

Power Quality Issues in Hospitals

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Abstract: This paper describes power quality audits conducted at hospitals in Western Australia and Puerto Rico. Voltage and current measured at various points were used to assess the quality of the power used at both facilities. The main power quality problems found were voltage flicker, neutral currents, and harmonic distortion. Measurements of the total harmonic distortion (THD) were used to locate harmonic sources. Recommendations were made based on the results of each of the audits. Both studies serve as awareness for the importance of power quality in sensitive equipment found at hospitals. The power quality audits in this paper were part of the programs of study for students participating in the projects, which makes these efforts important pedagogical tools.

Keywords: Power quality, harmonic distortion, voltage disturbances, Flickering, Neutral Current, Total Harmonic Distortions

I. INTRODUCTION

The widespread use of sensitive, microprocessor-based equipment at hospitals requires that the power delivered to such sensitive facilities be of a higher quality. Power quality problems may be caused by external sources (e.g., lightning) or internal sources (e.g., interaction of loads) [1]. Power quality events such as voltage transients may cause a microprocessor to read voltage levels incorrectly, resulting in incorrect data processing (ones being read like zeros) or altered stored data/settings. Other malfunctions in medical equipment caused by power quality events include: distortion of displays (due to distorted voltage, altered data); incorrect diagnostic results (due to EMI, grounding), equipment lockup (due to Voltage surges or sags), Control/alarm malfunction (due to Microprocessor malfunction) [2]. These examples illustrate the importance of taking care of power quality issues at a medical facility. These problems may cause serious situations especially at intensive care or operating areas.

Common sources of power quality problems found in hospitals include: Inadequate wiring and grounding, high-wattage equipment, testing of emergency generators, physical plant renovations.

In order to deal with these problems, the electrical system should be improved as the number of sensitive, nonlinear loads at a hospital increases. However, many buildings were not required to implement system improvements suggested in

new or revised regulations. Compounding the problem is the fact that many codes or regulations deal with safety issues, but they do not address power quality concerns [2]. Frequently, large-demand devices as x-ray machines are installed at facilities without a complete power quality survey. Since power quality problems are cumulative; small power quality events (detectable in an audit) can lead to loss-of-life and eventually premature equipment failure.

This paper presents a comparison of power quality problems found at medical facilities in Western Australia and Puerto Rico. An important aspect of this work was the educational value of each of the two studies, which had an important role from students at both locations. An Honors Student from Curtin University of Technology participated in Perth, and a graduate student from the University of Puerto Rico-Mayagüez led the power quality audit in Puerto Rico.

II. DESCRIPTION OF THE SYSTEM

A. Australia

Sir Charles Gairdner hospital in Perth, Western Australia receives its electrical power from:

- Normal Supply (NS) is a direct utility (Western Power) supply for non-essential areas such as public areas, recreational facilities, washrooms etc.
- Essential Supply (ES) is used for areas of medical importance that are not critical to patients in the case of supply interruption
- Uninterruptible Power Supply (UPS) is used for

- emergency lighting, operating theatres, patient monitoring and other equipment that is important to the well being and safety of patients. Five UPS systems are used (2 X 63 kVA and 3 X 80 kVA).

The essential supply is backed up by an emergency generator. Figure 1 shows a simplified electrical layout of the hospital's cardiovascular operating theatres.. It is to be noted here that a single phase voltage supply all emergency lighting and a three phase supply feeds the X-ray equipment in the cardiovascular operating theatres of the hospital.

The interchange circuit breakers in Fig.1 are controlled automatically according to the availability of various supplies. In case of a utility failure all circuit breakers to the left of the UPS change over and normal supply is discontinued.

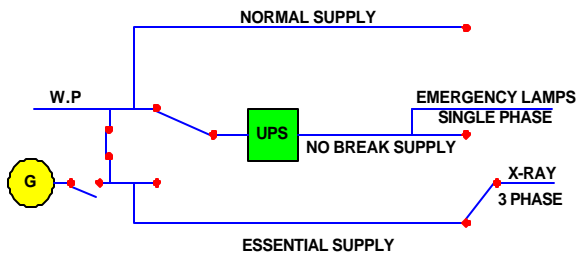


Figure 1. Simplified Electrical Layout of the Cardiovascular Operating Theatres

B. Puerto Rico

The peak load at Bella Vista Hospital (BVH) is 1 MVA, as measured by the local utility. The load is distributed among thirty-seven circuits, using two 1 MVA dry-type transformers. Fig. 2 shows the main circuits of the system. Service from the Puerto Rico Electric Power Authority (PREPA) comes from a 4.16 kV feeder. The hospital is located in a residential area over the top of a hill.

