THE USE OF PROTECTIVE EARTH AS A DISTRIBUTOR OF FIELDS AND RADIATION

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Abstract. Apart from being a safety arrangement, the protective earth, PE, is also defined as an equipotential plane which serves as a reference voltage for a circuit. Interest in the PE for EMC reasons is focused on an equipotential point. Still, most PE installation on site is carried out as a safety arrangement.

In order to fulfill EMC standards regarding low emission, equipment is shielded and the shield is connected to the PE wire.

The purpose of this paper is to show that electrical equipment distributes its electrical fields using the PE wire.

Measurements have been taken on light fittings.

Keywords. EMC, electrical field, protective earth, shield, leakage current.

I. INTRODUCTION

Noise in the protective earth wire (PE- wire) causes problems in many areas: [1] PWM AC drive problems such as bearing current [2] or conducted emissions [3]. It also causes the problem of disturbance in audio [4] and TV studios [5] and signal-to-noise problems in LV Powerline Communication [6].

In order to limit radio disturbances the EMC regulations have restrictions that apply to conducted emissions.
[7], [8] Power lines and other conductors are able to act as transmitting antennas.

Increased noise in the protective earth wire (PE- wire) [1] together with increased connection of shielded equipment to the PE- wire could cause an increased electrical field and radiation. Today, the use of equipment that has a low generation of noise is not enough to achieve low emissions. The whole grid could be a distributor of noise and all connected equipment would thereby act as transmitting antennas.

There are at least two ways of stopping this development: Less noise from equipment or a new concept for the grid.

This paper describes the use of PE in power distribution systems and explains why the PE- wire acts like a distributor of fields and radiation. The normal use of PE in power distribution and the use of PE as a signal ground are presented in section II. This section also describes how the body of a building may act as a ground plane. Section III presents measurements on different types of light fittings. Measurements have been performed on light bulbs, compact fluorescent lamps and HF fittings. Finally, section IV presents results and an evaluation of the measurements.

II. NORMAL APPLICATION OF PE

Originally, the PE-wire was introduced to protect human beings from dangerous voltages and to protect properties from being destroyed if an electrical fault occurred. The PE-wire is designed to form a low impedance circuit for fault currents at power system fundamental frequency, 50Hz or 60 Hz. The use of non-linear loads and power electronics causes harmonics and radiated emissions. A normal practice today is to use filters and screened cables to reduce these harmonics and radiated emissions, the filters and screens being connected to the PE-wire. The currents injected from the filters and screens to the PE-wire are not of fundamental frequency, but often of a high frequency. At these high frequencies the PE-wire will not form a low impedance circuit.

A. Power distribution and the protective earth (PE).

The transmission of energy in a three phase distribution system only needs three wires L_1, L_2, $L_{3,}$ as illustrated in figure 1. Figure 1 shows the three main parts of a power system: generation, transmission and distribution. The power generated in the generator is transformed from a low voltage, below 10 kV, to high voltage above 100 kV. The reason for using a high voltage is to achieve lower losses for the transmission of energy over long distances. The transformer used to increase the voltage from 10 kV to 100 kV is called T1 in the figure. It is worth noticing that only three wires are needed to transmit the energy from the generator to transformer T1 and then via the transmission wires to the distribution transformer T2. The distribution transformer T2 has three wires on the high voltage side and five wires on the low voltage side. Apart from the ordinary three wires for the energy, two additional wires, N and PE, are used. The neutral line, N, is only used for one-phase loads. Balanced loads such as three phase induction motors need no neutral line. To meet security aspects both for human beings and properties there is a protected earth system including the protected earth wire, PE-wire. In the figure, dotted circles enclose the wires. The sum of the currents enclosed by the circles shall under normal operating conditions be zero. Current in protected earth wire appears only when there is a fault. The protected earth system is built to carry high fundamental current for a short time.

