INCREASED POLLUTION IN THE PROTECTIVE EARTH

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Abstract. EMC has received increasing interest over past decade. Several standards regarding EMC have been developed. Although manufacturers design and manufacture interference-free equipment in accordance with standards, disturbances are still a problem. According to the current EMC legislation, conducted emissions are to be measured using a LISN between the utility grid and the equipment under test. However, it should be noticed that there is no correspondence between the EMC environment measured at an installation site and the EMC environment measured by the LISN. In this paper some documented cases where electrical equipment are disturbing each other are highlighted and EMC standards are discussed. In the paper it is shown that EMC related problems occurring in the examples all have the same origin: current flow in the PE. The leakage current is fed into the PE via the filters or by a capacitive coupling to the ground. The increased use of power electronic equipment might lead to the need of a complete re-build of the entire grid. An alternative solution to the problem would be to stop the leakage current from being fed into the PE.

Keywords. EMC, LISN, protective earth, leakage current.

Electro-Magnetic Compatibility (EMC) has rapidly recieved increased attention. EMC implies that different units and types of electrical equipment do not interfere with each other, i.e. that electrical equipment does not disturb, nor be disturbed by other electrical equipment. International and national recommendations and standards Swedish Standard [1] and IEC Standard [2-5] have been developed, and manufacturers are today obliged to design interference-free electrical equipment. In spite of these efforts, some electrical equipment designed to meet and fulfill the new standards and recommendations does interfere with and disturb other electrical equipment.

An example of a phenomena thats affects EMC is the increased pollution of the Protective Earth (PE). It should be noticed that the Protective Earth wire is denoted as PE wire. The PE is, except from being a safety arrangement, also defined as an equipotential point or plane which serves as a reference voltage for a circuit or a system. To serve as an reference point, there must be no current flow in the PE. Pollution of the PE seems to have two causes: electric devices equipped with filters, and capacitive coupling to the ground. Typical sources which give rise to leakage currents in the PE are devices using high switching frequencies. For example, in order to fulfill the EMC standards regarding low emission, screened induction motor cables are often used during Pulse Width Modulated (PWM) operation. Maggs et.al. [6] found that the major source of the radiated emissions from variable speed drives was the shielded cable which was connected to the motor.

Another example of disturbances caused by PWM drives are bearing currents. Bearing currents generated by capacitive coupling between the stator windings and the stator shell may cause bearing material erosion and early mechanical failure. The use of a PWM inverter sources increases the magnitude of this problem. Erdman et.al. [7] found that the rotor voltage rose to a value of fifteen times larger when an AC induction motor operates with a PWM inverter compared with a pure sine wave.

HF-fluorescent tubes are equipped with filters which produce a leakage current through the earth conductor. The number of HF fluorescent tubes that can be operated on one Residual Current Device (RCD) is limited to 50 tubes by the leakage current in a balanced three-phase grid, Osram [8].

Unbalanced screened cables, for example coaxial cables, are frequently used in audio and TV studios. The loop formed by the PE wire and the screen of the cable is a source of disturbances. Measurements show that low amplitude currents (10 mA) give rise to an increased noise level, Muncy [9]. This disturbance source also creates flicker in TV, Lidberg [10].

This paper highlights some documented cases with EMC related problems. The examples are from various fields; PWM motor drives, fluorescent lights and TV audio studios. This paper shows that EMC related problems occurring in the above examples all have the same origin: current flow in the PE. The function of filters as well as different kind of interference factors which occur on the grid are described.

INTERFERENCE FACTORS

Interference problems can in the case of a three-phase grid be illustrated as in figure 1. Under normal operating conditions, the transmission of energy from the grid to the load passes via the wires L_1, L_2, L_3 and N. There are other system configurations such as IT-grids and four-wire systems. However, the various systems are all about the same in princip. In the figure, the wires are enclosed by a circle. The sum of the currents enclosed by the circle shall under normal operating conditions be zero. The circle also indicates a proper location of the RCD. Current ”A” represents the radiated emission (for example capacitive coupling to the ambient). Current ”B” represents the guided emission which does not flow through the PE wire. The current flow through the PE wire is in a similar way denoted ”C”. All three currents ”A”, ”B” and ”C” try to form a circuit back to the source.

