The Undamped Nature of the Modern Power Distribution System

by **Seth Johnson**

DESPITE TECHNOLOGICAL ADVANCEMENTS THAT HAVE IMPROVED THE ENERGY EFFICIENCY OF CONNECTED LOADS, POWER CONSUMPTION IN COMMERCIAL AND INDUSTRIAL MARKETS HAS STEADILY INCREASED, WHICH IS ATTRIBUTED TO MANY FACTORS, WITH THE PRIMARY REASON BEING THE ELECTRIFICATION OF EVERYTHING.

Photo: Powerside

Power distribution systems have significantly evolved since their inception in the late 19th century. Their primary purpose was to provide lighting to homes and businesses. The first power distribution system was direct current (DC), later converted to alternating current (AC) due to transmission efficiency. This dates to the infamous "Battle of the Currents" between Thomas Edison and George Westinghouse. Who won? One could argue that the battle is ongoing, but this article will focus on AC for power distribution.

The evolution of the power distribution system for incandescent lighting to industry electrification has posed many challenges that power systems engineers continue to navigate carefully. Nearly everything used in the modern day is electrified. Electrification demands increased distribution capacity and significant integration challenges when looking at practical ways to generate and supply power to modern commercial, industrial, and residential consumers whose load profiles have drastically changed over the last 30 years.

IN 2023, RENEWABLE ENERGY RESOURCES IN THE UNITED STATES CONTRIBUTED TO 22.5% OF THE TOTAL POWER GENERATION[1]. NEARLY A QUARTER OF POWER GENERATION COMES FROM RENEWABLE RESOURCES, WHICH IS ONLY EXPECTED TO GROW.

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Consumers' Modern Connected Load Profile

Despite technological advancements that have improved the energy efficiency of connected loads, power consumption in commercial and industrial markets has steadily increased, which is attributed to many factors, with the primary reason being the electrification of everything. In conjunction with this are the numerous advancements in power electronics used in most modern-day connected loads. For example, LED lighting is known for being more efficient than traditional incandescent and fluorescent lights, but LED lights convert AC-to-DC through an LED driver. As with all non-linear loads, this conversion generates harmonic currents and injects them back into the AC power source. Harmonics are currents at multiples of the AC fundamental frequency, and a high percentage of most power system loads have this non-linear nature. Another example of a non-linear load is a motor controlled by a variable frequency drive (VFD). VFDs augment electric motors with rotational speed control but rely on AC-to-DC conversion. This process again introduces harmonic content back into the AC power feed. It can be definitively stated that most modern loads have become non-linear and inject harmonics back into the power distribution system.

Modern-day Power Generation

Power generation continues to change rapidly, with considerable initiatives aimed at decarbonization and green alternatives to traditional coal, natural gas, and nuclear power generation. Most notably, these initiatives target renewable power generation via wind, solar, and energy storage. In 2023, renewable energy resources in the United States contributed to 22.5% of the total power generation[1]. Nearly a quarter of power generation comes from renewable resources, which is only expected to grow.

Traditional power generation focuses on large rotating generators to

[1]*Lucía Fernández, Renewable Energy in the U.S. – statistics & facts*

produce high-inertia three-phase power transmitted and distributed across large areas, referred to as centralized power generation. This generation method is tried and true, and the foundation of our power system infrastructure. In today's modern approach to power generation, we are utilizing solar arrays and wind power at a massive scale to power distribution grids worldwide. These power generation assets are referred to as decentralized or distributed power generation, which involves many contributors to the power distribution system infrastructure.

Many renewable energy sources naturally generate DC power, which must be fed through inverters to bring power back to the AC power distribution system. Large-scale renewables require a host of inverters to generate the AC waveforms, which are then coupled back to the power distribution system. Like LED lighting or VFDs, the process of converting DC-to-AC, or AC-to-DC, relies on power electronics that create harmonic currents, which then get injected back into the power distribution system. Unfortunately, now we have a harmonic source for both consumption and power generation.

Resonance and Harmonics

Capacitance and inductance are key elements of the AC power distribution system.Capacitors maintain voltage and power factor, release capacity, and reduce losses. There are several ways capacitors are utilized, from substation to grid edge, and control methods match the tasks for which the capacitors are used. In many cases, these capacitors are fixed-on or controlled by a switching mechanism. Inductance presents itself in power distribution systems in conventional generation, overhead lines, cables, voltage regulators, and transformers. While each of these is not purely an inductor, they inherently have inductive reactance while being the most deployed assets in the power distribution system.

Resonance occurs in an electrical system when both inductance and capacitance are equal and in a shunt arrangement. The resonant point depends on the system and the location, but every AC power system has a resonance point. Historically, this resonant point had little consequence regardless of where it was in frequency. With the traditional power system relying on linear loads and power generation (lacking significant harmonic currents), the risk of exciting a resonance condition was minimal. However, in the modern power distribution system, this has changed significantly. Resonance conditions are excited regularly and intermittently depending upon the connection arrangements of power generation sources, capacitors, transformers, overhead lines, feeder cables, and many prolific non-linear loads. **Figure 1** shows an example of an actual 11^{th} harmonic resonance on a power distribution system. When a resonance occurs, high harmonic current and voltage levels are observed at the resonant frequency. For a resonant point to be excited, there must be both a resonant network and a harmonic source at that frequency.