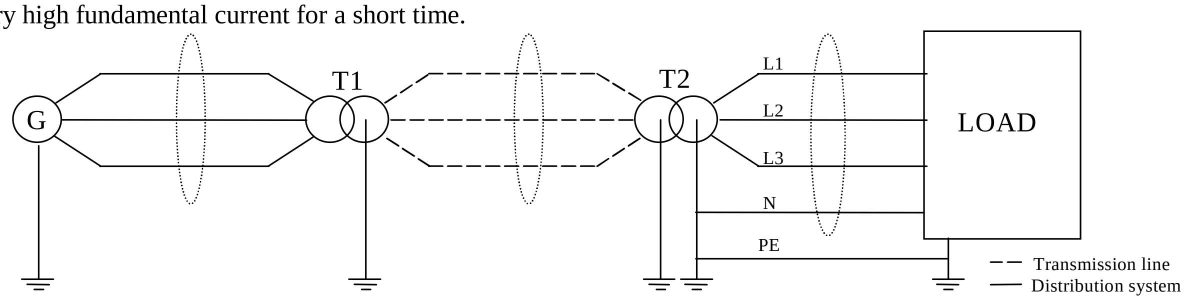

Figure 1. *The transport of energy in a three-phase distribution system. The neutral line N is only used for one-phase load. The protected earth system including PE-wire meet security aspects for both human beings and properties. The sum of the currents enclosed by the dotted circle shall under normal operating conditions be zero.*

B. EMC and the protective earth (PE).

All equipment using electronics for converting, amplifying or any other purpose can, in some way, bee seen as a signal source for conducted or radiated emissions. In order to reduce radiated emissions from cables and electronic equipment, the technique of screening is often used. The principle is to collect radiated emissions using a screen and transform the collected signal to a current and send the current the shortest way back to the source.

In measurement applications, the signal ground is based on the same idea as the PE-wire: "a better definition for a signal ground is a low impedance path for current to return to the source " Ott [9]. In equipment feed from public mains (400/230 V) the PE-wire is an easy way to get a return connection for the current from the screen.

Adjustable speed AC drives with Pulse Width Modulated, PWM frequency converters often use screened motor cable to meet EMC regulations regarding radiated emissions [10]. The screened motor cable acts like capacitors with one leg connected to the phase line and the other to the PE- wire. In this case the radiated emission is converted to conducted emission from the screened motor cable to the PE- wire (see figure 2 and figure 3). The motor cable earth current (screened motor cable) for a 15 kW induction motor drive system reaches peak-value of 0.5 A at a frequency of about 106 kHz [11]. The 106 kHz frequency component is below the EMC filter frequency and is not regulated by EMC standards. The frequency range concerned by the current EMC regulations is set between 150 kHz and 30 MHz [12].

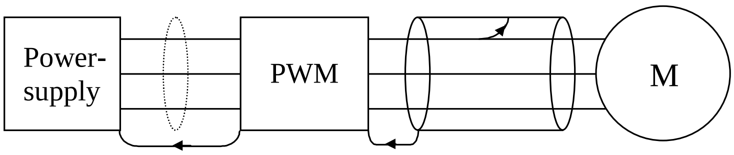

Figure 2. *This figure, that could be the load in figure 1, shows the principle for the screening technique. The power electronics in the Pulse Width Modulated (PMW) Converter (used to convert the power frequency from the power supply to the motor M achieving variable speed) generates noise radiating from the motor wires. A screen collects the radiated emissions and transforms the collected signal to a current and sends the current the shortest way back to the source, the PWM- converter. Unfortunately, and depending on the frequency of the noise, the shortest way often passes the power supply.*

