

# Power Quality for Water Treatment Plants

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## ABSTRACT

Power quality issues are pervasive throughout most industries. They can cause premature equipment failure and increase energy losses. This paper presents the power quality issues to a public of diversified technical background. The intention is to remove some of the mystery surrounding the subject. I used concepts familiar to water treatment plant personnel to explain electrical concepts. This paper includes a simple survey to identify potential power quality problems. The information gathered by the plant personnel will be useful to decide if further investigation is needed. The last section describes the usual correction methods used in the industry, identifying their strength and weaknesses. With this information, the plant personnel should be in a better position to evaluate their cost versus benefits and communicate with the experts in the field. This paper is not intended to provide all the answers to power quality issues but should provide the readers with a base to build on.

## INTRODUCTION

Power quality issues are pervasive throughout most industries. They are not always easy to recognize because their symptoms and intensity vary widely. Most plants have some power quality problems. Unless the plant is experiencing extreme problems, it may be difficult for the manager to justify mandating a power quality expert to perform a full survey. This is why I designed a simple survey to identify potential power quality problems. Plant personnel with basic electrical equipment knowledge can conduct this survey. The result cannot guaranty a full coverage of the plant electrical systems, but the information gathered will be useful in deciding if further investigation is needed. The survey consists of tables listing typical equipment found in water treatment plants. The technician records the equipment capacity and uses the multiplier provided to evaluate its effect on the plant power quality.

I also discuss solutions for typical power quality issues, identifying their strengths and weaknesses. The intent is to help the plant personnel identify the corrections needed and to improve communication with the power quality experts.

## POWER QUALITY PROBLEMS

### Typical symptoms of power quality issues

The typical symptoms of power quality issues include: light flickering, transformer overheating, false tripping of breakers, motor protection tripping, premature lighting ballast failures, premature power supply failures, computers and PLC malfunction, capacitor bank failures, neutral wire overheating, large neutral to ground voltage, false readings of instruments, electro-corrosion of piping and structures. I hope that your plant is not experiencing them all...

### Water treatment specifics

The typical water treatment plants electrical load profile is different from most industries in that two or three major loads consume the majority of the electrical power. The rest of the electrical service has a small effect on the electrical consumption. The flow of electricity in your plant wiring is similar to the flow of water in an aqueduct. The few big water-consuming factories represent a large part of the aqueduct flow and have a very large effect on the system pressure. Similarly, the few major electrical loads in the plant are likely to govern the power quality.

The operation of emergency power supplies such as UPS and/or diesel generators tend to magnify the effects of power quality issues and should be evaluated independently. Emergency power supplies have less capacity than the electrical utility. They are similar to using smaller pumps to feed your aqueduct. Changing the water flow has more effect on the pressure.

## Terms used in power quality

**The line voltage** is the force that pushes the current through the load. It is equivalent to the pressure in a water line. The power utility is equivalent to the pump that creates the water pressure. The higher voltages (pressure) need thicker cable insulation (pipe wall thickness). High voltages like high pressures are dangerous. A 200 bar (3000 PSI) water line can be very dangerous, so is a 2400 Volt electrical feeder. This contrasts with the 4 bar (60 PSI) water hose are commonly used for plant service and can be handled safely, just like a 120 Volt extension cord.

**The line current** is the quantity of electrons (electrical charges) that flows through the load each second. It is equivalent to the flow of water. The power utility connection is equivalent to the plant main water feed. The higher current requires a larger conductor (similar to pipe diameter).

**The apparent power** is the current times the voltage. This is the concept normally used to size equipment. It is the capacity used whether the energy is consumed or not. Apparent power is measured in kilo volt-ampere (KVA) or in mega volt-ampere (MVA). The water circuit analog of the apparent power is the size of a pump used to generate a pressure of and a water flow. The pump capacity has to be bigger or equal to the water flow or the pressure that you need.

**The real power** is the net amount of energy consumed. This is the quantity that the power utility writes on its invoice. On a load with a perfect power factor, it is the product of the current and the voltage. It is measured in kilowatts (KW) or in megawatts (MW). As for the water equivalent, if the apparent power is the size of the pump, the real power is the pressure times the water flow actually consumed. The real power is always smaller (seldom equal) to the apparent power similar to a pump that always works at less than its full capacity.

