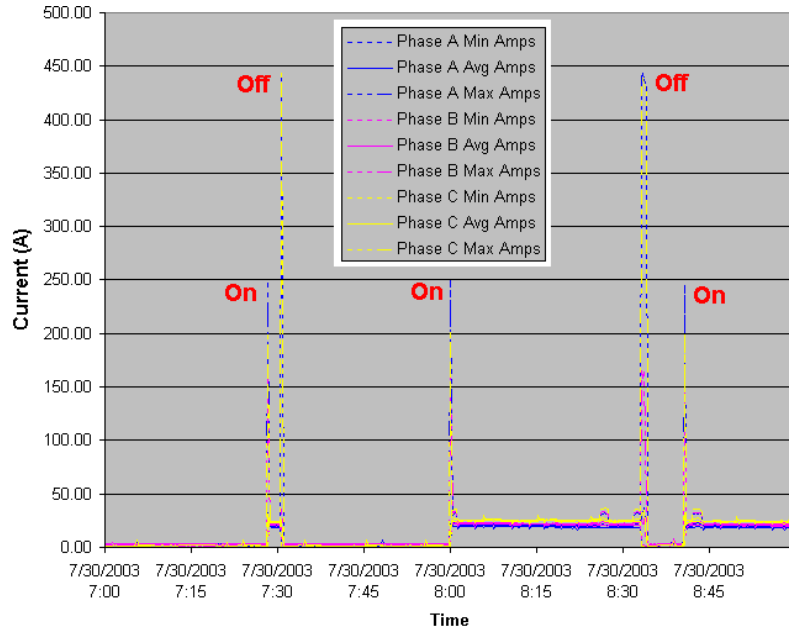
2. A medical X-Ray system was experiencing component failures during tube arcs. Such arcs are a normal, end-of-life behavior of an X-Ray tube, but the X-Ray generator should not fail during tube arcs. In this case, a particularly low impedance source was able to supply high fault currents during this sort of fault, exceeding the maximum current ratings of the devices, and resulting in power semiconductor failure.

The solution: *adding impedance (in the form of a 1:1 isolation transformer) limited the available fault current, and prevented component damage during tube arcs.*

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3. A press brake (metal bender) in an industrial facility was spuriously tripping a circuit breaker during operation (specifically, when the brake cycles off). A high current related to the hydraulic system power off cycling, was drawing excessive current for the installed overcurrent protection. Unexpectedly low source impedance at the facility permitted the high currents to flow.



The solution: *installation of a circuit breaker with a higher magnetic trip characteristic was required to permit system operation from the low impedance source.*

These three cases demonstrate that *minimizing* mains impedance is not always the goal. However, these three cases are truly aberrations – far outnumbered by the other impedance problems. Most of the time, a power quality impedance problem is related to excessive impedance, and *optimizing* mains impedance means *minimizing* mains impedance.

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Optimizing Impedance via Nominal Voltage Level

One way to optimize mains impedance is to select an appropriate nominal voltage level and system type for the power of the load to be applied.

In 1997, PowerLines was retained to look at an image quality problem on a large video sign possibly related to power quality. We traced the problem to voltage waveform distortion, caused by the load current waveform (phase controlled SCR) and the mains impedance, but a primary contributor was the nominal voltage level.

This particular sign was a behemoth – fed via a dedicated 12.5 KV / 1500 KVA service. But the sign design, and the power distribution for it, had been scaled up from smaller designs that were successfully run from 208 VAC power. Thus the power feed had hundreds of feet of distribution at 208 VAC. Had the sign manufacturer transitioned to 480 VAC internal distribution, the current levels in the distribution would have been halved, and impedance would have been much easier to minimize / control.