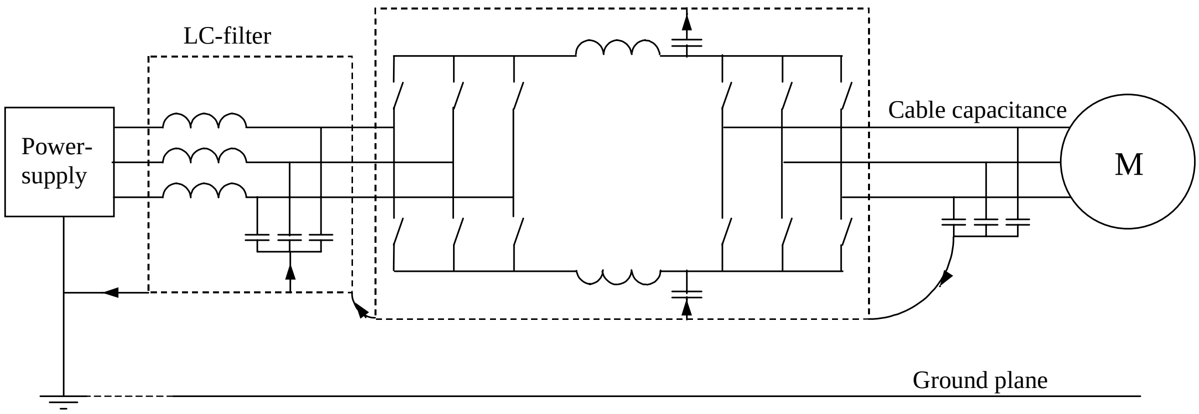

Figure 3. *Showing some of the ways taken by the noise current in figure 2. The mutual capacitance between wire and screen collects the radiated disturbance as a noise current to the PWM-converter´s casing. Mutual capacitance's between the power electronics and the casing collect or add noise current depending on construction and frequency. An EMC- filter of LC- type returns most of the noise current between 150 kHz and 30 MHz back to the PWM- converter. Most of the noise current passes the power supply by the PE- wire before reaching the PWM- converter.*

Figure 4 shows the impedance for 2.5 mm^2 Cu -wire with a length of 1 m and 100 m. $l<\lambda/10$ gives an upper limit of 30 MHz for a length of 1 m and 300 kHz for a length of 100 m.
The self-inductance of a round straight wire can, when $l<\lambda/10$, (where l is the length of the wire, r is the radius of the wire and λ is the wave length for the corresponding frequency, all units are in meter) be approximated by:

$$L_S = 2l\left(\ln\frac{2l}{r} - 1\right)\cdot 10^{-7}\,(H) \qquad [1]$$

When $l>\lambda/10$, the impedance of the wire approaches the characteristic impedance Z_0 for the wire.

The noise current in the PE is only a fraction of the short circuit current, but the frequency is much higher. *If the calculations for the power system are made for 50 Hz or 60 Hz it might appear to meet EMC regulations, but this could be a big mistake. The reactance for the PE wire increases with the increasing frequency and would soon dominate the impedance. This knowledge is of great importance when using the PE wire as a grounding wire for high frequency component. "The ac power ground is of little practical value as a signal ground* "Ott [9]

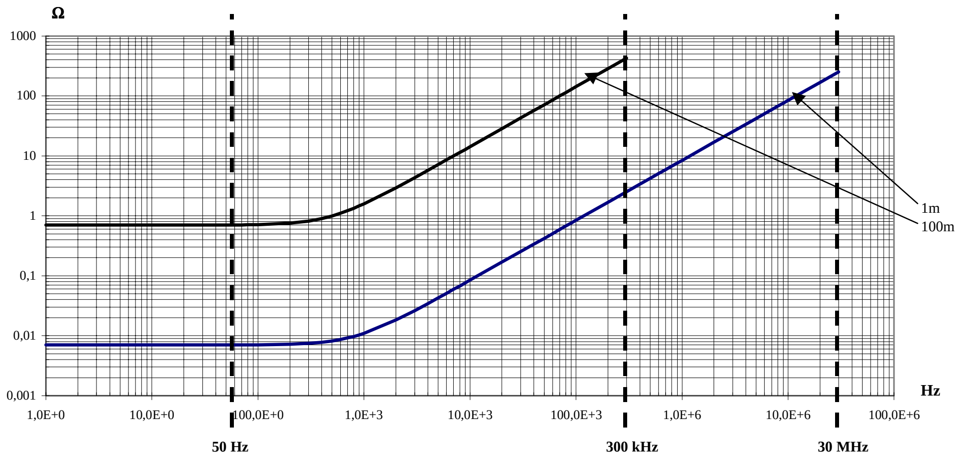

Figure 4. *Showing the impedance for 2.5 mm^2 Cu -wire with a length of 1 m and 100 m.*

C. Protective earth wires (PE -wires) and ground plane.

Normally the protective earth is connected to the water conduit and other conductors in a building, which together function as the ground plane. This will reduce the impedance in the grounding system for the EMC purpose, but normally the distance between all connections is long and still the conducting system is not made especially for the EMC purpose, it only happens to be there, as illustrated in figure 5.

Power distribution in the case of a three-phase grid is established by using four wires L_1, L_2, L_3 and N as illustrated in figure 1. The fifth wire, the PE, is a safety arrangement. In the case of a three-phase grid inside a building, the body of the building or other conducting parts may operate together with the PE- wire. But the body of the building or other parts cans never replace the PE- wire as a safety arrangement. It is important that the protected earth system is always intact, all the way from the transformer to the protected equipment.