**The power factor** quantifies how much of the energy flowing in a load is being consumed. The rest is returned to the utility company. Since the utility company only charges for the net energy consumption they do not like low power factors. A low power factor means that the load returns a good part of the energy that flows through it. Low power factor is similar to a customer that continually returns a good fraction of his purchases to the store for credit. It adds operation costs to the store. This is why the power utility imposes penalties if your plant power factor is too low. The power factor is measured using a power meter. It is the ratio of the real power consumed to the apparent power. It is given in percentage or in a 0 to +/-1 range. By convention, most loads have a positive power factor but capacitors have a negative power factor. This is why capacitor banks are often used to correct low power factor loads.

**Harmonics** are distortions on the electrical current. They are equivalent to vibrations of water pipes. A small amount is acceptable but too much will eventually damage something. The vibration frequencies that match the resonance frequencies of the pipes will be more damaging than the others. The same concept applies to electrical harmonics. The harmonic order is simply the frequency expressed in multiples of the line frequency. This concept is used to simplify calculations. Harmonics are mostly produced by non-linear loads such as motor drives, power controllers, and ozone generator Power Supply Unit (PSU). Harmonics make the current waveform look "dirty". Referring to figure 1 below, the graph on the top shows a "clean" current flow with a nearly perfect sinusoidal shape. These nice current waves flow smoothly through the wiring and the equipment. The graph on the bottom shows the "dirty" current consumed by a six-pulse ozone generator PSU without filtering. The stepped current does not flow smoothly through the wiring and equipment. Harmonics waste energy and reduce electrical system reliability. Inter-harmonics are a special type of current distortion produced



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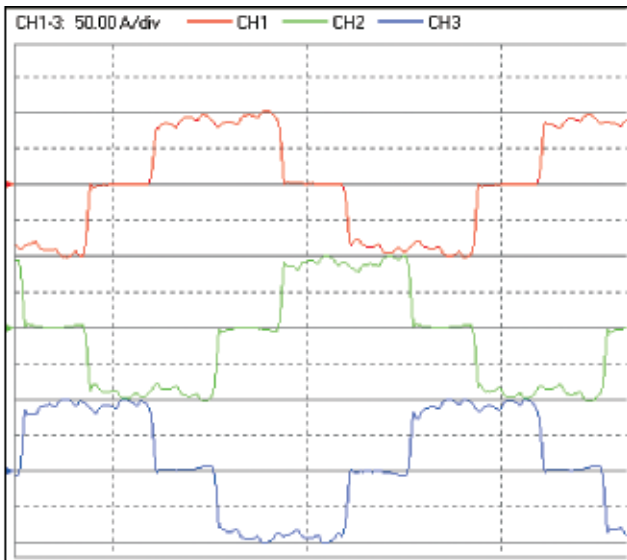
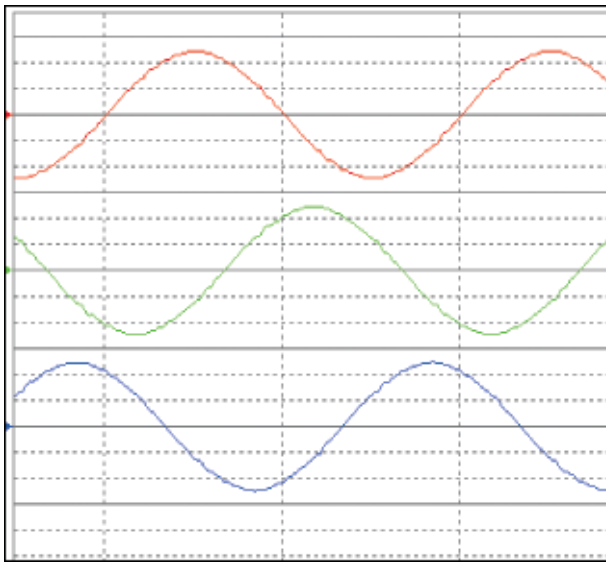
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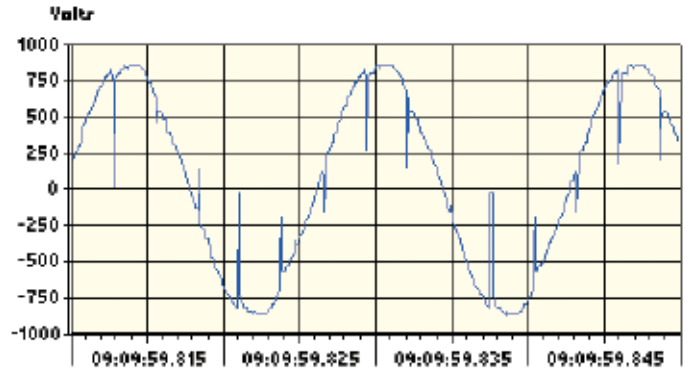


