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Some Power Quality Issues in Hospital Facilities

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Abstract. The present approach focuses on some specific power supply and power quality issues in hospital environment. This environment is always a special one and changes dramatically one day after another, due to the last decade boom of biomedical engineering. The authors' opinion is that in medical facilities, one should go beyond the standard EN 50160, on voltage characteristics of electricity supplied by public electricity networks, taking also into account the standard EN 60601 on general requirements for safety on medical electrical equipment and the related standards on electromagnetic compatibility. Otherwise, a power quality analysis should result in the unpleasant situation in which products designed and placed on the market according to all relevant legal and product standard requirements, may become unsafe or even be damaged due to a supply voltage consistent only with the standard EN 50160. The paper depicts a relevant case study analyzed in the intensive care department of the Emergency County Hospital from Cluj-Napoca, Romania.

Key words

Power quality, EMC, EMI, conducted immunity, common mode interference, leakage current, grounding systems.

1. Introduction

The electromagnetic environment in modern hospitals has changed dramatically, especially due to the development of biomedical engineering, a mix of medicine, engineering and science, which have created new opportunities of development for diagnosis tools, monitoring and therapy of human diseases and has expanded remarkably in the past ten years. The link thus formed between engineering and medicine is so important that no one can think of distinguishing them anymore. Progress are made in all engineering subspecialties: from signal processing of heart and brain signals to mechanical human-like organs; from robust and accurate devices for clinical analysis to devices for real-time applications in surgery. The development of telemedicine, using modern telemetry techniques in order to exchange medical information from one site to another, via Internet, creates a significant impact on the way patients are diagnosed, monitored and treated.

Much of the activity in biomedical engineering, be it clinical or research, involves measurement, processing, analysis and display of electrical signals. It is already well known that the human body presents an intense electromagnetic activity. Consequently, many physiological processes produce energy that can be detected directly.

What distinguishes technologically produced electromagnetic fields from most natural ones is their much higher degree of coherence, i.e. their frequencies are well-defined and therefore, more easily discerned by living organisms, which opens the door to the frequency specific influences of various kind. In this case the organism will respond in a way akin to a radio, if the frequency of the external field matches or is close to that of its endogenous oscillatory electrical activity (e.g. like a tuned circuit). Some oscillatory endogenous activities of the human body are quite familiar and their results are usually given in the term ExG, where the *x* represents the physiological process that produces the electrical energy: ECG, electrocardiogram; EEG, electroencephalogram; EMG, electromyogram; EOG, electrooculogram; ERG, electroretinogram, and EGG, electrogastrogram [1]. A broad spectrum of interpretation ExG devices have been developed in recent years. Usually, these devices are equipped with integral problem-oriented expert systems of different levels of complexity. No matter how sophisticated they are, their bio-transducers (commonly named electrodes), are often the most critical elements in the system, because they constitute the interface between the subject (the life process) and the rest of the system.

Electromagnetic noise stability is one of the main requirements for reliability and safety of medical equipment. Unfortunately it can be induced in medical equipment just by switching on and off electric circuits, by lightning discharges or electrostatic discharges induced by medical personnel and radio-frequency electromagnetic waves emitted by various devices. Also, electromagnetic noise can be caused by dynamic changes in power line voltage (drops, spikes, or power failure). Physiological-monitoring equipment is vulnerable to pulsed RF, which can be demodulated by non-linear elements in amplifier circuits. Some monitors are connected directly to the patient, in order to detect small physiological signals (ECG 1 mV, EEG 100 μV, EMG 10 μV). Mains-powered equipment, including ventilators, anesthesia machines and syringe pumps, can also be vulnerable to conducted interference on the mains supply. Battery/mains equipment, which runs on a battery with continuous

charging from the mains, has very good immunity to mains voltage variations such as drop-outs and sags.