Optimizing Impedance via System Type

In the mid-90's, there was a lot of buzz in the medical imaging world about a "Single-phase X-Ray Generator". Such a device might find a niche in small clinics and offices where three-phase power was not available. However, the sales and marketing folks in the industry were equating "single-phase" with "low-cost", and were not considering the impact that moving to a single-phase power converter would have on the installation costs (conductor sizing, transformers, etc.), nor the impact of what a large, single phase pulsed load would have on a typical three-phase electrical system. The "low-cost" product (from a device cost stand-point) had a much higher installation cost, and as a result, did not have the expected sales success.

Optimizing Impedance at the System Level

*Increase source voltage (for example, 120 VAC to 240 VAC, or 208 VAC to 480 VAC)
as equipment power levels rise*

Migrate to three-phase power as equipment power levels rise

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Conductor Size / Run Length

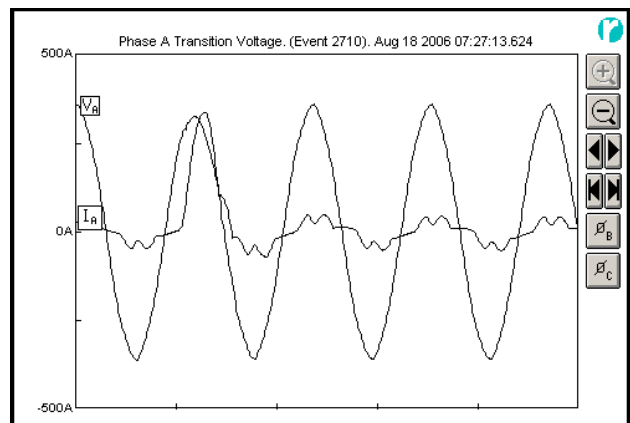
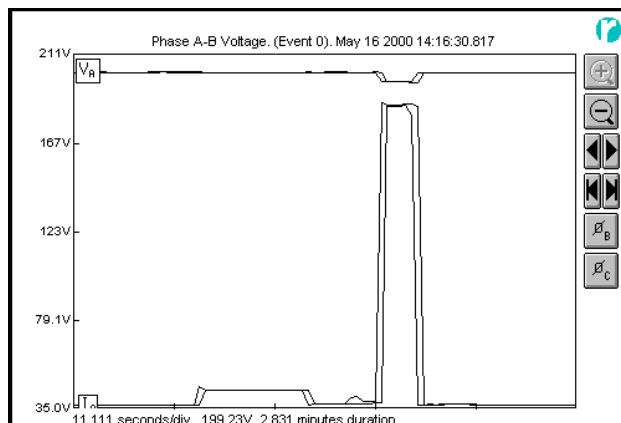
Engineers must consider the impact of conductor size and run length on mains impedance.

In most cases, conductor sizes are selected based on thermal performance and safety. Oftentimes, these are derived directly from the National Electric Code or other safety standards – related to the specified equipment circuit rating or overcurrent protection. And in most cases such sizing is both safe and appropriate. However, in some cases conductors sized only based on thermal requirements or overcurrent protection may cause problems.

If run lengths are long, consider increasing the conductor size to minimize impedance.

Similarly, if equipment has specific characteristics that make impedance important, consider increasing conductor sizes (even if the run length does not appear to be excessive. For example:

- If the load is known to be intermittent or pulsing
- If the load has a high inrush current or a large current swell during some operating conditions
- If conductor or source derating (related to duty cycle) is permissible by the electrical code(s) – a good example is medical imaging equipment, where a 50% derating from maximum current is allowed.



Whenever impedance is a potential problem, conductor sizes should be chosen based on thermal requirements, as well as impedance / voltage drop requirements. However, manufacturers may not clearly indicate the importance of impedance and the need for increased conductor sizing.