**Figure 1:** The graph on the top shows a “clean” current waveforms from a motor that draws little harmonics and the graph on the bottom shows a “dirty” current waveform with a 30% harmonic content from an ozone generator PSU. Note the inconsistent current ripple caused by the inter-harmonics.

mostly by ozone generator PSU’s and show up as an inconsistent current ripple on top of the waveform on the right. Their effect on the electrical system is similar to harmonics with increased chances of resonance with all capacitive filters due to their variable frequencies. The quantity generated depends on the technology used to design the PSU. Unfortunately, most power meters do not recognize them and large “invisible” amount of inter-harmonics can be present in a plant electrical supply. Capacitor bank and filter designers must take these into account when doing their calculations to avoid premature failures or large resonances. A spectrum analyzer must be used to measure inter-harmonics.

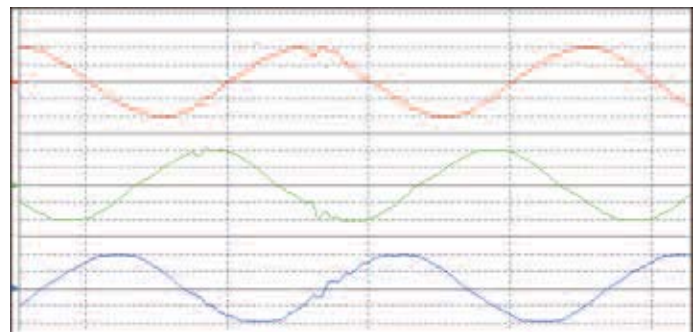
**Line notching** is caused by the switching of current rectifiers found in DC motor drives, motor starters, or

thyristor converter PSU's. Its water circuit equivalent is a water line containing air bubbles. As the bubbles pass through the equipment, they create large stresses. Line notching can be destructive to capacitor banks and other sensitive equipment. Line notching produces high frequency harmonics. This results in overheating of power distribution equipment and can affect the operation of some electronic equipment.



**Figure 2.** Line notching from a DC motor drive. This level of notching is likely to cause problems and damage throughout the plant.

**Switching noise** is produced by equipment being turned on or off using electrical contactors. This produces rapid voltage variations. This is equivalent to the pressure variation in a water pipe when the valves are open or shut rapidly. Switching noise can affect sensitive equipment and severe cases can produce high voltage spikes that can damage them.



**Figure 3.** Switching noise caused by a small motor starting. This level of switching noise on the line voltage is not likely to cause any problem in the plant.

**Voltage dips** are usually caused by large loads coming on line. They are like the pressure drop in a water line. They usually cause annoying changes in light intensity. In severe cases with more than a 15% dip, some equipment can shutdown, contactors can open and re-close reducing their

useful life. AC motors on constant torque load (most water pumps) will draw more current under lower voltage reducing their efficiency and sometimes tripping their overload relays.

**Voltage swells** are usually caused by large loads going off line. They are like a pressure increase in a water line. They also cause annoyance from the change in light intensity. In severe cases with more than a 10% swell, some equipment can shutdown or be damaged by the higher voltage. Higher line voltage increases the transformer magnetic saturation, increasing both the voltage distortion and the power losses.

**Dilution effect** is a very important concept in electrical power quality. It is used to evaluate if a "dirty" load is going to cause problems to the rest of the plant. As long as the load is small with respect to the plant feeder capacity, its distortion will be diluted to the point of becoming negligible. It is similar to the dilution of substances in a chemical process. Take for example adding 80L of a 30% salt solution to 200 L of water. It will make it very salty. But if the same 80 L of solution is added to 2000 L of water, the salinity will not change as much. Similarly, a 100 HP (80KVA) motor drive that gives a 30% of harmonics current will have much larger effect on the power quality of a small plant with a 200KVA power feeder than on the larger one having a 2000 KVA feeder.