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 events, such as voltage transients, may lead to the malfunction of the microprocessors or controllers, resulting in incorrect data processing 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 electromagnetic interference or poor grounding), equipment lockup (due to voltage surges or sags), control/alarm malfunction (due to microprocessor malfunction). A wobbly picture on a monitor would probably be regarded as no more than a nuisance, whereas failure of a ventilator, infusion pump or automated defibrillator could be fatal. These examples illustrate the importance of taking care of power quality issues in medical facilities. These problems may cause serious unpleasant situations, especially in intensive care or operating areas.

Since power quality problems are cumulative, small power quality events (detectable in an audit) can lead to loss-of-life or eventually premature equipment failure, in possible mal praxis procedures from the part of the medical staff and the most important, loss of human lives.

In order to deal with these problems, the electrical system should be improved as the number of sensitive, nonlinear loads from a hospital increases. EMC should become a real concern not just for manufacturers, but also for those who install, use, modify or maintain medical equipment. The existence of directives and standards has encouraged good EMC design practices, but should not be relied on to prevent in situ EMI problems, owing to the nature of the hospital electromagnetic environment. Much can be done by promoting awareness of EMI and its underlying coupling mechanisms. Many potential problems can be resolved by ensuring adequate separation of sources and victims of interference. In this respect, in modern hospitals, it is recommended to create an “electromagnetic interference risk distribution map"[2].

2. Power Quality and Electromagnetic Compatibility

In literature, one can find several definitions on power quality, more or less accurate. In the IEEE Standard Dictionary of Electrical and Electronics Terms “power quality is the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment” [3]. The principal limitation of this definition is that the concept cannot be applied anywhere else than toward equipment performance. On another hand from this definition one could infer that harmonic current distortion is only a power quality issue if it affects sensitive equipment. The International Electrotechnical Commission definition of power quality, as in IEC [4], is: “Characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters.” This definition of power quality is related not to the performance of equipment but to the possibility of measuring and quantifying the performance of the power system.

A more accurate definition of “power quality is the combination of voltage quality and current quality” [5] and any deviation of voltage or current from the ideal is a power quality disturbance. Voltage disturbances originate in the power network and potentially affect the customers, whereas current disturbances originate with a customer and potentially affect the network. Again this classification could generate confusion, because one event generally leads to different disturbances for different customers or at different locations. The term voltage quality is reserved for cases where only the voltage at a certain location is considered.

In the authors’ opinion there is no power quality in the presence of electromagnetic interference, i.e. the process by which disruptive electromagnetic energy is transmitted from one electronic device to another via radiated or conducted paths (or both) [6]. In this respect, every disturbance is a power quality issue (even within the IEC standards, a distinction is made between an (electromagnetic) disturbance and (electromagnetic) interference): “A disturbance is a phenomenon which may degrade the performance of a device, equipment or system, or adversely affect living or inert matter” [7]. In power quality terms, any deviation from the ideal voltage or current can be labeled as a disturbance. Interference is much stricter defined, being the actual degradation of a device, equipment, or system caused by an electromagnetic disturbance. The term power quality problem could be used as a synonym.

However, high-frequency transients do occasionally receive attention as causes of equipment malfunction and are generally not well exposed in the power quality literature. For example, the European standard EN 50160, [8] gives useful information for variations (voltage fluctuations, dips, interruptions, etc.) which are regulated disturbances, but says nothing for events (fast transients).

The authors consider that the investigation area of power quality should be widened, considering power quality as part of the larger concept of electromagnetic compatibility and treated in consequence.

It is well known that electromagnetic compatibility (EMC) has two complementary aspects: it describes the capacity of electrical and electronic systems to operate without interfering with other systems and also describes the ability of such systems to operate as intended within a specified electromagnetic environment. Electromagnetic interference (EMI) can propagate from a “source” to a “victim” via the mains distribution network to which both are connected. The transfer of electromagnetic energy (with regard to the prevention of interference) is broken into four subgroups: radiated emissions, radiated immunity, conducted emissions, and conducted immunity.