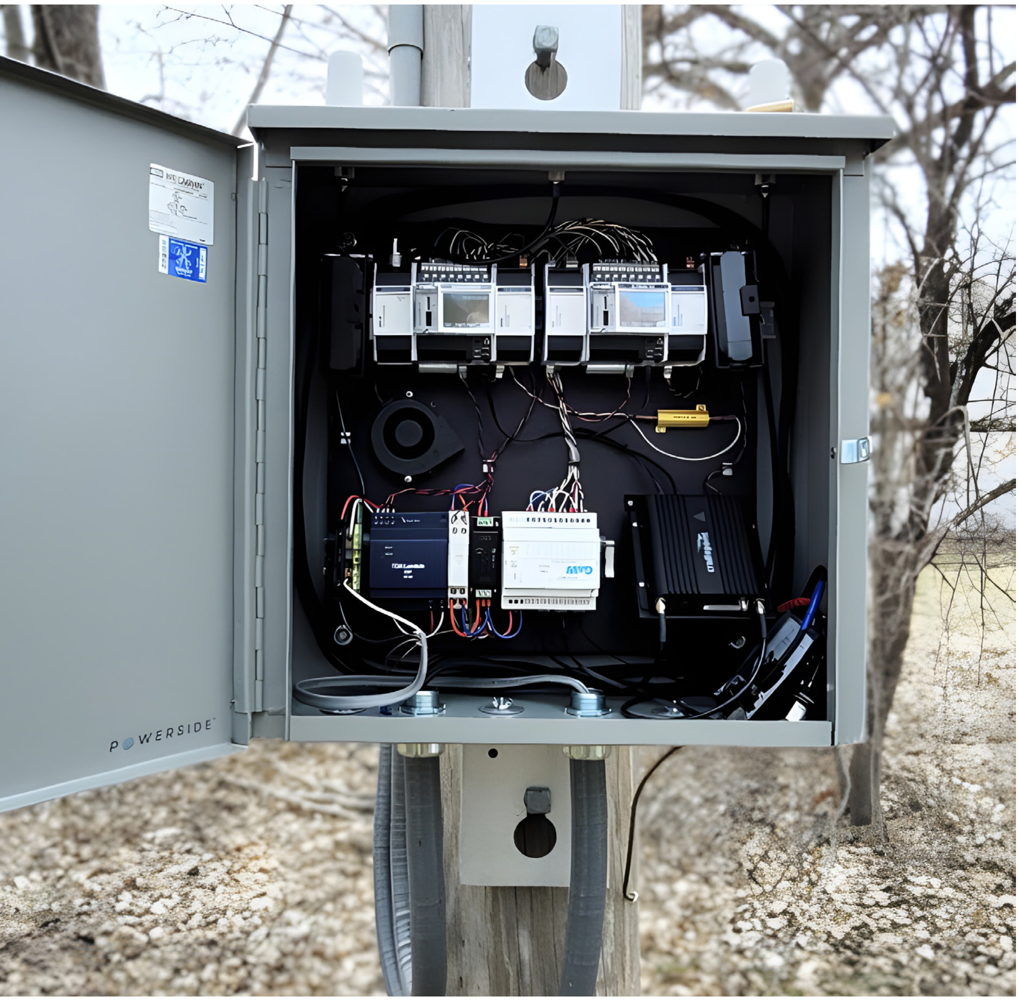

Photo: Powerside

Power Quality Analyzers

From our foregoing discussion, it is evident that the modern power distribution system needs dedicated monitoring via power quality analyzers deployed throughout the entire power distribution system. These devices need deployment at the substation through to the grid edge, and they are immediately required at renewable power generation sites and large primary fed power consumers. However, employing these devices is just the beginning. A platform that allows these high-fidelity analyzers to stream data and provide data analytics at a fleet level is the future of intelligent and effectual monitoring. Utility power providers often rely on feeder protection relays or voltage regulators to provide power quality data.

While these devices have some power quality capabilities, it is not their primary function. Power quality analyzers must be able to deliver thousands of trending data points with event-triggered waveform capture, harmonics detection at high frequencies, and ultra-fast transient detection. With these functions, power anomalies such as resonance conditions can easily be detected and categorized through a fleet management platform.

Dampening the Modern Power Distribution System

The traditional power distribution system, in which load profiles and power generation have vastly evolved, is vulnerable to power quality issues at an unprecedented level. Resonance is a significant concern for power providers and distribution engineers who lack adequate field data, primarily due to inadequate sensors and the intermittent nature of many resonant conditions.