The following clues can indicate the potential for impedance problems:

- If the manufacturer publishes an impedance specification (ohms or percent drop)
- If the manufacturer publishes a conductor size chart (size vs. run length)
- If the manufacturer specifies particular overcurrent protection (adjustable magnetic trip, or time-delay fuses)
- If the manufacturer specifies a separate / dedicated circuit or warns to keep a particular load separate from other loads

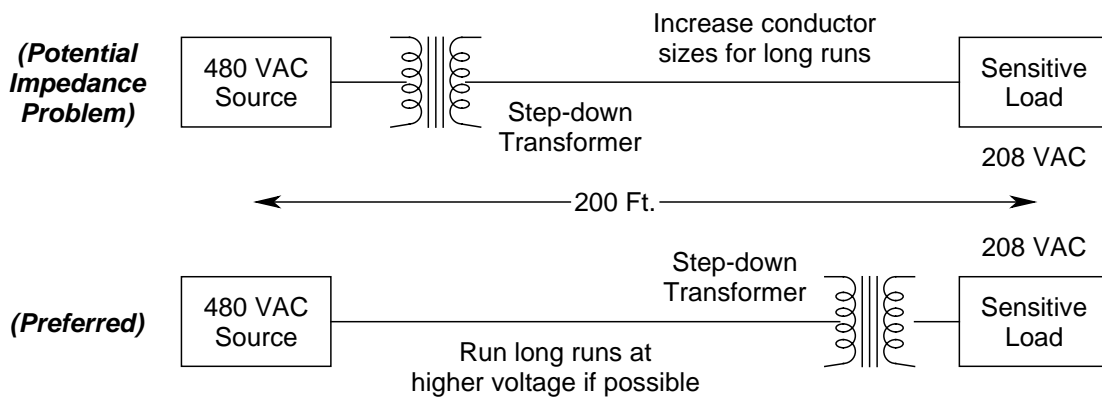
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Two typical design and construction situations can cause problems from an impedance perspective. Contractors often bid a project based on overcurrent protection ratings, and might even go so far as to rough-in conduit before the electrical design has been completed. As a result, increasing conductor sizes (to minimize impedance) might not be included in the cost of the project, or require significant changes.

Right: *Conduits are often sized based on circuit breaker size, and may not accommodate impedance-driven increases in conductor size*

If step changes in voltage are required (up or down), placement of transformers is critical. Position transformers so as to minimize the length of lower voltage runs (208Y/120 VAC, for example) in favor of higher voltage runs.



Optimizing Impedance Related to Conductors

Consider increasing conductor sizes for long runs

If you have the option, design long conductor runs at the highest available system voltage

Be on the lookout for code-minimum electrical designs, and conductors sized solely on the basis of thermal loads, with no consideration of impedance

When conductors need to be increased in size, get that information out early in the design / construction process to avoid extra costs and project delays

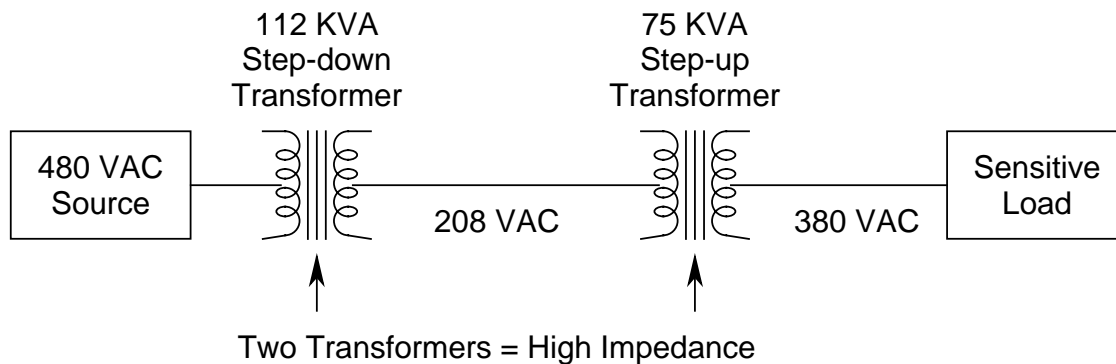
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Isolation Transformers

Isolation transformers are invariably the highest impedance devices in an electrical system. In most cases where high impedance has evolved into a power quality issue, an isolation transformer (or two!) is often involved. Typical problems include:

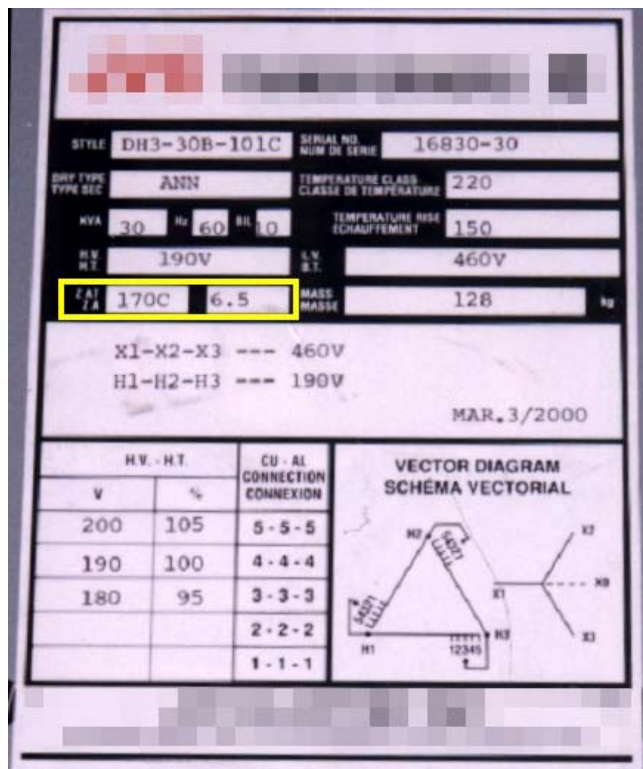
- Isolation transformers sized for demand (KW) but with high impedance
- Heavily loaded isolation transformers (transformer impedance typically rises with temperature)
- Multiple isolation transformers, combined to step voltage up and down to match equipment requirements



Transformers complicate impedance discussions. Transformer impedance is typically specified at a high (maximum) temperature, and actual impedance is often significantly lower. This is especially true if the transformer is oversized (e.g., harmonics) or if the load has a low duty cycle.

Special low impedance transformers are available, often at a premium price. These may be simply derated and oversized (to reduce impedance at the fundamental frequency), or may incorporate advanced materials and construction techniques intended to reduce impedance at higher frequencies.

Right: This 30 KVA transformer has a specified impedance of 6.5% at 170°C – but the actual operating impedance may be much lower, depending upon the applied load and resultant transformer operating temperature.



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Optimizing Impedance at Isolation Transformers

Never combine or daisy chain similarly sized isolation transformers

Consider worst case loading (maximum load, inrush currents) when sizing transformers

Include impedance in your transformer selection criteria

Derate transformers or consider premium transformer designs

Power Conditioners

Power conditioning devices can be a “wild card” in terms of impedance.

Some devices, such as a double conversion UPS or rotary power conditioner, provide an output that is for the most part independent of the input voltage. So for all intents and purposes, the impedance of these devices cannot be calculated or analyzed using conventional calculations. It's important to understand the step load response, the device response to non-linear load currents, and the output regulation characteristics to ensure device compatibility with the load. Assuming that compatibility is established, the devices should be effective over a wide range of source impedance.

Other devices, such as transformer or autotransformer-based regulators, can correct for voltage changes at the fundamental frequency. However, these devices often are not fast enough to compensate for inrush currents or pulsing loads, nor do they correct for sub-cycle issues, related to non-linear loads and impedance. High harmonic load currents can cause voltage distortion if source impedance is high.

In general, any time that active power conditioning or voltage regulation is employed, traditional impedance measurements (whether in ohms or in percent) are less likely to be meaningful, and special care should be taken to ensure that the output characteristics of the power-conditioning device are compatible with the load requirements.