For ease of measurement and analysis, radiated emissions are assumed to predominate above 30MHz, while conducted emissions are assumed predominant below 30MHz. There is of course no magic changeover at 30MHz. But typical cable lengths tend to resonate above 30MHz, leading to anomalous conducted measurements, while measurements radiated fields below 30MHz will of necessity be made in the near field closer to the source giving results that do not necessarily correlate with real situations. At higher frequencies, mains wiring becomes less efficient as a propagation medium, and the dominant propagation mode becomes radiation from the equipment or wiring in its immediate vicinity.

In the specific electromagnetic environment of hospitals, one must take a special care to the electric supply system, especially in the intensive therapy and surgery areas, because here the medical staff uses several patient connected devices. The level of electrical shock protection provided to patients by the isolation of applied parts classifies them as follows [7]:

• *Type B*: applied parts that provide a direct ground connection to a patient

• *Type BF* (the F stands for "floating"): indicates that the applied part is isolated from all other parts of the equipment to such a degree that the leakage current flowing through a patient to ground does not exceed the allowable level even when a voltage equal to 110% of the rated power line voltage is applied directly between the applied part and ground

• *Type CF*: similar to type BF, but refers to applied parts providing a higher degree of protection, to allow direct connection to the heart

The use of F-type applied parts is preferable in all cases to type B applied parts. This is because patient environments often involve simultaneous use of multiple electronic instruments connected to the patient. In any case, type B applied parts are prohibited whenever patient connections provide either low-impedance or connections to the patient.

These classifications have more than an academic purpose. The standards provide the designer with clear indications regarding the minimal level of circuit separation and the application of insulation between these parts to accomplish acceptable levels of isolation.

As such, *insulation* is not only defined as a solid insulating material applied to a circuit, but also as spacings that establish creepage distances and air clearance between parts. The minimum separation distance between elements of two parts is determined by the working voltage between parts as well as by the insulation rating required to afford protection against electrical shock.

A basic insulation barrier is applied to live parts to provide basic protection against electrical shock. Supplementary insulation is an independent insulation barrier applied in addition to basic insulation in order to provide protection against electrical shock in the event of failure of the basic insulation. Double insulation and reinforced insulation provide protection equivalent to the use of both basic and supplementary insulation.

Evidently, the purpose of the various isolation barriers is to ensure that leakage currents are maintained within safe values even when a single-fault condition occurs (ground, enclosure and patient leakage currents). For instance, in compliance with the standard EN 60601-1 the enclosure leakage current is 0.1 mA in normal conditions (0.5 mA in single fault conditions) for all types of medical equipment.

3. Measurements and Discussions

The power quality investigation in the emergency department of the above mentioned hospital was determined by the fact that the patients' heart activity surveillance monitors (Fig.1.) delivered frequently parasitized registrations (Fig. 2.). In the situations of older monitors, these parasitized records were due mainly to the pilosity of the patients' chests and arms, which affected the firm electrical contact between the electrodes and the patients. But, modern monitors have high input impedance amplifiers and often digital filters for power line noise, which do not necessitate hair abrasion for high accuracy records.