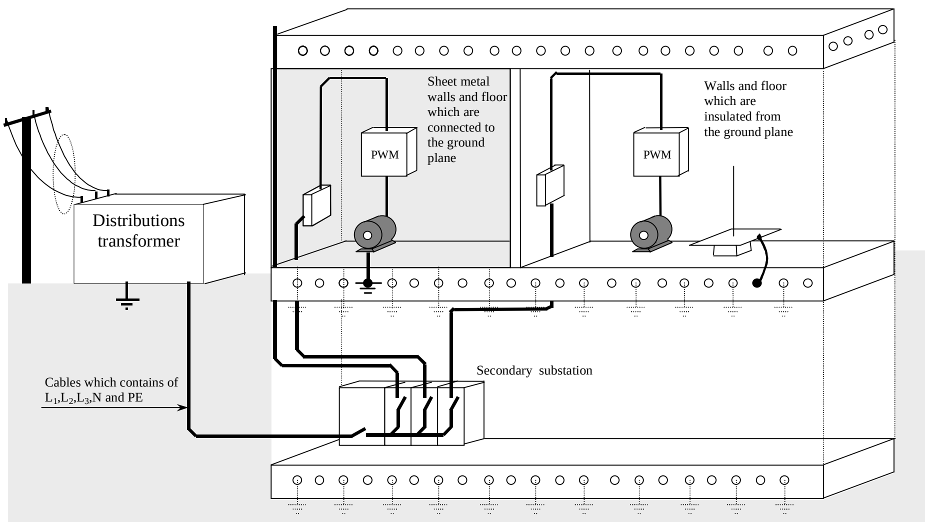

Figure 5. *Grounding system for a building. The distribution transformer has a grounding point for the grid. Also, the fundament for the building acts like a grounding point at the same time as it functions as a ground plane for the entire installations. Depending on how the electrical equipment is connected to the ground plane, different situations arise in the electrical field. Measurements according to MIL-STD 461D are made with respects to the floor ground plane in the room.*

For EMC reasons, the body of the building or other conducting parts operate like a ground plane. If the PE-wire connected to this ground plane is impedance-free, they act together and there will not be an electrical field. If there is different potential on the PE-wire with respects to the ground plane there will be an electrical field.

Normally, there is a grounding point at the transformer as seen in figure 5. This grounding point is used to avoid potential differences between conducting parts and the protected earth. Ground loops can appear when the PE-wire is connected to equipment that is already connected to ground through reinforced concrete, water mains systems or other conducting parts. These loops normally cause no problem if there is no current flowing in the protected earth system. If the PE-wire is used only for fault currents at fundamental frequency there will be no current flowing in the protective earth.
If current is flowing in the protected earth system and causes magnetic fields, there are at least two solutions: galvanic insulation and common-mode chokes. The first one - the use of insulation, means that all connections to the ground plane are cut for the PE-wires. The second way - the use of common-mode choke, figure 6, is common in the electronics and communications field, [9] but also for power frequency handling [13]. The common-mode choke acts like a 1:1 transformer balancing the current to be alike, and the current that flows in one wire prefers to go back in the other wire instead of using any other ("stray current", I_S) way. One common way to make that 1:1 transformer is to use a toroid core and put the signal or power line through the hole.

For power frequency handling, the drawback with these two methods, is that they could affect the grounding system for EMC reasons. The first method - insulation, could increase the electrical field by only using the PE-wire for high frequency grounding. The second method - using common-mode choke, (only for power frequency handling) can possibly increase the impedance in the PE-wire, but if there is a low-impedance contact with the ground plan system, a low electrical field is effected.