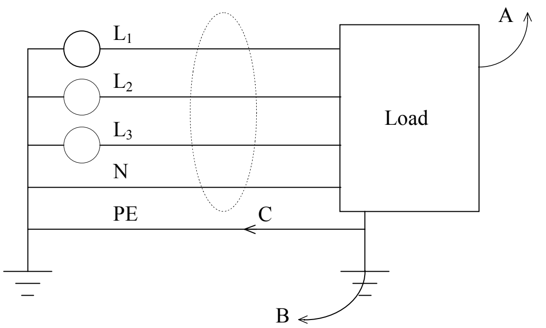

Figure 1: Interference factors in a three-phase grid.

In figure 1 it can be seen that if all currents are brought back via the phase wires or the neutral wire, the system is a good definition of a grid with low emission levels. On the other hand, if the sum of the currents enclosed in the circle is not zero, some kind of leakage currents exists.

Ott [11] states that common mode current on cables can be measured with a high-frequency clamp-on current probe and spectrum analyser. The clamp-on current probe should then enclose the L_1, L_2, L_3 and PE wires as indicated in figure 2. The common mode current is related to the radiated emission measured during EMC tests carried out in the laboratory, Gokani et.al. [12]. Since common mode emission is the predominant emission mechanism in most products this common mode current determines the maximum emission. At an actual installation the situation resembles that shown in figure 1, where the load is connected to the PE. The PE connection can be effected by means of a wire or by means of a steel foundation. If the current probe is connected according to this method not only will the radiated emission of type ”A” be measured, but also the current of type ”B”. However, if the current clamp-on probe is instead placed according to the circle in figure 1, the common mode current containing types ”A”, ”B” and ”C” is measured. The proposed technique makes it possible to measure common mode currents and the EMC status for an entire plant.

LISN

According to the current EMC legislation, conducted emissions are to be measured using a Line Impedance Stabilizing Network (LISN) between the utility grid and the equipment under test. Figure 2 shows the layout of a LISN network connected to equipment under test. LISN is an excellent circuit as regards to realizing stable and reproducible measurement of conductive noise without influence from the utility grid, by keeping the impedance of the grid at the terminals of the equipment under test constant. The LISN also suppresses noises on the utility grid Nitta [13]. However, it should be noticed that there is no correspondence between the EMC environment measured at an actual installation site and the EMC environment measured by the LISN.

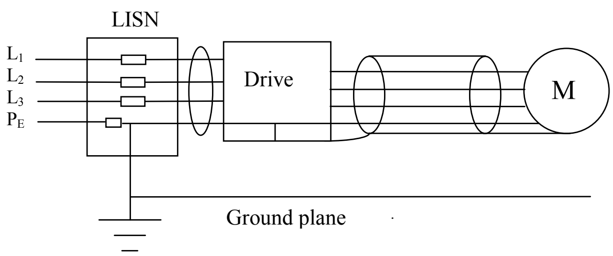

Figure 2: Diagram of LISN network connected to equipped under test.

Nitta [13] claims that: ”As there is no correspondence between the electro-magnetic environment measured at installation site and the evaluation value specified by regulations, the matter that noise reduction/tolerant techniques are separate from regulation and still remain in skillness of trial and error shows the fundamental features of EMC techniques”.

EMC filters

In order to fulfill the EMC standards regarding low emission, HF devices must be equipped with filters. These filters fulfill two functions. The first is to prevent conducted disturbances, which are traveling from the load to the power supply, differential mode disturbances. The second is to short-circuit the voltage formed between the PE wire and the phase-neutral wires, common mode disturbances. Figure 3 shows a grid and a load equipped with filters. The figure, the noise voltage (differential mode voltage) between the phase and the neutral wire is disconnected by means of the capacitor C_x. The capacitive leakage current (common mode current) generated by the stray capacitance C_s at the load is disconnected by means of the capacitor C_y. In the figure, Z_{L1}, Z_N and Z_{PE} represent the impedance of the phase, neutral and PE wires. The PE wire feeds the leakage current back to the load.

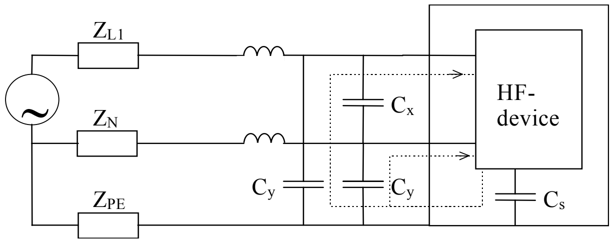

Figure 3: Diagram of the grid and load equipped with filters.