BVH has an alternate power supply consisting of two generators. The first one has a capacity of 625 kVA, and can supply emergency power within 5 seconds of an outage, as required by healthcare standards [4]. The second is a backup in case of malfunction of the main generator. It has a capacity of 487 kVA. The emergency energy is supplied through fifteen transfer switches. Individual loads can be selectively turned off/on with this configuration. However, the topology increases significantly the number of components in the systems that can have troubles.

The hospital has 37 major circuits available in the two switchgear at the substation, and more than 50 panel boards distributed through the building. Thus, the single line diagram was indispensable for the power quality audit.

Changes in the quality of power have been observed at the Bella Vista Hospital in Mayagüez, PR. An increase of sensitive medical equipment, recent problems with an expensive catheterization equipment and the installation of million-dollar equipment, motivated the Hospital's Engineering Department to conduct a power quality audit. The main objectives of the survey were to assess the quality of service re-

ceived from the utility and to identify areas within the hospital where power quality problems currently exist or may develop in the near future. This information will be used for better planning when installing sensitive equipment and in future expansions. Other objectives were to study the impact of portable medical equipment upon other sensitive devices and to evaluate the condition of the hospital's electrical system.

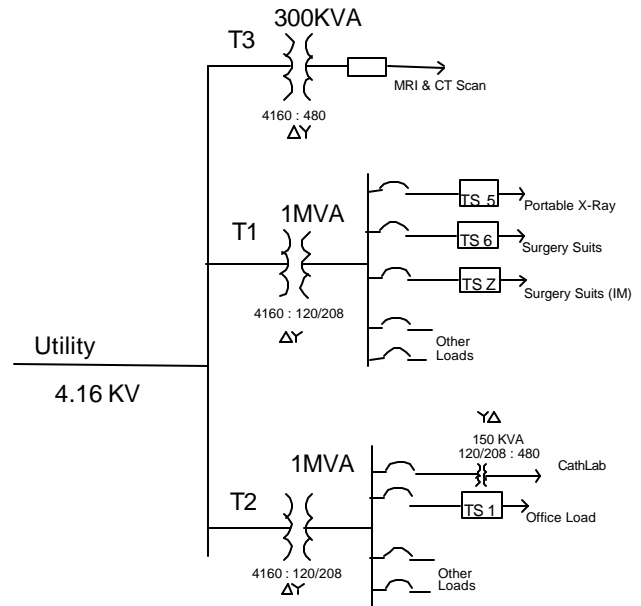


Figure 2. Pictorial for the hospital's electrical system

III. METHODOLOGY AND PROBLEMS FOUND

A. Australia

The X-ray equipment in the operating theatres at the hospital is supposed to be normally run from the UPS system. However, due to light flickering while being supplied by the UPS, the X-ray machine was supplied by an essential power supply instead. Hence in a blackout situation the X-ray equipment would loose power until the start-up of the diesel generator. During the two minute change over the operating theatre staff are unable to monitor patients condition. The neutral current on the essential supply is found to be large and have very high total harmonic distortions. The X-ray machine operates on two modes:

- Screening : This mode is a continuous mode of operation for patient monitoring purposes. This mode produces relatively small amount of X-raying energy compared to the next mode.
- Snapshots : This mode produces high levels of X-raying energy but for a period of up to 20-30 seconds. Longer periods could cause excessive heating and damage the X-ray tube.

For both modes, the X-raying energy is adjustable. This is an important observation as it is crucial to maintain similar conditions between different measurements for valid comparisons.

B. Puerto Rico

The first step of the power quality audit was an inspection of the hospital's electrical system. Even though numerous renovations had been made in the last fifteen years, a one-line diagram of the electrical system was not available at BVH. A complete schematic of the system, shown in Fig. 2, was developed using the information gathered after a thorough inspection of the system.