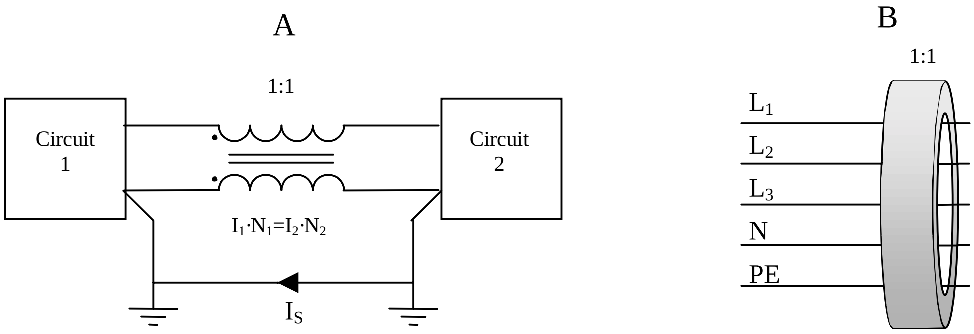

Figure 6. *Common- mode choke acts like a 1:1 current transformer balancing the current to be alike. The current that flows in one wire prefers to go back in the other wire instead of using any other (I_s) way. One common way to make that 1:1 transformer is to use a toroid core (B) and put the signal line or power line through the hole.*

D. Installation of equipment tested for EMC reason and the use of LISN.

Normally, when measuring the conductive noise transmitted from Equipment Under Test (EUT) to the AC-main, a Line Impedance Stabilization Network (LISN) is put between the AC- main and EUT. The LISN is an excellent circuit with regards to realizing stable and reproducible measurements of conductive noise without influence from the utility grid, by keeping the impedance of the grid at the terminals of the equipment constantly under test. The LISN also suppresses noises on the utility grid. Nitta [14] meant "that the real conductive noise on the AC – main can't be measured by LISN and 50 Ω-input impedance instrument specified by regulations such as CISPR". There are at least three factors behind this statement: (i) Normally the test is made with a short connection between EUT and the ground plane. The use of a short connection means low impedance for the PE-connection to the ground plane, which is very difficult to achieve in a normal installation. (ii) Only one EUT at a time is tested. One EUT makes it easy to handle the test, but no attention is being given to problems like the interaction between different EUT. (iii) EUT that has passed the EMC-test is often equipped with an EMC- filter. The test has no specification on the filter characteristics regarding disturbances from the grid or interaction between different filters connected to the grid. EMC filters in equipment are often able to connect signals and noises between phase, neutral and protected earth wire even if the equipment is turned off.

E. Passive and active source.

The grid is designed for the fundamental power frequency (50 or 60 Hz). For all sources the electrical field at the power source can be handled by the PE-wire system. This is not so for high frequencies. Sources for electrical fields have to be divided into two groups - passive and active sources. An active source has some kind of electrical conversion and injects noise currents to the PE-wire. One example of an active source is a PWM converter. A passive source is a device connected to the PE-wire that does not inject noise currents to the PE-wire. Examples of passive sources are light fittings with light bulbs or metal enclosed apparatuses like electrical machines. A passive source is only able to work like an antenna, which radiates the noise current fed through the PE-wire as an electrical field to the air. If there is no active source, there will not be any electric field from the passive source

III. MEASUREMENTS ON LIGHT FITTINGS.

A. Measurement set-up

Figure 7 shows the set-up used to measure the noise in the PE-wire generated in the load. In this case three different kinds of light sources have been used; light bulbs, compact fluorescent lamps and HF–fittings. In order to minimize disturbance from the power supply, a single-phase toroid transformer (700 VA) was installed together with an LC-filter on the primary side of the transformer. The feeder cable, rubber insulated mains flex, 3 core, conductor area 2.5 mm^2 had a total length of 165 m, and it was never placed less than 10 cm from the ground plane along the whole length. No LISN was used.

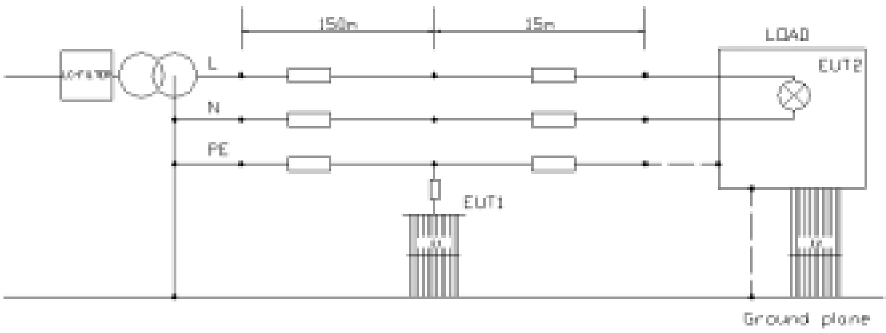

Figure 7. *Set-up for measurements on light fittings*

Equipment Under Test, EUT1, at 150m, consisted of a round aluminum plate with an area of $0{,}09\pi$ m^2 which was connected to the PE-wire with a 2 m PVC cable 3 core international mains lead, conductor area 1.5 mm^2 using only the PE-wire. EUT1 could represent a device with no active component within itself e.g. a stove that only consists of linearly loads and has a casing that is connected to the PE-wire.
The EUT2 (load), at 165m, consisted of five configurations, no load, six light bulbs, nine compact fluorescent lamps, nine compact fluorescent lamps with added shielding, two HF–fittings.