Ground

The term ”ground” originates from the very beginnings of electric power. For safety reasons, a ground or earth ground which prevented objects of becoming ”live” was needed. In the disipline of the electronics age this same term is now used to denote a reference point or an equipotential plane that serves as a reference potential for a circuit or a system. According to [11], ground is subdivided into ”safety ground” and ”signal ground”. In practical applications, the signal ground is a low-impedance path for current to return to the source.

Safety ground systems are required for electrical safety, and are clearly defined and specified by electrical codes. Safety ground systems ensure safety by providing a low-impedance path for fault current so that circuit breakers and fuses will operate rapidly in the case of overload or insulation failure.

It should be clearly understood that ground systems are effective in controlling electromagnetic interference at low frequencies. The grounding techniques everywhere in use today were developed to deal with power-line frequency problems over a century ago, when high frequency meant 20 kHz. Success in noise free system design depends on always knowing where the current flows [9].

ANALYSIS OF SOME DOCUMENTED PROBLEMS RELATED TO EMC

PWM-inverter motor drives

Bearing currents and voltages under 50 Hz and 60 Hz sine wave operation of AC induction motors have been recognized problems since 1924. Bearing currents generated by capacitive coupling between the stator windings and the stator shell may cause bearing material erosion and early mechanical failure. The use of PWM drives increases the magnitude of this problem. In [7], it is found that the rotor voltage rose to a value of fifteen times larger when an AC induction motor operates with a PWM drive compared with a pure sine wave. In the paper a new electrostatic shielded induction motor is suggested as a possible solution to the bearing current problem during PWM operation. The copper folio shield is grounded to the motor frame which in turn is connected to the PE. It should be noticed that the currents which formerly flowed to the ground through the bearings merely take a different course when this method is used. When the copper shield is used, the current will no longer flow through the bearings, but via the copper shield. However, the current will still flow through the ground giving a leakage current of type ”B” or ”C” in accordance with figure 1.

In order to fulfill the EMC standards regarding low emission, screened induction motor cables are often used under PWM operation. In [6] it is found that the major source of the radiated emissions from variable speed drives was the shielded cable which was connected to the motor. The radiated emissions are designated as ”A” in figure 1. The shielded cable that connects the motor to the drive provides capacitance between each phase and ground as well as between the phases. As both ends of the shield in the cable are connected to the ground, a capacitive current will be induced when the drive operates, see figure 4.

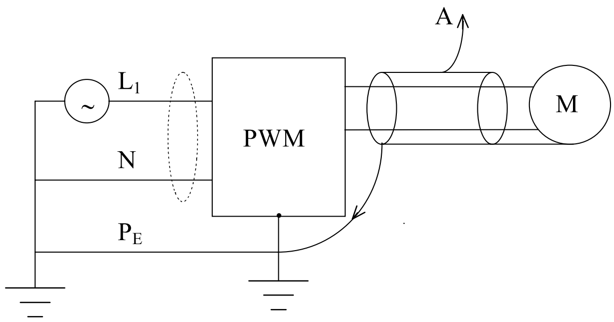

Figure 4: Diagram of a PWM drive and a grid. The PWM drive causes leakage current to the ground and radiated emissions denoted ”A”.

The amplitude of the induced capacitive shield current is not negligible. Measurements on a 15 kW PWM induction motor drive with a fixed carrier frequency reveal current with a peak to peak amplitude of 1 A in the earth from the motor cable, [12]. In the test, the motor was connected to the drive using a 10 m length of screened cable with the screen connected to the frame of the drive and the frame of the motor. In order to prevent damage or failure of the equipment, the capacitive shield current must be limited. High capacitive shield currents may not only lead to over-current in the PWM inverter, but also lead to over-current in the filters and to nuisance tripping of the RCD. For a given motor and drive, the amplitude of the current is determined by the type and the length of the cable. Hence, the cable must, according to the manual provided by the manufactures of the drives, not exceed a given length Euroterm [14].

The use of filters may also attenuate conducted emission on the PE, ABB [15] and CEGELEC [16]. These emissions can lead to several technical problems in floating (IT) networks, (TN) networks and (TT) networks. ABB and CEGELEC recommend an alternative solution to filters. This is to fit a single filter to suppress the conducted emission of the whole installation ("global" filter approach). A further solution is, instead of using filters, to isolate all disturbed equipment from the disturbing equipment by means of a transformer.

