

POWER QUALITY ISSUES AT UTILITIES SERVING RURAL AREAS AND SMALLER TOWNS

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ABSTRACT

Many small and medium size industries and very large farming operations move into rural areas and small towns equipped with the latest technologies in motor drives, power electronics for process control, welding apparatus, etc. They generate non-linear loads and create unique power quality problems. The fairly low capacity medium voltage substations serving these loads also aggravate these problems. Numerous complaints about light flicker, poor voltages, early equipment failures are on the rise and in many instances it requires good electric detective work to determine the source or main culprit of the power quality problem.

A data acquisition tool with specially designed multifunctional application software was successfully used by the authors in the field investigation to identify the causes of the problems mentioned above. A brief description of the functional capabilities of the data acquisition unit will be presented.

*Some important case studies and a listing of commonly encountered problems will also be presented in the paper. Some hidden **problems** will also be identified. Suggestions to improve existing power quality standards, definitions of tolerable limits, test laboratories, etc. will also be discussed.*

GENERAL INTRODUCTION AND ASSESSMENT OF POWER QUALITY ISSUES

Several years of investigative work at hundreds of sites at many electric utilities reveal a multitude of problems, which can be classified as power quality problems. They can be broadly divided into several categories.

- Problems generated by the electric utility causing problems at the customers' premises.
- Problems generated by a customer causing problems to other customers.
- Problems generated by a customer causing problems to his own equipment.

On the electric utility side many of the problems seemed to be related to voltage regulation, capacitor banks placements and sizings, line design, transformer sizings, etc. The electric utility is assumed to generate 60 Hz power with some uneven harmonic components due to transformer magnetizing currents only.

At the customer's side most of the problems are generated by electric welders, rectifiers and variable speed drives, switching power supplies, motors and motor starters, broken or poorly connected equipment, heavy unbalance loading, inadequately designed low voltage network, etc.

The natures of the problems are voltage distortions, transients, voltage sag or swell and voltage unbalance. On many occasions customers blame the utility or another customer for the cause of their problems.

During the past 15 years, a dramatic increase in problems caused by high harmonics was observed and seems to be worsening as time goes on. Thus far we only see the tip of the iceberg.

In the newly deregulated environment, the mandatory requirement to serve a load to a customer inside the utilities' service territory is slowly disappearing. Instead, the retail wheeling concept allows utilities and customers to sell and buy power based on competitive pricing like any other commodities.

Utilities are also thinking of imposing limits of voltage distortions that customers' loads generate. The customer will be responsible for improving their load power factor. In order to survive, electric utilities have to improve customer services. If at one time the utilities served the role of reliable power provider only, new types of appliances and equipment generating new types of electric phenomena literally force the utility to expand customer services into areas that they are not too comfortable with. Also unique for the smaller utilities serving smaller towns and rural areas is the explosive growth of small to medium size industries and commercial institutions in their service territories. To meet the increased demand it is necessary to upgrade the distribution network.

To avoid finger pointing when a problem arises, it is necessary to identify the source and the cause of the problem and who is suffering from the problem. This requires a certain degree of expertise and the availability of monitoring and analytical tools that are easy to operate. Upgrading of substations, the distribution network and operating tools are unavoidable and costly. This burden has to be shared with the customers. Will the customer accept this without improvements in services?

There is also a strong need for more comprehensive standards for power quality that utility engineers can utilize directly. Harmonic pollution limits have to be defined which can be used to implement operating policies such as penalizing the customer that generates the pollution, sharing the costs of installation upgrades, consulting, etc.

TYPICAL POWER QUALITY PROBLEMS AND CASE STUDIES

Several cases of power quality problems are listed below and some detailed case studies are also presented in later chapters. These actual cases illustrate the confusions and misconceptions that typically occurred when customers experienced problems.

A cookie baking company has microprocessor based process control equipment that kept aborting its operation. The initial suspicion was that the utilities' feeder conductors and transformer size are not adequate to handle the load and leading to occasional short-term voltage sags. A more in depth investigation showed something different. The transmission substation that belongs to the investor owned utility from which the smaller utility buys power, had many instantaneous circuit breaker trippings and reclosings. During a period of one month 11 of such operations were detected. The solution was to switch the feeder to another source.

At a cooperative farm maintenance office building the complaint was that once the fluorescent lights go out it is very difficult to restart the lights again. The first thought in peoples' minds was that there was a power quality problem. It turned out that the old fluorescent lights had been replaced by new quick start ones. But the old style ballast was not replaced.