HF–fittings and compact fluorescent lamps are to sources of light that reach energy-efficient light working with high frequency switching electronics like the PWM- converter in figure 2 and 3. The compact fluorescent lamps are only connected to phase and neutral wire, while the HF–fittings also have a filter that is physically connected to the PE-wire. The HF–fittings also have a conductive glass to achieve a better shielding.
In order to get similarity in the measurements, the luminous flux was compared between the different loads in EUT2. Therefore, measurements were taken on six light bulbs (100W/1380lm each), nine compact fluorescent lamps (15W/900lm each) and two HF–fittings (58W/4800lm each).

EUT1 and EUT2 were placed in different rooms, with sheet metal walls and metal girders in the floor and ceiling, so that the disturbance between them was minimized. In all measurements the ground plane was used as a reference point. Measurements were taken in several different ways, shielded and unshielded light fittings, connected and unconnected to the PE-wire and connected and unconnected to the ground plane.

B. Carrying out measurements

The electrical field, E-field was measured with a spectrum analyzer and an active rod antenna according to MIL-STD 461D and STD 462D, both in MP1 and MP2, [15], [16].

The STD 461D and STD 462D prescribe what test equipment to use and how to set up the test site. It also prescribes which frequencies to measure, and sets a limit for the levels. The standard covers several different measurement types, depending on the environment the EUT will be used in. Both conducted emissions and conducted susceptibility, as well as radiated emissions and radiated susceptibility are covered. There are also different tests for electrical fields and magnetic fields. The part of the standard applied in our measurements is called RE102, radiated emissions, electric field, 10 kHz to18 GHz.

The measuring antenna for frequencies between 10 kHz and 30 MHz should be a 104 cm rod with impedance matching network and a square counterpoise, measuring at least 60 cm on a side. The measuring antenna is to be placed 1 meter from the EUT. A measuring receiver or spectrum analyzer connected to the antenna measures the voltage induced in the rod, with respects to the counterpoise. The counterpoise is essential to the antenna´s sensitivity, and therefore it is important to bond the counterpoise electrically to the floor ground plane in the room.

IV. RESULTS AND EVALUATION

The results of E-field measurements on EUT1, when the light fittings were connected to the PE-wire, are shown in figures 8-12. In figure 8 the background noise is shown when the line is powered but no load is connected. In this case the wires, L, N and PE shown in figure 7 are only connected at one end, the distribution end. Although the wires have transfer impedance and there is a mutual capacitance between them. The background noise measured on EUT1 is a summation of the noise from the room and noise from the power wire L to the PE- wire through mutual capacitance. When line are not powered, the background noise is almost the same as in figure 8, but the level under 40 kHz is lower.

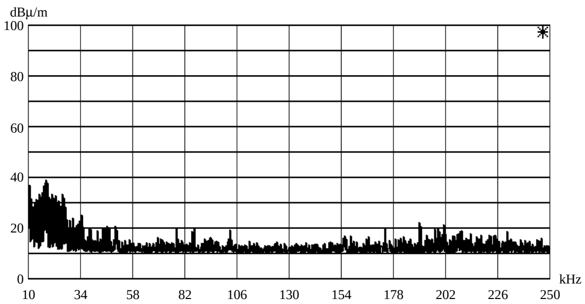

Figure 8. *Showing the background noise when the line is powered but no load is connected.*

When six light bulbs are connected on the load side, as shown in figure 9, the background noise levels are even lower than with no load, as shown in figure 8. Still, there is noise in the room and on the power wire L, but the connection between L- wire and the N- wire by the light bulbs rather lowers the level.

