Energy Efficiency & Power Quality Series

Power Quality Basics:

Fixing Low Voltage & Undervoltage Problems

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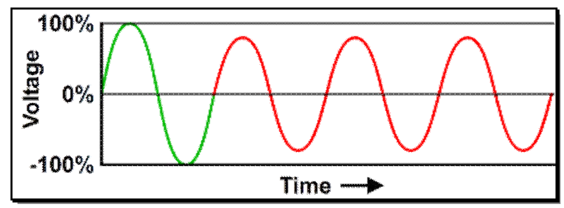
Fixing Low Voltage &Undervoltage Problems

Chronic low voltage levels are a common problem that can affect any electric customer. The causes of this power quality problem are relatively easy to identify but potential energy saving measures undertaken by the operators of the electric grid could make chronic low voltage levels a significant problem for many. This paper looks at causes, symptoms and solutions for chronic low voltage problems.

Chronic low voltage or undervoltage

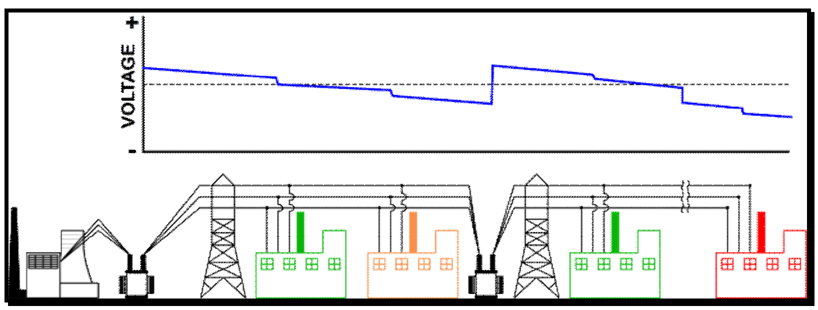
The term of art for chronic low voltage is "undervoltage" and undervoltage is defined as a voltage level 90% or less of the nominal voltage that exists for one minute or more. The key factor in this definition is that of the duration of one minute or more as this distinguishes undervoltage from shorter duration problems such as voltage sags.



Undervoltage – chronic low voltage

Causes of chronic low voltage – undervoltage

Undervoltage is most commonly attributable to reduced voltage levels on the utility's transmission and distribution system. In areas with low electrical load density, such as suburban and rural locations, voltage drop on electrical conductors is a significant issue. Conductor impedance driven by load demand serves to decrease the voltage along the length of a conductor. The electric utility uses on-load tap changing voltage regulators (OLTCs) at substations and line drop compensating voltage regulators (LDCs) along the length of a conductor to boost (raise) or buck (lower) voltage levels within a proper range for delivery to customers. Customers nearest to an OLTC or LDC will see the highest voltage levels while those farthest away will see the lowest voltage levels. As simply shown in the graphic above, location can play a significant role in voltage level as can the operational characteristics and reliability of OLTCs and LDCs.



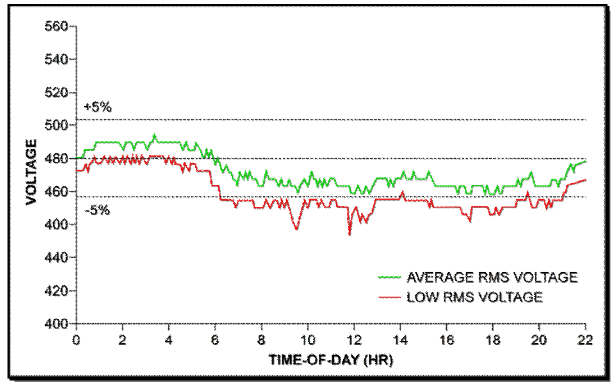
Voltage drop in utility lines

In many locations the impact of load-driven voltage drop is seen as daily fluctuations that result in voltage levels being the lowest at the time of peak load demand. Monday through Friday this typically occurs from the late morning through early afternoon when most work and educational activities take place. The daily voltage fluctuation becomes more severe when weather increases peak demand such as the air conditioning season in the U.S. If the peak demand for electricity starts to approach the maximum generating capacity, grid operators may intentionally reduce the voltage level of the grid up to 5% in order to maintain the margin between electricity demand and production. This intentional voltage reduction is frequently called a "brownout" however there is no strict definition for this term.