Fluorescent lights

The same lack of compatibility, or perhaps one can say incompatibility, between filters and RCD occurs during the operation of HF fluorescent tubes. HF fluorescent tubes are equipped with filters which produce a leakage current through the PE. The leakage current is equal to the current denoted by "B" or "C" in figure 1.

The leakage current limits the number of HF fluorescent tubes that can be operated on one RCD. One manufacturer stipulates a maximum of 50 HF fluorescent tubes in a balanced three-phase grid [8]. However, limiting the numbers of tubes does not solve the problem with leakage current injected to the PE. It is just one way to sweep the problem under the carpet. Figure 5 shows measurements of the PE at the terminal when one single and when two fluorescent tubes are connected Westlund and Andersson [17]. The measurements are performed with a 20 MHz current probe. As can be seen, one fluorescent tube causes a distortion at a specific frequency which corresponds to the switching frequency of the HF device. Since the switching frequency varies from one HF device to another, a beating will occur when two HF devices are connected. This phenomenon is clearly visible in figure 5.

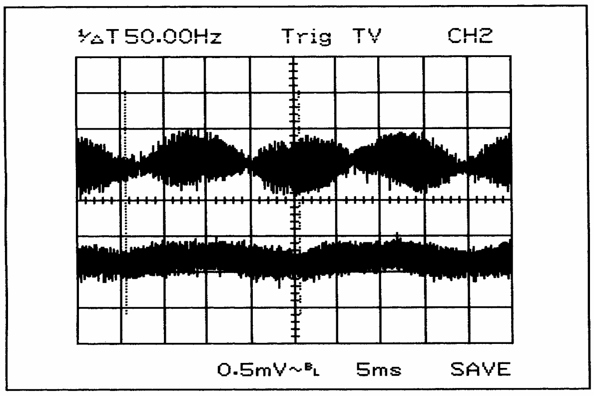

Figure 5: Voltage at the PE when one (lower curve) and two (upper curve) fluorescent tubes are connected.

In Figure 6, measurements from 24 fluorescent tubes are shown. The magnitude of the disturbances is high compared with one single fluorescent tube. In theory, for 24 tubes the peak to peak value will be 24 times higher, and the RMS value $\sqrt{24}$ times the value for one single tube. These are worst cases occurring when the tubes have a peak simultaneously, which will happen now and then.

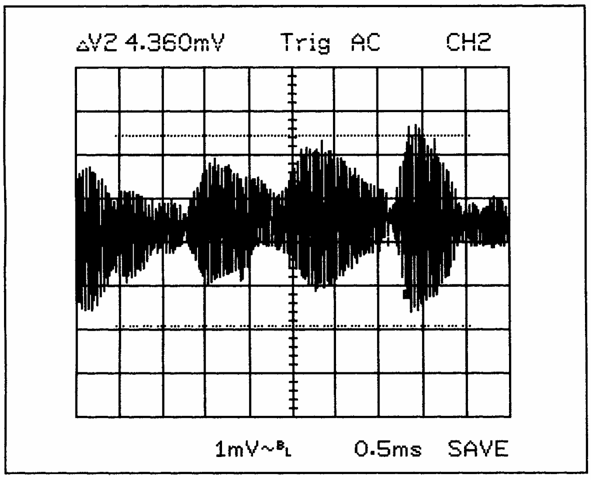

Figure 6: Voltage at the PE when 24 fluorescent tubes are connected.

The pollution at the PE if, say, 1 000 fluorescent tubes were connected would be substantial. In, for example, schools, hospitals and office buildings it is common that 1 000 fluorescent tubes are connected to the same transformer. The measurements presented were both performed when the lights were turned on. Measurements performed with the lights switched off also showed a leakage current to the ground. The capacitance of the cables in parallel with the filters of the HF devices form a path between the neutral wire to the PE wire for HF disturbances emanating from other sources.

TV and audio studios

Unbalanced screened cables, for example coaxial cables, are frequently used in TV and audio studios. The loop formed by the earth wire and the screen of the cable is an excellent source of disturbance. Measurements show that low amplitude currents (10 mA) give rise to an increased noise level, [9]. In order to avoid disturbances from the leakage currents in the PE the TV broadcasting company in Umeå, SVT, has obtained an exemption from the standard and introduced a system with six conductors. This system is based on three-phase conductors, one neutral conductor and two separate PE conductors, [10]. One is used as a signal ground while the other one is used as a "trash" earth, i.e. as an ordinary PE conductor. The reason for this division is the extreme sensitivity to TV equipment used. A noise input of 1 mV will result in visual problems such as tracks in the TV picture.