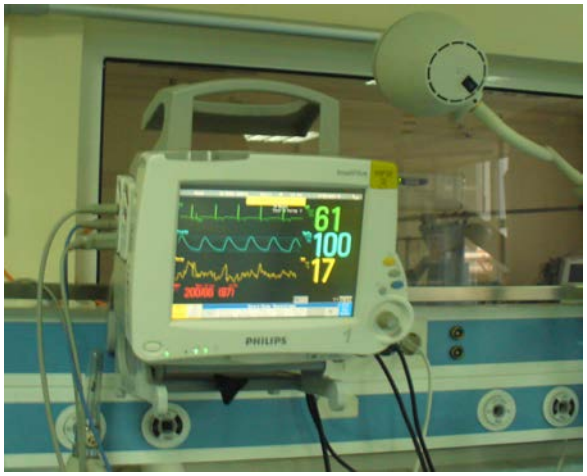

Fig. 1. Patient monitor

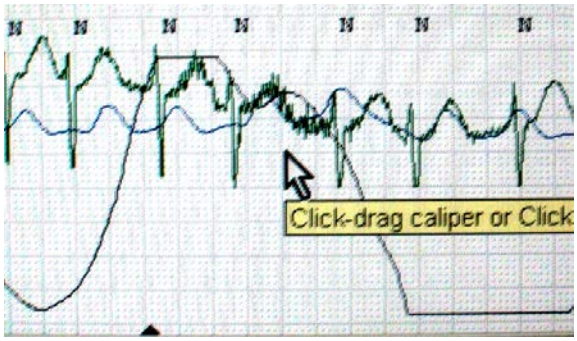

Fig. 2. Parasitized records of a patient monitor

The survey focused on the supply system performance. The very first measurement points were the secondary busbars of the transformer substation (10/0.4 kV, 100kVA), Δ-Y connected which supply the county hospital. The grounding system was TN-S, i.e a solidly grounded power system with one point directly grounded and the exposed conductive parts directly connected to

that point by protective conductors (separate neutral and protective conductors are used throughout the system).

One of the major advantages of the Δ-Y connection of the power transformers is that it provides harmonic suppression. Recall that the magnetizing current must contain odd harmonics for the induced voltages to be sinusoidal and the third harmonic is the dominant harmonic component.

In a three-phase system the third harmonic currents of all three phases are in phase with each other because they are zero sequence currents. In the Y-Y connection, the only path for third harmonic current is through the neutral. In the Δ-Y connection, however, the third harmonic currents, being equal in amplitude and in phase with each other, are able to circulate around the path formed by the Δ-connected winding. The same thing is true for the other zero-sequence harmonics.

Measurements were performed using the Dranetz-BMI PowerXplorer PX5, a portable, hand-held, eight-channel power quality meter/monitor, which can survey, record and display data on four voltage channels and four current channels simultaneously [9]. It can do PQ-optimized acquisition of power quality related disturbances and events. It is designed with a statistical package called Quality of Supply (QOS), with monitoring and setup protocols set to determine voltage measurement compliance required for EN50160 monitoring [8].

Before performing any power quality monitoring, one should clearly define the monitoring objectives, which often determine the choice of monitoring equipment, triggering thresholds, methods for data acquisition and storage, analysis and interpretation requirements. Power quality measurements are performed for a several number of reasons [10]. The two following reasons are in our opinion the most important in analyzing power quality issues:

- Monitoring to characterize system performance, which is a proactive approach to power quality monitoring; by understanding the normal power quality performance of a system, a provider can quickly identify problems and can offer information to its customers to help them match their sensitive equipment's characteristics with realistic power quality characteristics.
- Monitoring to characterize specific problems, which is a short-term monitoring at specific customer sites or at difficult loads. This is a reactive mode of power quality monitoring, but it frequently identifies the cause of equipment incompatibility.

It is equally important that the monitoring locations be selected carefully based on the monitoring objectives. Obviously, we could monitor conditions at virtually all locations throughout the system to completely understand the overall power quality. Fortunately, taking measurements from all possible locations is usually not necessary since measurements taken from one or several strategic locations can be used to determine characteristics of the overall system as we shall see further.

The three voltages depicted in Fig. 3. are well balanced (the upper graph presents the phase voltages waveforms, while the lower graph represents the rms values, quite superimposed).