The dilution effect is the one of the most important aspects of power quality. How bad a load is depends on its size with respect to the plant electrical feeder. This is why our survey evaluates the demerit points as being the equipment consumption multiplied by its "dirty current", divided by the plant feeder capacity. This gives the relative size of the distorted current to the plant supply and helps us evaluate its overall effect.

**Ground currents** are caused by the electrical current leakages and wiring errors. All electrical currents must return to their source dividing through the paths available. The neutral wire or the other phase conductors should be the easiest return path and therefore carry most of the return current. Unfortunately it is not always the case and some of the current "leaks" through the plant grounding system. All electrical equipment have leakage currents. It is usually below 1% of their consumption. Unfortunately, some design and wiring errors can produce leakage current levels reaching 10-20% without being noticed.

Ideally, the leakage current should flows through your plant ground wires to return to the electrical source. Unfortunately, badly implemented grounding networks allow some of the leakage current to use other paths including the building structure, the piping, and the sensor wiring. These un-intended paths can produce electro-corrosion, signal errors, and sensor failures. This is similar

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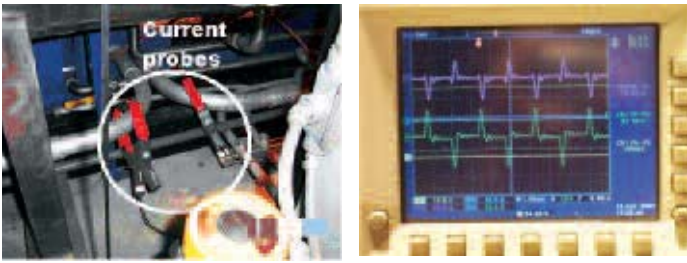
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**Picture 1.** The photo on the left shows the current probe location to measure the leakage current of an ozone generator PSU and the photo on the right shows the oscilloscope screen shot. Note the extremely high leakage current that approaches 30 amperes peak to peak, which is almost 30% of the PSU consumption.

to water returning to the lowest point using any path that leads downward creating problems along the way.

You can compare leaks of electrical currents to an acid solution slowly leaking from a pump. As long as a good drain is near the small leak, the effect is minimized. If the drain is too far, you have a dangerous situation at hand. This is why proper equipment grounding is imposed by regulatory entities to protect people from being shocked. This is one of the most important aspects of the plant electrical wiring. Unfortunately, it is sometimes neglected or badly implemented. If the grounding wires were suddenly removed from your plant, your personnel would get regular electrical shocks and some may even be killed.

Identifying excessive current leakage requires special tools such as large diameter current sensors and oscilloscopes. To track the leaks, the pipes and structures around the equipment are probed. Understanding of the equipment

operation is needed, a qualified person can evaluate if corrections need to be performed to bring the leakage currents within acceptable limits.

**IEEE519 recommendations** are a set of guidelines produced by a group of experts in power quality. These people came up with a much-needed base line and measurement methods for power quality from the power utility point of view. These recommendations are not intended to be applied directly to equipment terminals but to the plant main electrical feeder where the dilution effect is the highest. When these recommendations are applied directly to the equipment terminals, they force higher correction expenses than are really needed. Overall, these recommendations are good guidelines and have helped improve the power quality in the industrial world.

This covers most of the power quality concepts. We have left out numerous details and calculations that are not needed to understand what is happening to your plant's electrical supply. Specialized books and university courses are available for those interested in covering this subject in depth. Now that we have an understanding of the power quality issues, we can evaluate them and decide if any corrections are needed.

### Typical water treatment power quality survey

A typical plant electrical system operates on its own transformer(s) directly from the utility high voltage line. Each transformer can feed dozens of small pumps, two or three large ones, large compressors, some mixers, two or three ozone generators, a few banks of UV lamps, dozens of electrically operated valves, various control panels and automation systems, and finally some lighting and air conditioning.