Optimizing Impedance at Power Conditioners

Double conversion technologies can overcome impedance problems

Transformer based technologies can not correct impedance problems

Power conditioner compatibility with the load is critical

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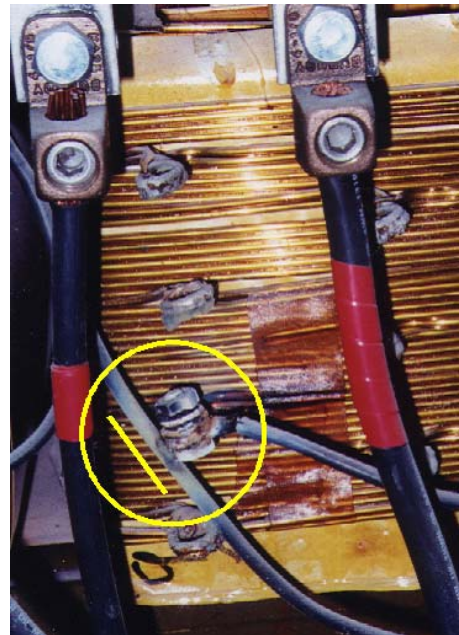
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Unbalanced Impedance

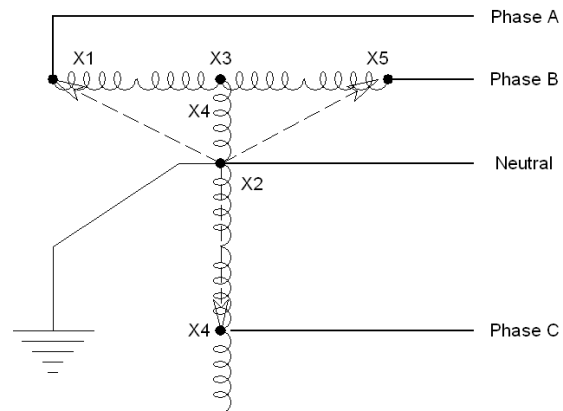
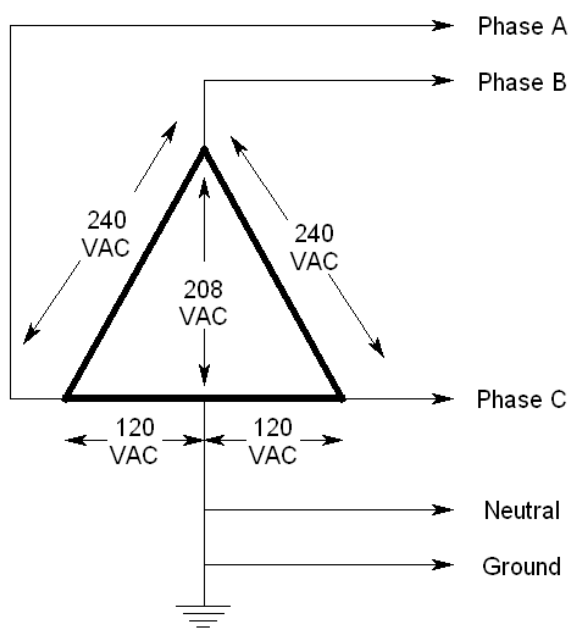
Mains impedance is typically balanced across the three phases. The voltage drop on any phase should be similar to that across other phases. When this is not the case, it's a certain sign of problems.

Most likely, an impedance imbalance points to a problem on one phase. Check for things like loose connections, corrosion, or conductors or devices damaged by overload or heating. In one noteworthy site visit, PowerLines found a loose transformer tap connection that was sure to cause a catastrophic failure (had it not been discovered and corrected) – the smoking gun that led to this problem being discovered was a measurement of the mains impedance.

Right: Mains impedance imbalance pointed the way to finding this loose transformer tap connection – the adjacent wire showing heat damage is a different phase, with 480 VAC potential to the tap it is touching.



One other situation can cause mains impedance imbalance. Unbalanced transformer secondary configurations (such as an Open Delta, a 240 VAC Delta connection with the center point of one leg grounded, or the exotic “Scott-Tee” transformer connection) will all produce imbalanced impedance measurements. Once these are identified, a careful study of the source characteristics and load requirements can help to determine if the unusual transformer connection is compatible with the load requirements.