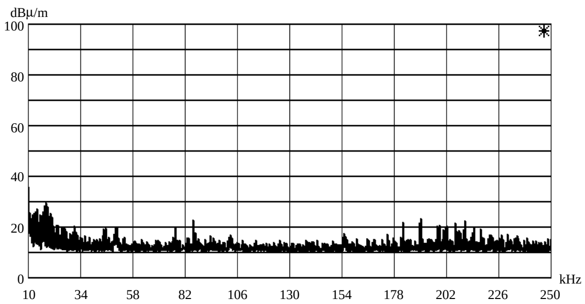

Figure 9. *Showing the background noise when six light bulbs are connected as a load.*

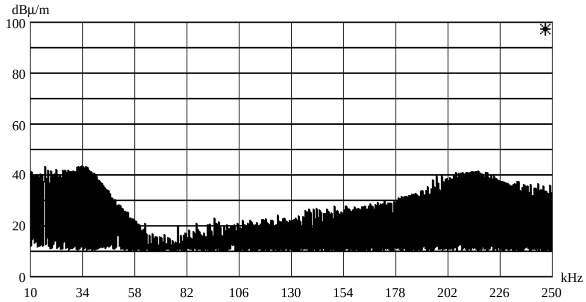

Figure 10. *The noise when the load is nine unshielded compact fluorescent lamps.*

Figure 11 showing measurements on nine shielded compact fluorescent lamps giving almost the same E-field on EUT1 as unshielded compact fluorescent lamps, seen in figure 10. The difference is small peaks in the frequency span 130 kHz to 155 kHz. The noise pick up by the shield is only a fraction of the noise by the mutual capacitance between the wires. For these types of light fittings (below 25 W) there is no filter and no physical connection to the PE- wire, there is still a leakage current. In this case it is obvious that the installation and the characteristic on the line has a great influence on the leakage current, not only the load itself. We also have to remember that the electrical field and radiation are proportional to the square of the frequency. Ott [9]

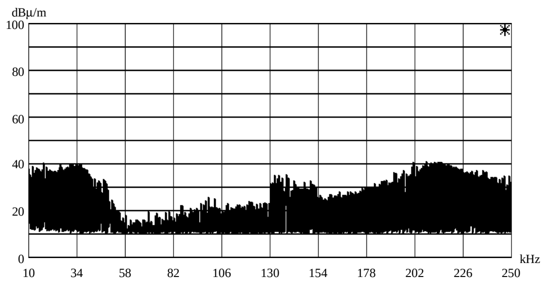

Figure 11. *The noise when the load is shielded compact fluorescent lamps.*

When loading with the HF-fittings seen in figure 12, we got higher noise even if, in this case, the HF– fittings have EMC –filters. The highest peak value, 58 dBµV/m, at 26 kHz, corresponds to the oscillator switching frequency. The measurement peak level for the two HF– fittings is almost ten times the level for corresponding oscillator switching frequency for the nine compact fluorescent lamps.

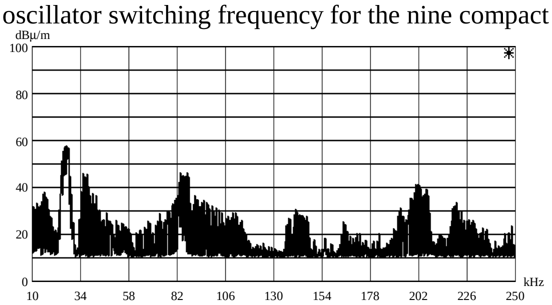

Figure 12. *The noise when the load is HF– fittings.*

The electrical field is measured with respects to the floor ground plane in the room (see III B). By connecting the PE-wire on the load side to the floor ground plane, in the same manner as on the distribution end, it is possible to lower the measured electrical field as seen in figure 13-14. Comparing this figure with figure 11-12 it is obvious that the electrical field is much lower when connecting to the ground plane. As seen in the figure 7 that is 150 m from EUT1 to the ground plane on the distribution end, but only 15 m on the load side. It has to be a short high frequency connection of the load to the ground plane. It is very important to understand grounding technique in order to minimise noise and disturbance. The ground plane, instead of wire, is often used to receive low-impedance at the circuit board or system design. "At 11kHz a straight length of 22-guage wire one inch above a ground plane has more inductive reactance than resistance" Ott [9]