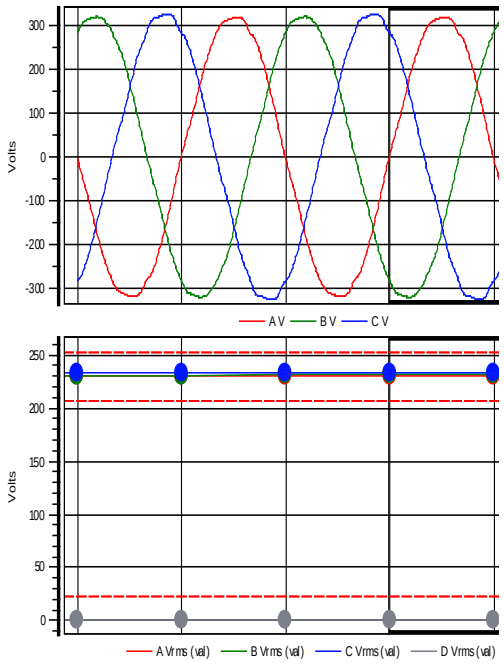

Fig. 3. The low voltage three phase supply system of the hospital

But, during the evening peak demand of energy a series of anomalies were recorded, especially on phase B. Fig. 4 depicts a series of four closed events, consisting in a severe impulse (marked with red triangle), followed in order by a mild impulse, an instantaneous dip of 77V/0.04sec., and finally a mild impulse, all marked with white triangles. The DFT chart during the events is presented in Fig 5. The example presented here is one of the 47 events found on phase B, during the evening peak-load survey.

The supply system of the intensive care unit, hosting the patient monitors was connected on phase B, which could be an indication that the records could be parasitized by the electrical power quality events occurred.

The authors presented some conclusions on this survey in [11], considering as statistically relevant that after the cross-examination of the heart activities monitors' records and the electrical power quality events, a 45% match was found and proposed as a solution to change the voltage supply path to another phase of the substation's transformer, considered more "healthy".

Unfortunately, the proposed solution did not entirely solve the problem. While the problem still existed, even in a less proportion, the authors decided to test the monitors to electromagnetic conducted immunity at the mains port, according to the immunity standard EN 61000-4.

The IntelliVue MP20 patient monitor was tested for dips and interruptions, electrostatic discharges, burst and surge, using the Ecompact 4 (Haefely) immunity test equipment.