The following tables are used to identify the electrical loads

**Table 1.** Electrical distribution loads.

Distribution system capacity (C) = _____ KVA	Load (L) KVA	Potential power quality issue "Dirty current" scale (D)		Demerit points = L x D/C
Loads below 10HP (7.5KW) are usually too small to cause problems and are lumped together into the total load.		Power factor	D = 15	
		Harmonic distortion	D = 20	
Voltage transformers: 500KVA and more.		Harmonic distortion	D = 2	
		Turn on inrush current	D = 10	
Utility generated power quality issues.	L = C	Harmonic distortion	D = 1	
		Voltage regulation	D = 1	
		Voltage spikes or dips from switchgears	D = 5	

**Table 2. Large motors for water pumps, compressors and aerators.**

<b>("C" from Table 1)</b>	<b>Load (L) KVA</b>	<b>Potential power quality issue "Dirty current" scale (D)</b>	<b>Demerit points = L x D/C</b>
AC motor, 10 to 100Hp. Across the line starter.		Inrush current.	D = 50
		Power factor	D = 15
AC motor, 10 to 1000Hp. Soft start starter.		Inrush current.	D = 20
		Power factor	D = 15
		Harmonic distortion when starting	D = 50
AC motor, 10 to 1000Hp Variable speed drive. (No harmonic filtering)		Harmonic distortion	D = 30
		Inter-harmonics	D = 2
		Line notching (DC motors only)	D = 60

**Table 3. Large electronics loads**

<b>("C" from Table 1)</b>	<b>Load (L) KVA</b>	<b>Potential power quality issue "Dirty current" scale (D)</b>	<b>Demerit points = L x D/C</b>
Ozone generator PSU's; six-pulse technology without harmonic filters or power factor correction filters. (Diode converters behave differently from thyristor converters)		Power factor (diode)	D = 5
		Power factor (thyristor)	D = 20
		Harmonic generation	D = 30
		Line notching (thyristor)	D = 60
		Inter-harmonic generation (diode)	D = 5
		Inter-harmonic generation (thyristor)	D = 1
Ozone generator PSU's; twelve pulse and more, without harmonic filters and power factor correction filters. (Diode converters behave differently from thyristor converters)		Power factor (diode)	D = 5
		Power factor (thyristor)	D = 15
		Harmonic generation	D = 10
		Line notching (thyristor)	D = 30
		Inter-harmonic generation (diode)	D = 5
		Inter-harmonic generation (thyristor)	D = 1
Ozone generator PSU's; six pulse and more, with harmonic filters and power factor correction filters.		Power factor	D = 7
		Harmonic generation	D = 10
Ozone generator PSU's; active front-end converters.		Power factor	D = 2
		Harmonic generation	D = 5
Ultra-Violet lamps.		Power factor	D = 5
		Harmonic generation.	D = 30
		Inter-harmonic generation	D = 3
Electronic Uninterruptible Power Supplies.		Power factor (diode)	D = 5
		Harmonic generation	D = 30
		Active front end converters	D = 5

**Table 4. Compiling the survey results for the whole plant**

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Sum of the demerit points for the power factor

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Sum of the demerit points for the harmonic and Inter-harmonic generation

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Sum of the demerit points for the line notching

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Sum of the demerit points for the inrush current

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of the plant and to evaluate their effect. One survey per plant main transformer (feeder) needs to be completed. Note that if many equipment of the same type operate simultaneously, their capacity can be added on the same line.

After each type of equipment has been identified and sized, we see if any single equipment is causing a problem by looking at its demerit points. Then, we can look at the sum of the demerit points for each power quality issue to see if the plant feeder is at risk of exceeding the IEEE519 recommendations. If it does, the power utility company could demand corrections or impose penalties. While this survey is not a precise measurement, a very high result is indicative of problems while a low result means that the power quality is good. There are other issues not covered here pertaining to special equipment, cabling layout, and grounding as they are beyond the scope of this paper. If

the plant manager suspects problems not covered here, he should call in an expert to investigate.

1. If the demerit points for an item are above 10, it is certainly affecting the plant power quality. Corrective measures at the equipment level, as described in the next section are recommended.
2. If the demerit points for an item are between 5 and 10, it might be affecting the plant power quality. This equipment should be evaluated and correction might be needed.
3. If the demerit points for an item are below 5, it's not likely to be affecting the plant power quality.
4. If the sum of the demerit points for an issue is above 15, the plant has a problem with power quality. If this high result comes from one or two loads, the corrective measure should probably be placed locally otherwise the plant electrical feeder might be a better location. See the next section for details.
5. If the sum of the demerit points for an issue is between 7 and 15, the plant might have a power quality issue. It would be wise to select future equipment with a low demerit factor to dilute the effect of the old equipment. Corrections might be needed.
6. If the sum of the demerit points for an issue is below 7, it's not likely that the plant has power quality issues.