At a manufacturing plant voltage unbalance was observed. The distribution transformer tap setting was low and to boost the low voltage, a three-phase autotransformer was used. One phase was used to supply power to the adjacent main office. The load at the office was large enough to cause unbalance at the plant. Because of the unbalance, motor starting times were longer causing visible nuisance light flickers.

A new motel repeatedly experienced damage to the window cooling and heating units of the individual rooms. The story we received seemed to give the impression that many of the window units were destroyed. The electric utility was blamed for the cause of the problems by not providing overvoltage protection. A careful investigation revealed that the extent of the damage was only at the electronic control board. The electronic circuitry does not have any surge protection. Each time the window unit was repaired, the same type of electronic control board was used for replacement. Hence the same type of problems keep on recurring.

These few examples clearly show that in some cases what is perceived as a power quality problem may have nothing to do with power quality supplied by the utility. Yet it is also necessary to perform a field investigation to determine the cause of the problem and thereby eliminate finger pointing.

This leads to the subject of instrumentation for measurement and monitoring [3]. Most data acquisition units available in the market are expensive and in many cases highly specialized in terms of their functionality and quite often require a high degree of expertise to operate. In order to do site investigation, the data acquisition should be easy to operate and without too much typing of specific commands or looking into multilevel menus. It should be capable to do a quick assessment about the quality of power. The ability to do long-term monitoring is also necessary. Also, anyone should be able to use a set of simple instructions to collect specific data that lends itself for detailed analysis by an expert. The device has to be a multi-channel voltage and current measuring unit, a device for very short-term and long-term monitoring and also capable to take large amounts of raw data for detailed analysis. Supporting software tools, easily expandable and flexible for on site analysis and report generation should be an integral part of the device. Advantage Engineering practically has to design its own unique data acquisition unit to facilitate the field investigation that covers a very broad range of types of problems.

The next chapter presents several interesting field studies in greater details.

CASE STUDIES

A Case of Tree Trimming

A medium power television station recently suffered occasional outages. The engineer in charge of the television station blamed a farm equipment repair shop as the main culprit of the outages. This repair shop is fed from the same medium voltage feeder as the television station and is located about one mile away from the station. After our investigation, the following was found:

- A single-phase undervoltage relay at the television station was connected to phase V_{AN} only.
- An interview with the television engineer revealed that the undervoltage relay tripped during periods of high winds preceding a thunderstorm.
- The outage periods had no correlation with the working hours of the repair shop.
- Studying the voltage waveform and its harmonic content at the electric service entrance point of the repair shop revealed nothing unusual that can cause power quality problems.

After patrolling the feeder it was found that phase V_{AN} was very close to the branches of several poplar trees. A wind

gust can easily cause the branches to whiplash and touch the feeder conductor of phase V_{AN} . The solution was for the utility to do tree trimming. It was recommended to increase the undervoltage relay time delay by a small amount.

A Case of Voltage Distortion, Swell and Sag

The medium voltage network of a small town is served by a 34.5 kV subtransmission line. During working day hours, fluorescent lights flickered, speed variations of cooling fans of computers and electronic devices emitted very low frequency audio noises, some uninterrupting power supplies for banks of computers switched in and out, etc.

A harmonic analysis performed on the voltage waveforms at different locations in town revealed a slight increase of the 5th harmonic compared to what one normally observed. The Total Harmonic Distortion was well below the norm of 2.5% [1]. The RMS voltage monitoring device did not indicate swell or sag of the voltage beyond the normally tolerated range. The first assessment of the situation was that somewhere in the network, a sequence of short duration nonlinear loads might be the culprit.

A data acquisition unit was used to collect voltage data at a sampling rate of 25 kHz at the moment when light flicker was observed. To extract burst type phenomena from the voltage waveform a type of comb filter was applied to the voltage sampled data. The filter equation is as follows:

$$R(j) = S(j) - S(j + mN) \quad (1)$$

- $S(j)$ is the j^{th} sample point of the voltage.
- $S(j + mN)$ is the $(j + mN)^{\text{th}}$ sample point of the voltage.
- M is an integer.
- N is the equivalent of a period of the fundamental of the voltage waveform.
- $R(j)$ is the residue.