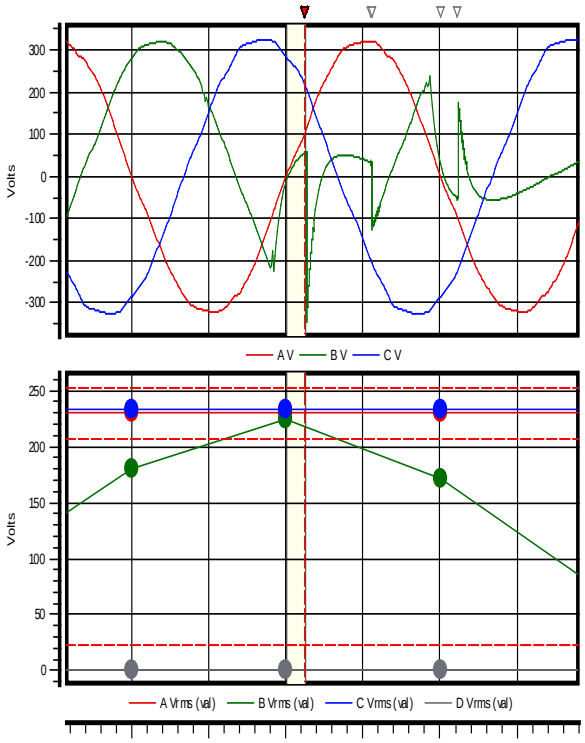

Fig. 4. Events' waveforms and the corresponding rms values

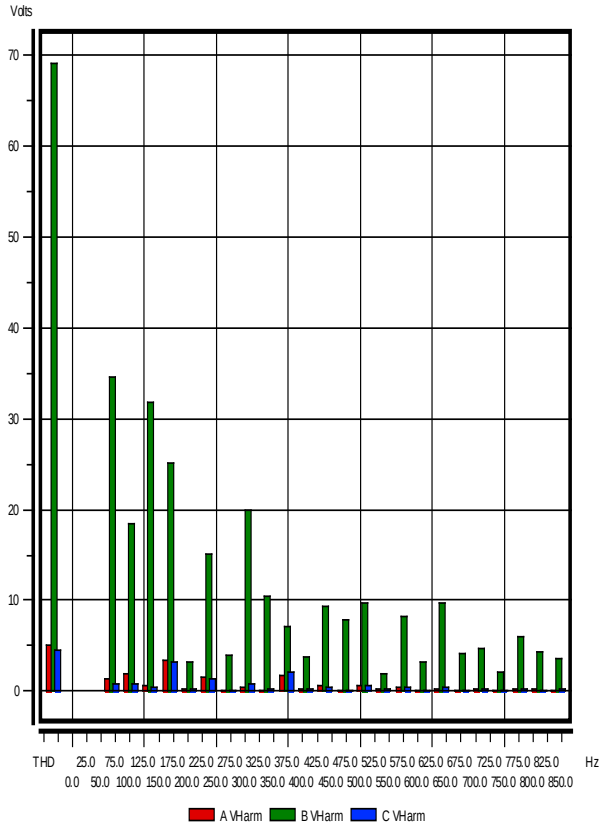

Fig. 5. Events' corresponding DFT chart

The equipment passed the dips and interruptions [12] and the surge (1.2/50μs) and to the burst tests.

In this situation, the low voltage grid was tested for conducted emissions. The test setup used the spectrum analyzer HM 5014 and the line impedance stabilization network LISN HM 6050-2 (Hameg Instruments), depicted in Fig. 6, in which the LISN connection is reversed.

According to Romanian specifications, the maximum allowed RF noise level injected in the low voltage network in the frequency range 150 kHz - 30 MHz, should not exceed 52 dBμV. Measurements revealed a RFI spectrum levels of almost 70 dBμV (20 dBμV in plus), both on the L (the blue line) and the N (the green line) conductors versus the protective conductor PE (Fig. 7.).

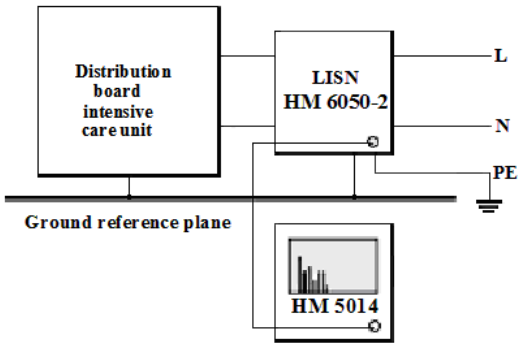

Fig. 6. Setup for measuring conducted emissions in the low voltage grid

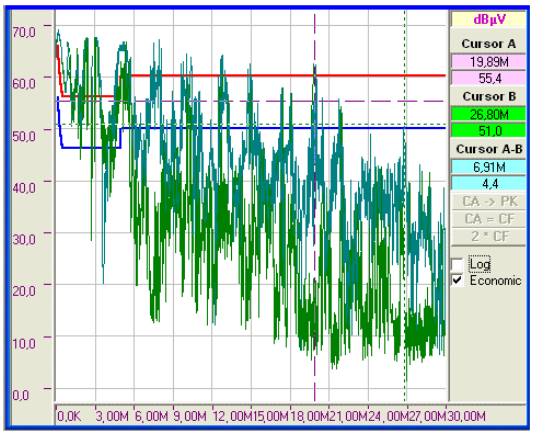

Fig. 7. RF conducted emissions injected in the mains network

As a result, on the low voltage grid incoming in the intensive care facility, a great amount of radio frequency interference was found, due probably to the medical equipment from the rest of the hospital. These common mode interferences can justify the patient monitor issues. It is also important to note the great radiation capacity of the cables in common mode interference which may also affect the monitor operation.