A portable, stand-alone, single-phase power quality analyzer was used to record the measurements [5]. One 500 amperes clamp-on CT and a 2000 A flexible clamp-on CT were also used. Measurements were made at the substation transformers, at the output of each circuit breaker, at the input of each distribution panel, and finally at the individual loads. Voltage and current values as well as power and power factor were logged. After taking the first voltage and current measurements, it was evident that harmonics were the main problem in the facility. Therefore, both current and voltage THD were measured.

A method based on the current-source model was used to locate harmonics [6]. A harmonic source can be traced from multiple measurements of THDI in the system. The closer one gets to the source, the higher the THDI will be. Measurements were taken starting at the substation, then going all the way up to the individual loads. The "harmonic tracing" used in this study was validated in a previous study at an industrial food-processing facility [7].

An infrared study was performed in the main circuits and critical services in the facility. This study revealed several hot points in circuits (one as high as 349° F), which gave evidence of deterioration of the contacts. Harmonics were present at some of these hotpoints.

The physical facilities at Bella Vista Hospital range from 25 to 45 years old. Although the electrical system of the five-story building has undergone many renovations, it is not suited to deal with power quality conditions related to the operation of a large number of sensitive, microprocessor-based devices. The neutral wires were not designed to support nonlinear loads and harmonic flow. There is a possibility of grounding problems caused by corroded wiring. Rooms that had one or two medical devices in the past, now house complex medical systems and/or numerous portable devices.

The interaction between loads is also a concern at BVH in terms of voltage sags. Office equipment and medical devices with high distortion can affect the operation of other microprocessor-based equipment even if the latter has built-in power conditioners. For example, imaging systems cause sags that may generate some of the problems shown in Table 1.

There have been problems with a catheterism equipment. This is an image processing equipment known as C-Arm, used for fluoroscopy studies. This study is similar in concept to an x-ray process in which the image is projected continuously in a monitor. The device's power drivers and its emission tube had to be replaced. A surge was blamed for the failures, even though the device's surge protection was in good condition

and showed no evidence of operation. Other power quality issues needed to be considered to explain these failures.

The main power quality problem found was harmonic distortion. Measurements of the total harmonic distortion (THD) were used to locate harmonic sources. Potential problem areas were identified within the facility. Table 2 presents the areas with significant levels of Current Total Harmonic Distortion (THDI).

The harmonic impact of the hospital to the outside world is less than 3%, which is within permissible range [8]. However, there are problems inside the facility that are related to harmonics (and other power quality concerns). As an example the office load shows a 14.3% THDI due mainly to lighting loads and UPS. The computer center and various servers are connected to that circuit. There were continuous computer lock-ups that were caused by harmonics.

Portable x-ray machines are another significant source of harmonics. In this case the problem is worst since it is random in nature, as the machines are operated in different locations, at any hour of the day. Due to this situation the effect is dependent on the actual location of the equipment. Thus, portable equipment can be identified as a potential source of power quality concerns, especially when operating these loads close to sensitive devices.

TABLE 2

Voltage, current and THDI measurements in medical facility

Site	Vrms	Irms	THDI
Main Transformer # 1	123.56	995.64	3.91%
Main Transformer # 2	119.28	1230.42	5.26%
Office Loads	120.34	84.65	14.29%
Portable X-Ray	119.63	13.88	23.61%
Surgery Suits	121.81	18.78	29.17%
Surgery Suits (IM)	122.65	74.35	21.76%
CathLab Idle	277.40	20.80	47.10%
CathLab ON	272.44	40.40	34.00%

IV. RESULTS AND RECOMMENDATIONS

A. Australia

We investigated the emergency light flickering and high neutral current situations in the power supply to the operating theatres.

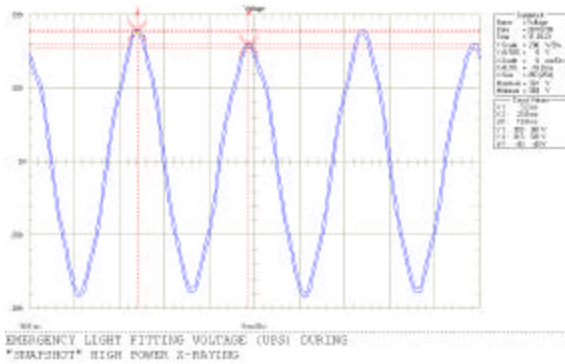


Figure 3. Emergency Lamp Voltage while Snappshot x-raying.