The residue obtained by choosing $m = 4$ by sweeping the values of j between 1 and a few hundred thousands were quite revealing. Sampled set of values for the residue in relation to the voltage waveform is shown in Figure 1. The comb filter filters out the steady state fundamental harmonic and all its integer multiples and the dc component of the voltage. A short duration swell of the voltage and all kinds of transient spikes are visible on the lower waveform in Figure 1. The upper waveform shows some non-integer harmonics and transient spikes. A plot of the variations of the RMS voltage on a cycle by cycle basis using equation (2) and simultaneously plotting the peak voltage using the same time scale is shown in Figure 2.

$$V_{RMS} = \frac{1}{T} \int_0^T v(t)^2 dt \quad (2)$$

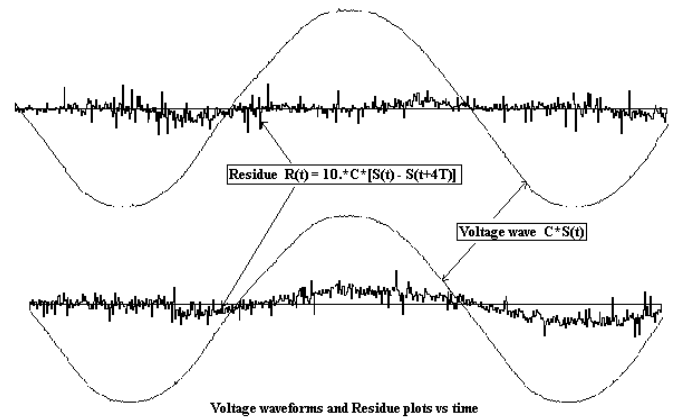


Figure 1

While the peak values vary quite a bit, the RMS values of the voltage seem to be constant. A hump visible on the peak value plot lasted close to 0.75 seconds. The short transients are caused by an interruption of arcs. The non-integer harmonics are in general transient oscillations and is a network response to load discontinuities. It was also observed that sag and swell of the voltage occurred lasting for a few cycles only. This type of phenomena indicated that a limited short circuit has occurred.

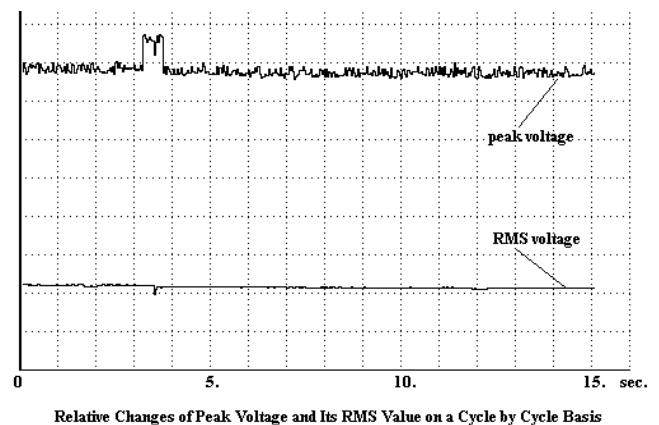


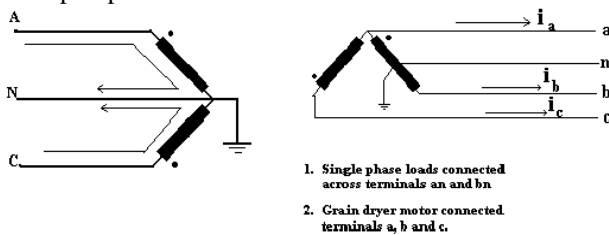
Figure 2

Taking all this combination of observed phenomena, the type of load had to have a lot of arcing followed by limited short-circuits. The conclusion was that an electric welding plant generated all the perturbations on the voltage waveform.

Later verifications indeed proved that it was a medium size manufacturing plant that operated a number of large electric welding equipment. This plant was served directly by the 34.5 kV subtransmission that also provided power to the small town.

A Case of Unbalanced Voltages

To save on conductors, some branches of the medium voltage distribution circuits use only two phase wires and a neutral. Figure 3 shows the step-down transformer to the service level voltage. It uses an Open Y - Open Delta configuration. One of the Open Delta windings has a grounded center tap connected to a grounded neutral wire. The line to line voltage has a nominal voltage of 240 V and the line to neutral voltages are 120 V and is primarily intended for light single-phase loads. This particular configuration is adequate for serving moderate size farming operations where 3 phase motors are used for blowers and small pumps.



OPEN - WYE CONNECTION

Figure 3

The situation that was encountered occurred at a farm that throughout the years has grown from a relatively small operation into a fair size farming business. The repeated complaint was that some of the fairly large grain drying blower motors kept tripping the breaker after starting. An electrician decided to change the setting of the thermal trip delay by increasing it an additional 20 Amps. The time delay before the breaker tripped was indeed increased but it did not really solve the problem. A conducted field investigation revealed that fairly large single phase heating loads are connected to the 120 V sources and causes large voltage drops in one of the transformer windings. Voltage measurements showed that $V_{AB} = 232$ V, $V_{BC} = 237$ V and $V_{CA} = 169$ V. The phasor diagram is depicted below in Figure 4.