The most common mitigation method for common mode interferences is to retrofit on the mains port of all equipments a power line EMI filter, provided with a common mode choke, which consists of two identical windings on a single high permeability toroidal core, configured so that differential currents cancel each other, allowing high inductance values, typically 1–10 mH, in a small volume without fear of choke saturation caused by the mains frequency supply current. In the given situation, the use of EMI power line filters was not advisable, because ready made filters are all provided with transversal capacitors, very effective in conducting the common mode interference to earth, but determining in the same time leakage currents. Patient monitors are medical equipment patient-connected and in this case the

patient leakage currents must be even smaller than the enclosure leakage currents. The limits imposed on medical equipments, especially if patient-connected, usually makes impossible to use any reasonable size of transversal capacitor (a 50-Hz current of barely 10 μA flowing through the heart has the potential of causing ventricular fibrillation and even death).

Unlike other standards, in EN 60601 electrical safety is not considered to be dependent on voltage, but on leakage currents, because even a very low voltage, when applied to internal tissue, can cause leakage currents through the body, which may be fatal. The only way to solve the problem was to provide a circuit separation, in order to mitigate the electromagnetic emissions and maintaining electrical safety in medical electrical equipment. The most important step in achieving compliance with the electrical requirements of the standard is the use of an IEC 60601-1 compliant power supply or isolation transformer.

A medical electrical product must be designed so that it operates safely not only in normal, but also in abnormal and single fault conditions. Single fault conditions include the shorting or opening of electrical/electronic components, the failure or locking of motors, the blockage of air vents, etc. The shorting of basic insulation is considered a single fault, while the characteristics of double or reinforced insulation are considered such that it is not shorted under single fault conditions. The standard does not require that the medical device remain safe under the conditions of two or more independent faults.

The most efficient and finally less expensive solution adopted, was to separate the low voltage grid in the intensive care facility from the rest of the hospital, using an isolation transformer as a possibility of complying with the electrical requirements of EN 60601-1. Separation provided the following advantages:

- The isolation transformer (in this case a 25 kVA - Bender) allowed using equipment which otherwise would not comply with EN 60601-1 (e.g. a standard PC power supply almost certainly does not comply with the electrical IEC 60601-1 requirements).
- For separately powered components (e.g. PC, screen, printer and other terminals), separation permitted a much simpler and cost effective solution, rather than using for each component an EN 60601-1 compliant power supply.
- Isolating the neutral line from earth made the system resemble the IT system (IT grounding system simplifies medical product design in many situations).
- A grounded primary winding transformer was used, so the conducted interference injected by the low voltage grid was drawn to earth, mitigating the conducted interference.

A drawback of IT systems is that RCDs neither can function nor can be blamed for not intervening as a protection for both direct and indirect contacts, because the nature of the fault-loop, in se, prevents their proper operation rending their installation ineffective.

4. Conclusions

The paper definitely shows that an analysis of the compliance of the low voltage supply system in a medical facility, with respect to electrical power quality, beyond the standard EN 50160 and taking into account the standard EN 60601 for medical equipments and its related standards on electromagnetic compatibility is mandatory. This analysis is necessary because the standard EN 50160 is not an EMC (electromagnetic compatibility) standard and does not give compatibility levels or emission limits, given in the standards EN 61000-X.

The results depict the importance of preparing a safe electromagnetic environment for medical equipment and of careful maintenance of the power supply. As one could infer from the paper, many potential problems can be solved by ensuring adequate separation of sources and victims of interference. Unfortunately the present approach was dedicated only to conducted interference, but in the electromagnetic environment of a hospital there is a plenty of equally important radiated interference (mobile phones, radiation from the vehicles' antennas crosstalk problems when installing mains and data cables), quite easy detectable, but rather difficult to mitigate without expensive costs.

The main conclusion drawn from this paper is that when building a hospital, from the early stage of design supplementary electrical precautions should be taken into account, in order to achieve electrical power quality and a clean electromagnetic environment.

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