Levels of capacitance and inductance locate the resonant point of an electrical system, but this resonant point also changes when the system impedance changes. Due to the various power generation sources, this happens frequently in the modern power distribution system. Ultimately, the resonant point can be a moving target with little visibility.

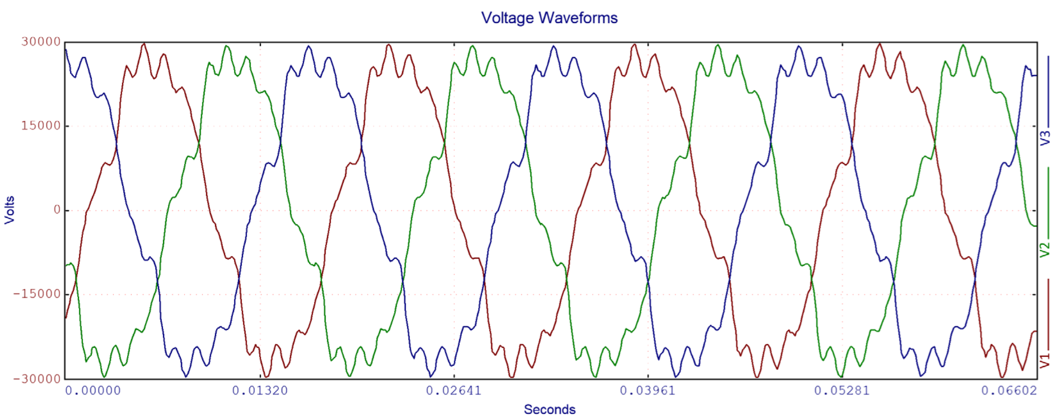

Figure 1.
11th harmonic resonance visible on voltage waveform.

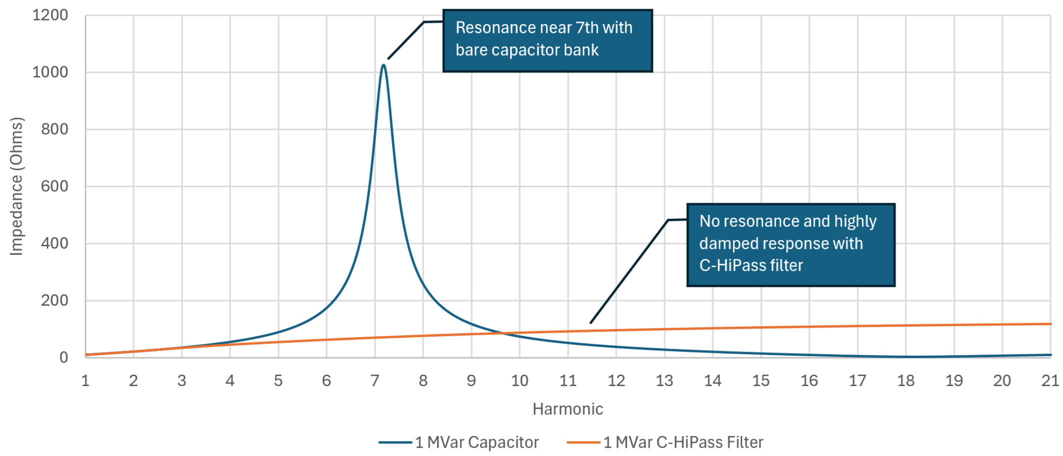

Figure 2.
Impedance vs. frequency for bare capacitor and C-HiPass Filter

One way to dampen an entire power distribution system is to avoid deploying capacitors and install filters instead. If appropriately sized, this will produce the same voltage stabilization and power factor correction that traditional capacitors provide. Moreover, a whole system deployment starting at the substation would be optimal. **Figure 2** shows the typical impedance scan of a system with a standard capacitor in an electrical network in blue and a C-HiPass Filter in orange.

IT IS EVIDENT THAT THE TRADITIONAL POWER DISTRIBUTION SYSTEM, IN WHICH LOAD PROFILES AND POWER GENERATION HAVE VASTLY EVOLVED, IS VULNERABLE TO POWER QUALITY ISSUES AT AN UNPRECEDENTED LEVEL. RESONANCE IS A SIGNIFICANT CONCERN FOR POWER PROVIDERS AND DISTRIBUTION ENGINEERS WHO LACK ADEQUATE FIELD DATA, PRIMARILY DUE TO INADEQUATE SENSORS AND THE INTERMITTENT NATURE OF MANY RESONANT CONDITIONS.

Photo: Shutterstock

Notice how the damped filter lacks resonance, preventing that condition from occurring. As a proposed network alternative, a large C-HiPass filter could be placed at the substation, and pole-mounted or pad-mounted capacitors could be replaced as more straightforward notch filters. Such a design would be specified to ideally dampen the power distribution system so that engineers would not have to consider resonant scenarios - the system is essentially protected for most conditions.
Of course, power providers still need their clients to abide by point-of-connection harmonic standards. However, if studies are done correctly at the engineering and design phase, deploying reactive power through filters can significantly limit the risk of harmonic-induced resonant events.