Note: If the plant power feeder is equipped with a recent power meter, chances are that it already measures the harmonics and power factor. Some power meters indicate if the IEEE519 recommendations are met. This is very useful to monitor the whole plant but does not identify which equipment is to blame if the recommendations are not met.

## POWER QUALITY CORRECTION MEASURES

### Solutions available:

1. **Capacitor banks** are a cost effective means of improving the plant power factor. Capacitor banks are similar to adding pressure swing absorbers at the end of water lines. Unfortunately, when combined with the

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feeder inductance, capacitor banks can create dangerous resonances, especially under light load conditions. This is often the case after a power failure. When the power comes back, most of the large loads are off, resulting in over-compensation. This can produce resonance or high voltage spikes during the numerous transients caused by the equipment coming back on line. This is similar to having air trapped in a water line that can produce dangerous water hammering. I recommend using a contactor that will automatically disconnect the bank during a power failure. The operator should then re-arm the capacitor bank once the plant is back on line. A better alternative for plants having varying loads is to use a group of switched capacitor banks controlled by a power factor controller. This eliminates the overcompensation problem.

The main limitations of capacitor banks are the possibility of large switching noise and of resonances with harmonics. The switching noise is similar to water hammering and is produced when the empty capacitors are connected to the line. The harmonics produced in the plant can also overload and damage capacitor banks. Compensation comes in steps offering low precision and obtaining reliable results is not as simple

as it seems. In most cases, the tuned capacitor bank described below is a better choice.

2. **Tuned capacitor banks (tuned filter) with slow controller** are used to provide power factor and harmonics correction while attempting to solve the problem caused by simple capacitor banks. The tuning inductors greatly reduce the switching noise. These inductors are sized to avoid resonance with harmonics. This greatly reduces the chances for problems. Unfortunately a compromise between power factor correction and harmonic filtering capacity has to be made. Compensation comes in steps offering low precision. A lot of expertise is needed to adapt them to the plant. Inter-harmonics produced by ozone generator PSU's can resonate with the tuned bank if they are not taken into account at design time.
3. **Tuned capacitor banks (tuned filter) with fast switches and controller** are used in plants where the power factor varies significantly many times per hour. In this case, the electrical contactors rapidly exceed their useful life and fail. To solve this problem, semiconductor switches coupled with a fast controller is used. This controller reacts so quickly that the power factor will be adjusted many times during the starting of a large motor. This reduces the line voltage transient produced



by activating large loads. Operation and trade off are the same as the tuned capacitor bank with a slow controller.

4. **Line chokes** are effectively used to attenuate the harmonics and line notching caused by DC motor drives and some ozone generator PSU's. One choke per drive is needed. The most popular sizes are 3% and 5% impedance. The harmonics are reduced by up to 50% at the expense of a reduced power factor. In some cases, a tuned filter is also added.
5. **Harmonic mitigation transformers** can attenuate certain groups of harmonics. They do a good job at reducing specific harmonics as long as the line voltages and the harmonic currents are balanced on the three phases. The twelve and eighteen pulse transformers are often used to reduce harmonics generated by motor

drives and ozone generator PSU's while the zigzag transformers are used to remove 3<sup>rd</sup> harmonics and DC currents. These transformers cannot be used to improve the power factor. They only mitigate specific harmonics directly at the load.

6. **Active harmonic filters** have been developed to solve the weakness of the techniques previously described. In an active harmonic filter, a microprocessor measures the harmonic content and the power factor of the load (or the plant feeder) and calculates a correction current. This correction current is injected into the line to cancel out most harmonic currents and improve the power factor. Contrary to all capacitor banks and filters, active harmonic filter are not subject to resonance problems. The construction is almost the same as an AC motor drive connected in reverse. The output is continuous