Emergency Lamp Flickering

In order to investigate the cause of lamp flickering, the voltage and current of the lamps were monitored. Figure 3 shows the lamp voltage with UPS while snapshot x-raying.

The voltage waveform clearly shows a 50 Hz variation of 40 V.

Figure 4 shows the lamp r.m.s voltage over a 4 minute interval. In this period two x-raying snapshots were taken as shown in the Figure. The variation of peak voltage was measured to be equal to 40 V between two successive period. Figure 4 clearly indicates severe voltage fluctuations while x-raying using the UPS system. However, with the ES supply no voltage fluctuations were found.

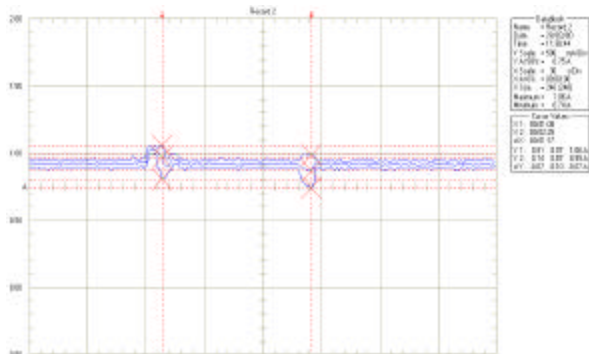
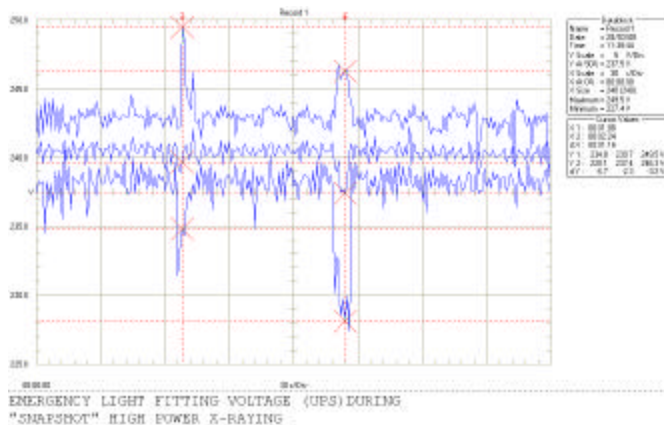


Figure 4. Lamp rms voltage over a 4 Minute Period.

The current drawn by the lamp is shown in Figure 5.

Figure 5. Lamp Current during the 4 Minute Period.

As the lamps running from ES supply did not show any voltage fluctuations, it was recommended that all emergency lamps be supplied from the ES supply. However, considering the fact that in the event of loss of ES supply, the stand by generator take 2 minute to take up load some measures are required. For this purpose, our recommendation was to replace all emergency lamps in the operating theatres by their energy storage type counterparts. The Atco power pack model DBL 1120N-01 is one such lamps suitable for 2X36 W lamp fittings which would provide back up for 2 hours.

Neutral Current

Before the investigations into the neutral current, the THDI's on the ES and UPS supply were measured and found to be 4.1% and 3.3% respectively. The rms voltage of the ES supply is also 4 to 5 V higher than the UPS supply.

Figure 6 shows the neutral current and its spectrum. The current waveform is severely distorted with a THD of 38.16% without x-raying from the ES supply.

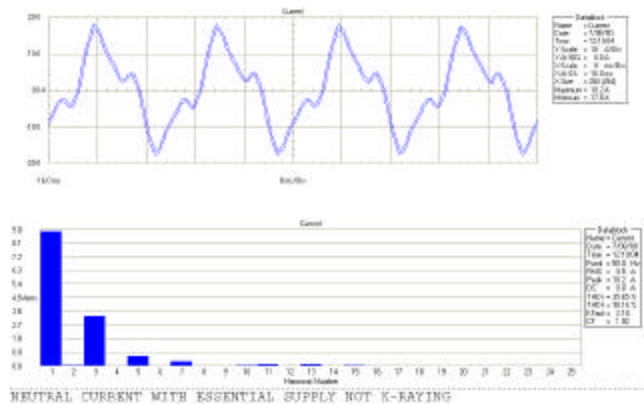


Figure 6. Neutral Current and its Spectrum.