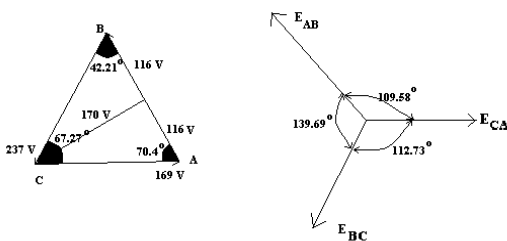


FIG. 2

Unbalance Phasor Diagram
Figure 4

The degree of unbalance can be calculated using the following formula (3) where $x = V_{AB}/V_{CA}$ and $y = V_{BC}/V_{CA}$. By inserting the values of the measured line to line voltages into the equation, the ratio of the negative sequence voltage with respect to the positive sequence voltage is found to be equal to about 20 % [7]. This unbalance generates negative

sequence fields rotating at twice the positive sequence rotational speed in the opposite direction. It not only creates negative torques, which increases the slip, but it also generates additional motor heating of the iron. Because of the increase of slip, the induction motor operating current increases and this may be the cause of thermal tripping of the motor breaker.

$$\left| \frac{V_2}{V_1} \right| = \sqrt{\frac{\frac{1+x^2+y^2}{6} - \sqrt{\frac{(1+x+y)(x+y-1)(1+y-x)(1+x-y)}{12}}}{\frac{1+x^2+y^2}{6} + \sqrt{\frac{(1+x+y)(x+y-1)(1+y-x)(1+x-y)}{12}}}} \quad (3)$$

The obvious solution is to balance the voltages by balancing the loads and to meet the required demand; the 2 phase medium voltage branch circuit has to be upgraded to a 3 phase branch circuit. At the same time all large single-phase loads have to be distributed over all three phases.

The Forgotten Capacitor Bank.

A medium voltage feeder serving a mix of residential and industrial customers has several capacitor banks along the feeder, not only for power factor correction but also for voltage control. It was hoped that by maintaining good voltages along the feeder there will be an increase of revenue. The capacitors were sized for summer loading when the load was high. The intention was to switch out some of the capacitor banks selectively during the fall when the load is much lighter. For some reason, all the capacitors remained connected when the fall season arrived. The line voltage went up to almost the allowed upper limit and caused all the distribution transformers on the feeder to go into the saturation region. The net effect was to cause all the uneven harmonics to increase. The additional voltage drop due to the high harmonic currents were sufficient to cause the feeder voltage to be heavily distorted. High precision motor drives that relied on accurate determination of the thyristor firing angles started to show erratic speeds. Many of the precision motor drives do not use the actual angle measured from the actual voltage zero crossing to determine the thyristor firing angle. Instead, it uses the voltage threshold level based on a pure 60 Hz sine wave to infer the firing angle magnitude. Referring to Figure 5 for illustration, the angular correction $\alpha^\circ = \arcsin(\Delta V)$. For an angular setting of δ° the actual thyristor firing angle is $(\alpha^\circ + \delta^\circ)$. If the voltage is distorted then an error creeps in. The angular correction α° is now smaller. The harmonic distortion of the fundamental wave shifts the calculated angle with respect to the true voltage zero crossing and hence creates an error in angle measurements.

The obvious solution was to switch off some of the capacitor banks.

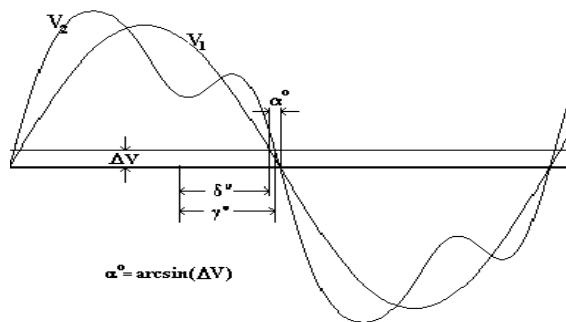


Figure 5

THE HIDDEN PROBLEMS

Accuracy of Energy Metering

Many papers have been written on the effects of harmonic distortion on energy metering. Even though the power quality standards tried to define the limits of distortion, there is still a need to standardize distortions for both currents and voltages, which can be used to calibrate energy meters. [4-6] There is a massive number of literature discussing this matter which is impossible to list in this paper. A few relevant ones are listed in the REFERENCE section.