**Table 5. Typical equipment and their local correction method.**

<b>Load type</b>	<b>Local correction method normally used. (Check with manufacturer for compatibility)</b>
Ozone generator PSU's. Six or twelve pulse technology without harmonic filters or power factor correction filters.	-Line reactor. (Only with capacitive DC bus) -Tuned harmonic filter. -Active harmonic filter. -Harmonic mitigation transformer.
UV lamps.	-Line reactor. (Only with capacitive DC bus) -Tuned harmonic filter. -Active harmonic filter. -Harmonic mitigation transformer.
Electronic UPS.	-Line reactor. (Only with capacitive DC bus) -Tuned harmonic filter. -Active harmonic filter. -Harmonic mitigation transformer.
AC motor 10 to 100Hp, across the line starter:	-Capacitor bank at the motor. -Soft starter. (Semiconductors or transformers)
AC motor 10 to 500Hp, soft start starter	-Line reactor. Use with caution as it increases the motor starting time and reduces torque.
AC motor 10 to 500Hp, Variable speed drives (No harmonic filtering included)	-Line reactor. -Tuned harmonic filter. -Active harmonic filter. -Harmonic mitigation transformer

**Table 6. Typical correction methods used at the plant feeder.**

Correction at the plant electrical feeder.	-Tuned harmonic filter. -Fast tuned harmonic filter. -Active harmonic filter.
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from zero to 100% eliminating the step changes affecting most capacitor-based filters. It also corrects for harmonics and power factor without compromises. The main disadvantage is their higher cost.

## Location of the correction equipment:

When a power quality problem is caused by one or two pieces of equipment, it can be cost effective to apply the correction directly to that equipment. For example, if a large pump running on a variable speed drive causes most of the harmonics seen on the plant electrical supply. One could add tuned capacitor banks or an active harmonic filter directly at the variable speed drive. This would filter out the harmonic current at the source and prevent it from flowing through the plant electrical supply. Technically it is usually better to correct the problems directly at the source. Local compensation is the only choice when using methods such as a line choke or a mitigation transformer.

Occasionally, local correction may not be the best choice as it can be more expensive or complicated. One must consider that the cost of multiple compensations directly at the loads can be higher than having one large correction equipment installed at the plant main feeder. Also, capacitor bank filters can be difficult to balance when multiple units are distributed through the plant. This is why many engineers often specify a single correction unit connected at the plant main feeder. Convenience and cost often wins over performance.

**Warning:** Always consult the equipment manufacturer before designing a power quality correction system for their equipment. Capacitor banks and filters affect certain equipment and can produce unforeseen problems.

## CONCLUSION

In this paper, I used a water circuit analogy to demystify electrical power quality issues. This analogy gives familiar images to electrical phenomenon. After presenting the basic power quality concepts such as power factor and harmonics, I covered the typical electrical loads present in a water treatment plant. The objective was to highlight their effect on the electrical supply. I then provided a simple survey method to help the plant personnel to evaluate the power quality issues in their plant. This simple survey is designed to identify the equipments that could cause problems and evaluate their effect on the plant power quality. Finally, I briefly covered the most popular correction methods and highlighted their strengths and weakness. The objective is to help the plant personnel in their effort to evaluate their suitability. The knowledge acquired through reading this paper should help the plant personnel to communicate with power quality professionals in the event that complex problems need to be corrected.



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## ACKNOWLEDGEMENTS

I would like to thank my colleagues at Imalog inc. for their suggestions and editing help. Special thanks to all the factory and water treatment plant personnel who over the years have helped me to apply the knowledge found in books to real life situations.

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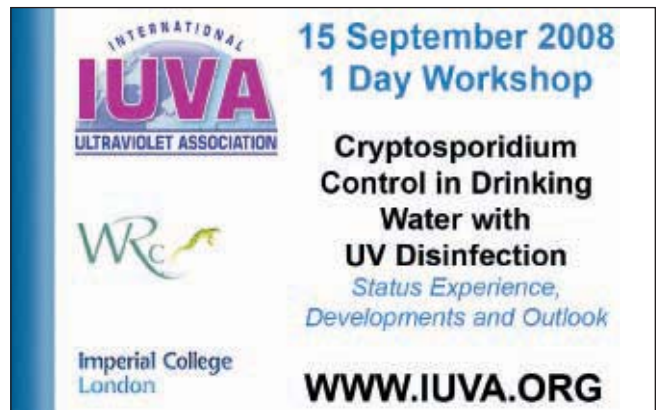
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