It is interesting to note that the THDI of the neutral current did not worsened significantly while screening or snapshot x-raying. The other observations was that the THDI of the neutral current was 7% to 15% lower for the UPS supply than the ES supply. These observations and the high fundamental component of the neutral component proves that the high neutral current is not so much due to the no-linear loadings but due to phase load unbalance. An inspection of the circuit diagram of the Philips xraying equipment revealed plenty single phase equipment connected to the Red phase. The

single phase equipment includes dc power supplies, computers and monitors as well as blower motor for cooling of the x-ray tube. Most of this equipment produces large third harmonic current and hence the violation of the third harmonic limit. This also explains why the process of x-raying did not have much effect on the THDI of the neutral current. However, the third harmonic current violates the IEC 61000-3-2 standard.

B. Puerto Rico

There are two main circuits for the surgery suits. One has general equipment connected to it, including the surgery luminaries. These luminaries were experiencing frequent burn out. This problem was identified thorough the audit. The solution was to use a circuit with less harmonic distortion

for the luminaries, which caused an increase in usable life. The other circuit has isolation monitors (IM in Table 2) for the suits and the anesthesia machine. It is interesting to note that the ground reference at this point is precisely the interface between the oldest and newest part of the Hospital. Grounding problems seem to be the cause of harmonic levels at this circuit.

Fig. 7 shows the in-line voltage regulator and the C-Arm equipment (described in section II) in idle mode. A high degree of distortion is observed for the current, but the voltage presents only minimum distortion. Fig. 8 shows the harmonics present in the current for the same catheterism machine. There is a high degree of third harmonic present in this case, typical of magnetic devices. At this point the current drawn was around 20 A.

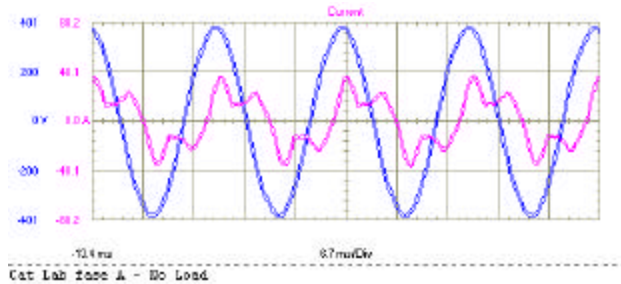


Figure 7. Catheterism equipment idle (phase A)

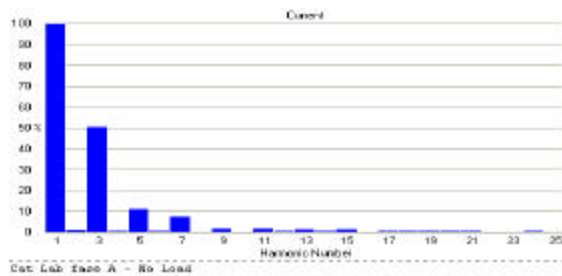


Figure 8. Harmonic strength for equipment idle (phase A)

In Fig. 9, the catheterism machine is operating. The current distortion resembles a step square wave. The steps follow a sinusoidal wave. This behavior agree with the way this

machine operates, were continuous x-ray "shoots" draw high current in steps. As with idle operation, there is minimal voltage distortion. The amplitude of current is almost twice in this case, but the distortion is very different. Fig. 10 is the corresponding frequency spectrum for the device's current. In this case the fifth harmonic is the largest, typical for switching devices. The current magnitude of the third harmonic is slightly reduced as compared to idle operation, and its percentage in the spectrum is significantly reduced since the total current magnitude has doubled.

The system is not affected by this distortion because as it can be seen in Fig. 2, there is a transformer in a wye-delta configuration. This configuration effectively isolates the triplen harmonics from the rest of the system. The only problem is in the transformer itself, where harmonics heat up the windings. This transformer presented some damage in its windings and is under schedule to be replaced. The deterioration was caused by the equipment harmonic distortion.