Another factor that may aggravate undervoltage problems is an energy saving concept known as conservation voltage reduction or "CVR". Proponents of CVR contend that a permanent 5 to 8% reduction in nominal grid voltage levels can achieve a 0.5 to 3% reduction in the amount of electricity that needs to be produced. The arguments against CVR include an increased susceptibility to voltage sag problems and the reduced efficiency of certain devices rated for higher voltage (e.g. motors).

The problem with low voltage - undervoltage

The manufacturer of an electrical device designs his product to operate at a certain standard voltage in order for the product to achieve specified levels of performance, efficiency, safety and reliability. Operating an electrical device near or outside the specified voltage level limitations can lead to problems such as malfunction, shut down, overheating, premature failure, etc. For example, an induction motor operating near its rated load on 90% of nameplate voltage can be expected to have its efficiency reduced 1 to 3%, have its operating temperature increased 10 to 15% and have its running torque reduced nearly 20%. In general, undervoltage tends to reduce electrical efficiency in many devices since lower voltage increases current flow which increases I^2R or "copper" losses.



Daily voltage fluctuation

Some of the more common symptoms of undervoltage include:

- Motors run hot than normal and fail prematurely
- Random equipment shut down due to voltage sags
- Batteries fail to recharge properly
- Dim incandescent lighting
- Hot and noisy equipment
- Unexplained malfunctions

Utility and utilization voltage levels

No discussion of undervoltage would be complete without an examination of the regulations and definitions concerning voltage levels. The first point to be noted is that there is no national (U.S.) standard for the voltage levels. Individual states usually point to ANSI standard C84 or some variation of the standard to define the voltage levels that must be supplied. ANSI C84 suggests that the voltage level normally supplied at a customer's meter (the "service voltage") should be within ±5% of the nominal voltage. However, the standard goes on to recognize that the voltage level may "infrequently" be -10% to +6% of nominal. No specific definition of "infrequently" is provided however the standard does say the utility-supplied voltage level may be worse than -10 to +6% for "brief" periods due to unexpected operational issues. And, this is not the end of the voltage level story.


Line drop compensating (LDC) voltage regulators (one per phase)

The ANSI C84 standard and other industry standards recognize that there will be an additional voltage drop with the customer's facility. This is most often assumed to be a voltage drop of 4% from the electric meter to the point where the electricity is consumed – the "utilization voltage". Many people wonder why motors are typically rated at 460 volts instead of 480 volts. The reason is that an assumption is made that 480 volts will be supplied at the meter and the voltage at the motor will be 4% less than 480 volts: that is 460 volts.

Most electrical equipment sold in North America is designed to accept a voltage range of ±10 of nameplate voltage. While that may seem to be a generous margin – it may not be enough in many cases. Let's say the voltage at the meter is 5% lower than nominal. Adding in the presumed 4% voltage drop within a customer's facility means the voltage level "seen" by an electrical device would be 9% below the nominal utility voltage level. This serves to highlight the need to consider the nameplate voltage and the voltage level limitations of electrical devices.

Fortunately, most electricity providers are pretty good at keeping voltage levels with the ±5% range – most of the time. However, even though electric utilities strive to do their best for everyone, reality dictates that not everyone can receive optimal voltage levels all of the time or even most of the time. Experience shows that complaints to the electric utility about low voltage levels most often result in a voltage level measurement by the utility and notification that the voltage level is "within specifications". This is the point when utility customers start to look for solutions for their undervoltage problems.

Substation transformer with on-load tap changing voltage regulator

Solutions for undervoltage

A natural question regarding the resolution of undervoltage problems might be, "Why not use what the utility uses?" The answer is that one certainly can try this; however it might not yield an acceptable solution. OLTCs and LDCs are designed for voltage regulation of bulk power and have some unique characteristics:

Requirement	Characteristic
Fine voltage regulation	Most OLTCs and LDCs use a 32 tap transformer with voltage each tap changing the voltage of 5/8%. This results in a maximum regulation range of ±10% of nominal.
Long maintenance intervals	Since OLTCs and LDCs are mechanical devices with servo-motors, mechanical linkages, brush-type contactors, etc., the number of operations is directly proportional to the maintenance requirements. To reduce maintenance costs, these devices incorporate controls to minimize the number of operations. Such controls often include operational delays ranging from seconds to minutes and adjustable voltage deadbands among others.
Correction speed	OLTCs and LDCs may a second or two to correct small voltage deviations up to 10 more seconds for large deviations. The utility purposes this is considered acceptable.
Small size and weatherproof enclosure	Oil is a very effective heat transfer medium very commonly used for cooling utility-grade electrical products. Oil helps to minimize product size and the use of weatherproof enclosures in high ambient temperature applications. However, oil-filled products are substantially more difficult and expensive to service than air-cooled devices.
Medium and high voltage application	Use at medium and high voltages minimizes the physical size of the devices for a given power level