Above: A Scott Tee transformer connection, used to connect a three-phase load to a two-phase source.

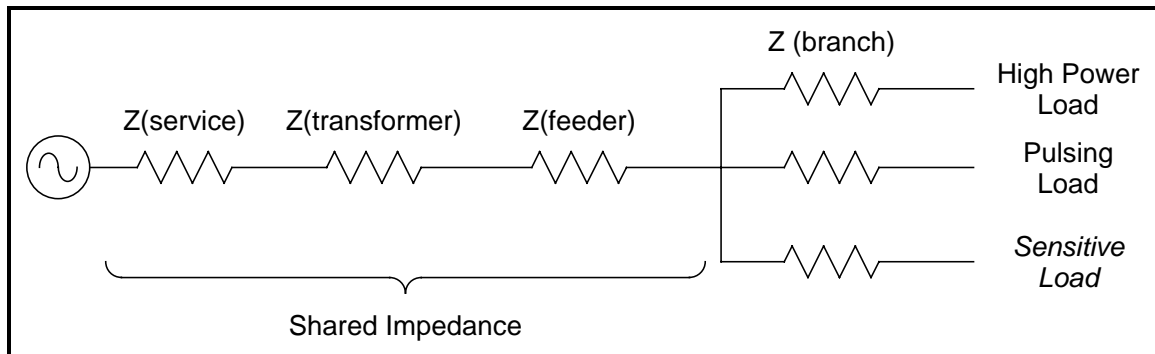
Left: A 240 VAC Delta transformer connection, with one phase center tapped to feed 240/120 VAC single-phase loads.

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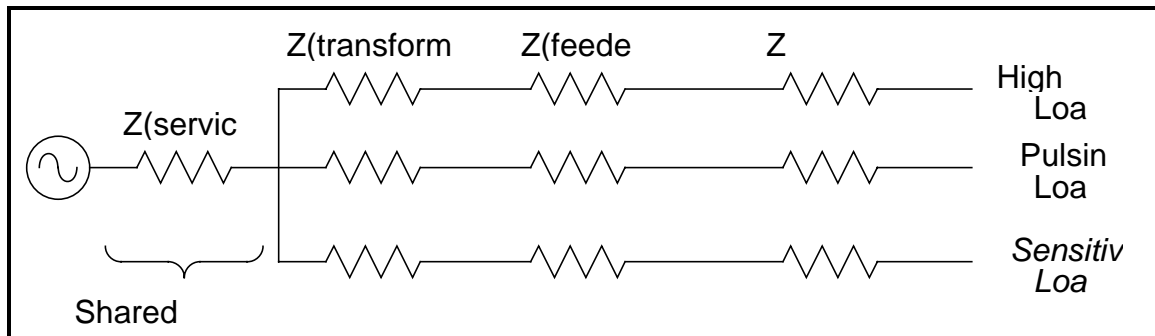
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Dedicated Lines

Specifying a dedicated line, kept separate from other loads, is often a technique used to optimize power quality. One way to consider a dedicated line is as an attempt to reduce or minimize *shared impedance*. In the drawing below voltage changes related to operation of the high power, or pulsing loads, could impact the power quality to the sensitive load.



By powering each device via a separate, or dedicated line, the shared impedance is reduced to only that of the service, and the likelihood of load-to-load interference is reduced.



Dedicated Lines: A Caveat

When working with dedicate lines, it is possible that impedance to a given load is actually *increased*. As an example, if a 30 Amp circuit is run 200 feet via a 200 Amp feeder to a distribution panel, and then an additional 50 feet (30 amp circuit), the impedance will be much lower than if the 30 Amp circuit were run the full 250 feet back to the service. In this case the power quality benefits of the dedicated line must be weighed against the higher mains impedance.

Acknowledgement: The author wishes to thank Alixe Cielo for proofreading and grammar checking this document.