This problem is becoming more acute with the influx of personal desk computers, quick start fluorescent lamps, energy saving lamps and thyristor controlled variable speed drives. They all generate non-linear load currents. In many cases the distorted load currents are large enough to cause voltage distortions at the metering points. Some of the smaller utilities are not aware about these customer generated power quality problems, especially if they do not cause problems to other customers. The loss of revenue due to errors in revenue metering is even less known. Even if the electric utility is aware about this problem, there is no place it can turn to for help in calibrating the meters for distorted waveforms.

Unbalance voltages

Unbalance in 3-phase systems not only causes problems with 3-phase rotating machines, but also with reactive power metering. A shortening of motor life due to operation under unbalance voltage conditions maybe more prevalent than what one dares to admit. Unfortunately no statistical data are available which correlates motor life to the degree of unbalance of the voltages. Combined with lower voltages, the problem becomes even worst. In areas with explosive growths, sometimes load growth was not followed by improvements of the distribution network. A changeover from a two-phase plus neutral to a three-phase system on the heavily loaded laterals are expensive. Each load site also requires an additional transformer and load balancing. It requires time to implement, not only by the electric utility but also by the energy user.

Effects of Harmonics

The effects of harmonics on motors/generators, transformers, power cables, capacitors, electronic equipment, metering, etc. are well documented. IEEE Std 519-1992 describes in general the harmful effects of these harmonics on the equipment. [1]. It also recommends practices for harmonic control and also set some limiting values for the harmonics not to exceed. Unfortunately no good standards of distortion for voltages, currents and phase angles commonly agreed to be used for calibration of different types of metering devices, for assessing incremental temperature rise in motors, etc. are available at this moment.

Some commercial customers and the electric utility serving these customers were not aware that harmonics were generated by the customers' equipment themselves. These harmonics also cause damage to other equipment. An example was that of a high power television transmitter station. The transmitter tubes requires rectified dc voltages. The filter that came with the high voltage 6 phase rectifiers was never installed because it was deemed unnecessary by the installer of the television station. The distorted ac voltages were also used to operate the cooling pump motors and according to the station engineer, these pump motors have to be replaced after several months of operation. As a matter of fact he has several of these motors in stock for quick replacements of the damaged motors.

The accuracy of the energy metering was also questionable and the electric utility remained unaware about some revenue losses due to customer generated harmonics.

STANDARDS ISSUE

One of the most commonly encountered problems is the lack of standards on how much distortion a device can generate under operating conditions. A single equipment installed in a plant may cause insignificant amount of distortion. But when many of them are installed and in operation, the net total effects can be a problem for the plant and the individual device itself. The electric utility is only concerned about spillover effects that will harm other customers. If spillover is detected, it is difficult to get a measure of damage it may cause. It is even more difficult to express the damage in terms of dollars, especially when there is a need to institute a policy of penalizing the customer, which is the source of the harmonic pollution.

The incremental losses in the system due to harmonics, the loss in revenue, the reduced life of certain equipment, etc. though written about extensively in many professional magazines cannot be quantified and available methods remain elusive.

The currently available standards, excellent as they are in their own rights, are difficult to read and understand by most practicing engineers at the smaller utilities. What

makes matters worse is the fact that the available power quality monitoring devices seemed to be designed for experts only.

There are no off the shelf energy meters that provide correction factors when operated under distorted voltage and current conditions. This is due to the fact that no standard for distortions exists that are accepted by the industry. Hence calibration standards cannot be started.

CONCLUSIONS

Our findings tell us that power quality problems are on the increase. We have indicated the variety of causes that lead to power quality problems. Some of them lend themselves to quick and low cost fixes. Others involve heavy capital investments by the electric utility as well as by the energy user. The electrical power industry may have to start something similar to Environmental Protection Agency in the USA. Policies have to be based on good and comprehensive standards defining limits of allowed unbalance and harmonic pollution. Also a method has to be devised for policing compliance and a measure for penalizing the guilty party needs to be developed. There may be also a need for some type of arbitration board to resolve the finger pointing issues.

Revenue metering is also affected by voltage and current distortions. Standards and calibration laboratories have to be developed for calibration of revenue meters.

There is also a need for life testing standards for equipment subjected to three phase unbalance voltages and voltage distortions.

Because of the highly competitive environment that deregulation has caused, the electric utilities are not only electric power providers but they also have to become service providers.

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