OLTCs and LDCs are not considered power quality correction devices since they lack the performance to solve undervoltage problems required by most end users. Specifically, the slow speed of correction (measured in seconds) and the limited regulation range (±10%) are not sufficient to protect sensitive loads or to prevent them from malfunctioning or shutting down. Use of OLTCs and LDCs as power quality devices pose some additional complications: medium and high voltage hardware is usually considered the responsibility of the electric utility and such devices do not lend themselves to protection of small or individual low voltage devices within a facility.

The most common types of products used for correction of undervoltage are:

• Servomotor-controlled variable transformers	• Electronic tap switching voltage regulators
• Servo-mechanical tap switching voltage regulators	• Ferroresonant transformers
• Servo-mechanical induction voltage regulators	• Electronic double conversion voltage regulators

Sections of a variac showing round variable transformers and brushes

Servomotor-controlled variable transformers – These devices are sometimes referred to as "motor-driven variacs". The simplest version of a variable transformer has a continuous, circular winding along which brushes are moved to alter the turns ratio and thereby the output voltage. A control system monitors the output voltage and moves the brushes by actuating the servomotor until the desired voltage level is achieved. These units are generally available in single and three phase models from 100 VA to 50,000 VA. Larger sizes may be available. ***Pros*** – the servomotor-controlled variable transformer is a very simple and reliable device capable of voltage regulation to very high tolerances such as ±0.5%. Electrical efficiencies of 97 to 99% are typical. ***Cons*** – like all mechanical voltage regulators, the speed of correction may be too slow to support certain sensitive equipment. Frequent operation increases the maintenance requirements, however the simplicity of this product makes service much less of a problem compared to other mechanical voltage regulators. These devices may not be appropriate in applications with large, frequent voltage variations.

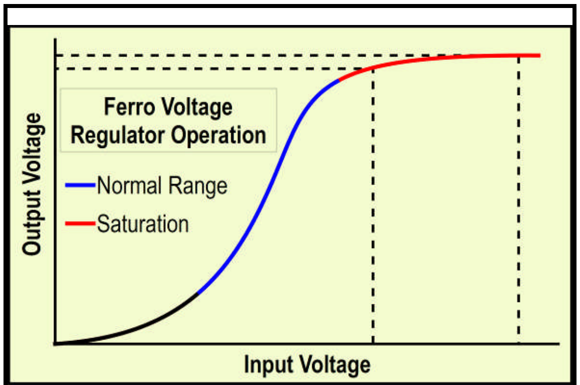
Servo-mechanical tap switching voltage regulators – These devices are very similar to OLTC and LDC except that they: 1) are designed for low voltage (<1,000 volts), 2) are air-cooled rather than oil-filled, and 3) typically have a much larger voltage regulation range (±20% to ±25%). The servo-mechanical tap switching voltage regulator uses servomotors to drive a mechanical system to position brushes on a particular tap to control the output voltage. These units are generally available in single and three phase models from 3,000 VA to 1,000,000 VA and larger. ***Pros*** – the simple technology and low component cost make these devices readily available at relatively low cost worldwide. Unlike OLTCs and LDCs, these devices can easily be placed indoors and sized and configured for the protection of individual loads. Electrical efficiencies of 96 to 99% are typical. ***Cons*** – like other mechanical voltage regulators, the slow speed of correction (0.3 to 4+ seconds) and potentially high maintenance requirements are the main drawbacks. In less expensive designs there may also a question about the device producing output voltages so high as to be harmful to the load when the device is energized or suffers a drive malfunction. Caution is advised when applying these devices in applications with large, frequent voltage variations.