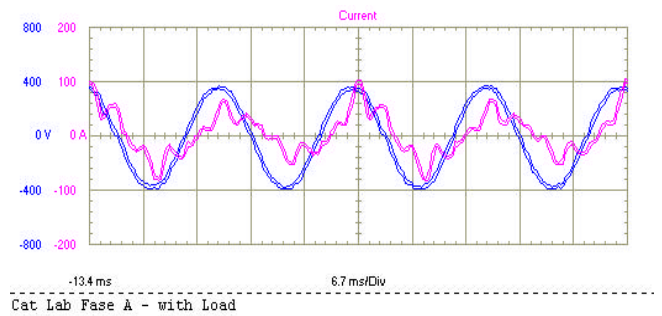


Figure 9. Catheterism Equipment operating (phase A)

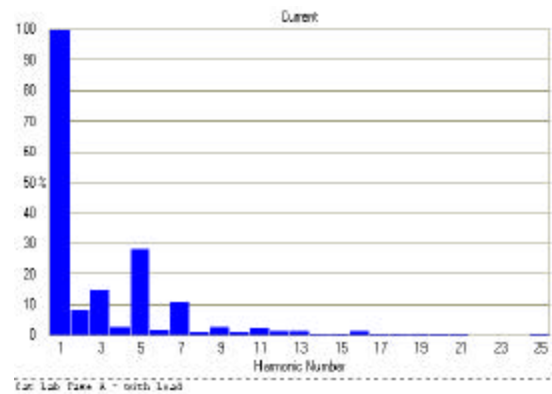


Figure 10. Harmonic strength for equipment operating (phase A)

Another important outcome of the power quality audit is in regard to the condition of the electrical system. Installation of new equipment did not go in-hand with improvements in infrastructure. As in most facilities changes occur at a fast pace, new equipment is added almost daily, e.g., office equipment, diagnosis equipment, and patient treatment equipment. In the past a single power outlet per bed in patient rooms was

more than enough. Today two or three outlets are insufficient. Unfortunately, services are added most of the time without improving feeders, panelboard capacity, circuit protection and infrastructure in general. Therefore, a system that was once stiff is now operating near its limits. This change in operating point has already caused malfunctions in equipment such as patients intravenous pumps (used to administer serum and other medicines to patients).

The main recommendation of this study is to establish a routine or periodic power quality assessment at Bella Vista Hospital. The study described in this paper will ensure compliance to codes/regulations and also as a preventive measure. The cost of such measure is low compared to the benefits that will be obtained [12]. Overall system efficiency may be improved, resulting on less repairs, reduced loss-of-life and better maintenance records. This kind of study would give an ability to identify and prevent power quality events. This study will also serve as a guide for installations of new equipment and future expansions in the hospital. The study is especially important for the BVH since its electrical installation is not suited to deal with many power quality events.

Further analytical investigation of harmonic propagation and unbalance conditions is required. As a first step, the grounding bonding in the facilities is being studied so that existing and future problems are mitigated.

V. CONCLUSIONS

This paper presented a description of a power quality studies carried out in medical facilities in Perth, Western Australia and Mayagüez, Puerto Rico. Both studies confirm the importance of maintaining a high quality of electric service to serve sensitive and critical loads at hospitals. The problems at the Sir Charles Gairdner Hospital in Perth were mainly related to lamp flickering and non-zero neutral current. Recommendations for this study included the use of different types of lamps to reduce voltage flicker problems. On the other hand, harmonic distortion was the main problem found at the Bella Vista Hospital in Mayagüez. The main result of this audit was the identification of areas that are sensitive to power disturbances and potential problem areas. THD measurements were taken to trace harmonic sources. Recommendations were made in regard to future installation of sensitive equipment near these harmonic producing loads. One of the major sources of harmonics is effectively isolated by a transformer, however, harmonics cause insulation degradation on the secondary that shortened the device's useful life. Both studies show the importance of periodic power quality audits to prevent future power quality problems as well as to assess the condition of the electric system the facilities. The studies were also an important educational tool because of the involvement of students in the process.

VI. ACKNOWLEDGMENTS

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