SOURCES OF ERRORS AND SOLUTIONS

All of these documented cases have EMC related problems with the same origin: leakage current flow through the PE. The leakage current is fed into the PE via the filters, by a capacitive coupling to the ground or by screens connected to the ground. In the cases documented, the EMC problem had been solved, or proposals for solutions made such as the use of sectioning of RCDs, isolation by means of transformers and by the use of two separate PE conductors. The question is whether these are proper approaches to the problem of leakage current in the PE. The increased use of power electronic equipment might lead to a complete re-building of the entire grid being required. An alternative solution to the problem would be to stop the leakage current from being fed into the PE.

Some of the reasons for the EMC problems being faced today are:

- discrepancy between LISN and the real utility grid
- resonance phenomena when filters are connected in parallel
- the fact that filters are balanced but connected in an unbalanced system (single phase and plug)
- noise voltages from the grid are not taken into consideration when devices and filters are EMC tested using LISN
- the PE is considered as a trash bin for unwanted voltages and currents

Solutions

Noise elimination takes place:

- at the source
- directly, the shortest path to the source
- in a way that prevents the leakage current to reach sensitive equipment.

An interesting filter layout has been produced by the manufacturer Schaffner [18]. Instead of being fed back to the source via the PE, the leakage current is fed back directly to the DC-link of the drive, see figure 7.

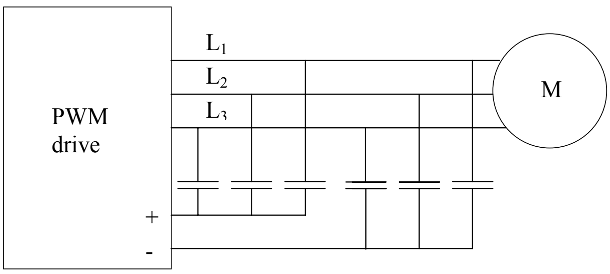

Figure 7: Diagram of a filter which feeds the leakage current directly back to the DC-link.

This filter concept will, according to the manufacturer, reduce the induced high frequency current in the cable. Thus, there is no need for a shielded cable and thereby no leakage current, in bearings or in the PE. The filter is, according to the manufacturer, intended to be complementary to PWM drives and there is not much information from the manufacturer avaliable.

Conclusions

EMC has received increasing interest over the past decade. EMC implies that different units and types of electrical equipment do not interfere with each other. In spite of these efforts, some electrical equipment which is designed to meet and fulfill the new standards and recommendations does interfere with and disturb other electrical equipment. This paper demonstrates that several units of equipment which are EMC approved cannot necessarily operate together in an actual installation.

In order to fulfill the EMC standards regarding low emission, HF devises must be equipped with filters. These filters have two functions to fill. The first is to prevent conducted disturbances from traveling from the load to the power supply; differential mode disturbances.The second is to short-circuit the voltage formed between the PE wire and the phase-neutral wires; common mode disturbances. According to the current EMC legislation, conducted emissions are to be measured using a LISN between the utility grid and the equipment under test. LISN is an excellent circuit for realizing the stable and reproducible measurement of conductive noise without influencing the grid at the utility grid, by making the impedance of the grid at the terminals of the equipment under test constant. However, it should be noticed that there is no correspondence between the EMC environment measured at an actual installation site and the EMC environment measured by the LISN.

In the paper, various documented cases where EMC related problems exist, are hightlighted. All these documented cases have EMC related problems with the same origin: leakage current flow through the PE. The leakage current is fed into the PE via the filters or by a capacitive coupling to the ground. The frequency of the leakage current in the cases documented often is at the 10-150 kHz frequency range. The experiences of measurements at these frequencies are often neglectible.

The increased use of power electronic equipment might lead to a complete re-building of the entire grid be required. An alternative solution to the problem would be to stop the leakage current being fed into the PE. An interesting filter layout has been produced by a manufacturer. Instead of being fed back to the source via the PE, the leakage current is fed back directly to the DC link of the drive.

Finally, in the paper an alternative method of measuring common mode disturbance has been proposed. The method proposed enables measurements to be made of the EMC status of an entire plant.

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