Servo-mechanical induction voltage regulators – This type of voltage regulator is quite unique in that it adjusts voltage by changing the orientation of the magnetic flux between the primary and secondary of the transformer rather by changing the turns ratio like tap switching and variable transformers. Looking somewhat like a typical induction motor, the servomotor in the unit simply turns the rotor within the stator through something less than 360° in order to alter the flux field thus altering the output voltage. These units are generally available in single and three phase models from 10,000 VA to about 500,000 VA. ***Pros*** – theoretically, the servo-mechanical induction voltage regulator offers a continuum of possible output voltages since it does not rely on taps set at fixed ratios. Unlike other mechanical voltage regulators, this device uses no brushes which should eliminate some of the problems associated with brushes like wear, maintenance and arcing.
Electrical efficiencies of 96 to 98% are typical. ***Cons*** – with its advantages, this is still a very mechanical device requiring servomotors and drive systems to move the rotor. As the unit's power rating increases, the amount of mass that has to be moved also increases and the speed of correction decreases. Larger sizes require large rotor bearings to accommodate the higher rotor weight: which can make service much more technically challenging.

Electronic tap switching voltage regulators – As the name implies, these all solid state devices switch taps to change output voltage but eliminate the slow speed and maintenance problems of mechanical by using power semiconductors to do the switching. Voltage corrections with these devices take place in about one electrical cycle (0.016 seconds) and are done non-sequentially: changing from one tap to another tap while bypassing the taps in between. These units are generally available in single and three phase models from 5,000 VA to about 2,000,000 VA. ***Pros*** – the correction speed of these devices makes them the device of choice to protect sensitive electronic and electrical loads. They are also ideal for applications with large and/or frequent voltage fluctuations since there are no moving parts to wear out. Electrical efficiencies of 97 to 99% are typical. ***Cons*** – the switching power semiconductors used in electronic tap switching voltage regulators can be very susceptible to the failure when used with certain types of loads: large inrush current, poor power factor, frequent overload, small minimum load, etc. Industrial-grade electronic tap switching voltage regulators eliminate all of the concerns about the weakness of the power semiconductors and can be easily applied almost anywhere.

Controls and electronic switches in an electronic tap switching voltage regulator

Ferroresonant transformers – This is the grandfather of voltage regulators having been designed in the 1930s. Little changed from the original design, these devices continue to see widespread application. The ferro takes advantage of a unique characteristic of transformers: when operated in the saturation region, a large change in the input voltage results in a small change in the flux density and therefore the output voltage. Ferroresonant transformers have no moving parts, fast correction speed and modern designs incorporate a tuned circuit to remove objectionable harmonics that can be produced by operation in the saturation region. These devices are only for single phase application in sizes from 100 VA to 20,000 VA. ***Pros*** – these units are very durable and may offer very long warranties. They are also effective at current limiting since they basically turn into a choke should the current exceed more than 150 to 200% of rated current. ***Cons*** – ferroresonant transformers may be best known for two characteristics – being incredibly noisy and hot – because they are very inefficient. Manufacturers often claim efficiency "up to" 90% or more but in actual practice it is frequently less than 85%. The current limiting capability that is a benefit in certain applications becomes a liability in high inrush current applications and results in the device needing to be sized much larger than the load and further reducing its electrical efficiency.



Ferroresonant transformer operation occurs in the saturation region

Ferroresonant transformer with capacitors for tuning circuit

Electronic double conversion voltage regulators – These devices are similar too or may actually be a UPS (uninterruptible power supply) without batteries. The incoming AC power is converted to DC and then converted back to AC. During the process of re-creating the AC power from DC, voltage, frequency and other characteristics of the output power can be very precisely manipulated: for example, converting 480 volt, 60 Hz to 380 volt, 50 Hz. The typical UPS is used to supply power from its batteries during a power interruption and provide voltage regulation when utility power is available but some models are marketed as voltage regulators when sold without batteries. These units are generally available in three phase models from 10,000 VA to about 200,000 VA. ***Pros*** – the double conversion process provides good voltage regulation with fast correction speed. The potential to add batteries and regulate output frequency are capabilities not found in other voltage regulators. ***Cons*** – a double conversion UPS with or without batteries must often be sized much larger than the load in order to handle load inrush current. The double conversion process (AC-DC, DC-AC) by its nature is relatively inefficient. Low inherent efficiency combined with low load factor due to over-sizing requirements can result in real-world efficiencies of 85% or less. Voltage regulating performance can be different between the same unit when used with and without batteries since the lack of battery power to stabilize the DC bus can compromise voltage regulation and unit performance.

500 kVA UPS w/o batteries

UPS battery racks

Utility Systems Technologies, Inc. is the leading manufactures of industrial-grade power conditioning products for voltage regulation, power conditioning and voltage sag protection. As a leader in the field of "green" power quality, all UST products have the highest performance and efficiencies available.