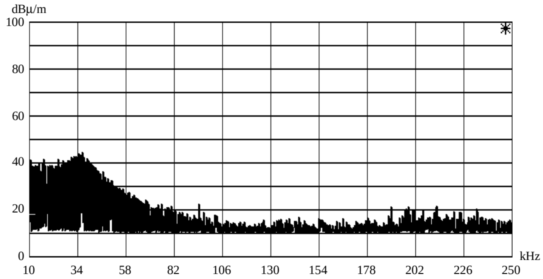

Figure 13. *The noise when the load is shielded compact fluorescent lamps and the PE-wire at the load is connected to the ground plane. Compare with figure 11.*

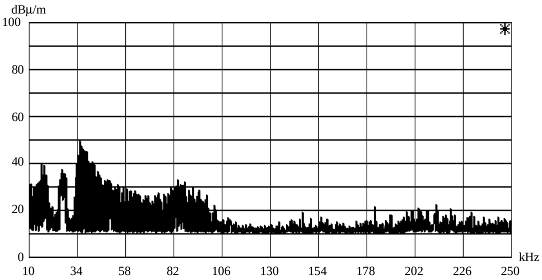

Figure 14. *The noise when the load is HF-fittings and the PE-wire at the load is connected to the ground plane. Compare with figure 12.*

V. CONCLUSION

The protective earth, PE, is more frequently used today than in the past. The reason for the extended use of the PE is not only the safety aspect. The protective earth is also used in both electrical and non-electrical equipment to limit electrical fields at power frequency (50 or 60 Hz). This is possible if the equipment is connected to a PE without potential through a currentless PE-wire.

If the PE or the PE-wire has potential with regards to the ground plane, the equipment will act like a source of electrical field. This problem increases with increasing frequency, one reason being that the radiation is proportional to the square of the frequency. It is important to understand how to use the PE-wire in order to achieve low electrical fields. It is also important to realize the difference between the PE-wire and ground plane according to the electrical field and safety arrangement. According to the electrical field, the body of a building or other conducting parts operate like a ground plane. If an impedance-free PE-wire is connected to this ground plane, they act together and there will not be any electrical field. If the body of the building, or other conducting parts that operate like a ground plane are connected together with the PE systems for EMC or other reasons, it is important to remember that this ground plane can never replace the PE-wires as a safety arrangement.

High frequency noise in the grid is generated by different types of switching technology, by power line communications or by switching transients. Switching technology has progressed so that modern frequency converters are lightweight, small in size and with low losses. Therefore, power supplies, variable speed drives, light fittings and other electrical equipment use this technology.

In order to meet EMC-standards regarding low emissions, equipment is laboratory tested. The tests are performed on one (1) equipment under test, EUT, at the time with an LISN put between the EUT and the grid. The LISN isolates the measurement circuit from the grid and gives the EUT stable and well-known line impedance. If there is a difference between the LISN and the site installation according to phase-, neutral- or PE-line impedance the radiated and conducted emission will be affected. The use of LISN affects both the construction of the EUT and the filter design.

There are almost no tests of site installations according to EMC-standards. The same thing may be said about the PE as a safety arrangement, but there is a big difference. The grid is designed to meet safety requirements, but the grid is not designed for EMC. Although it is expected that equipment meeting EMC-standards regarding low emissions in the laboratory shall also meet EMC at a site installation.

Receiving low impedance by choosing the grounding technique is a very important knowledge to minimise noise and disturbance. The use of a ground plane, instead of wire, is often selected to receive low impedance at a circuit board system or system design. This is achieved by careful calculations and tests. Tests on the grid are complicated and more tests have to be made in order to understand how to design the grid for EMC. In this paper it has been shown that electrical equipment distributes electrical fields using the PE-wire.

A growing number of active sources and the use of the PE-wire as a distributor of signals and noise will increase the electrical field from the grid. This problem will most likely expand in the nearest future. There are two possible ways to solve this problem. One way is to use electronic equipment without conducted emission. Another way is to reconstruct the grid so that the PE-wire does not distribute high frequency electrical field.

EMC-tests using LISN has lowered the radiated emissions from a single equipment. The emissions from a single equipment are not longer radiated, it has become conducted noise current. When the noise current is being fed into the PE-wire a high frequency noise potential will appear. This high frequency noise potential on the PE is then radiated. Suddenly, not only the single equipment that created the emissions will radiate, now all apparatus connected to the PE will radiate more or less. It must once again be pointed out that the PE-wire system has capability to handle power frequency (50 or 60 Hz) electrical fields but not high frequency noise.

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