Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

EMC Filter Common Mode Resonance

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***Abstract*-- This paper discusses the possibility that high common mode voltages occur in low-voltage distribution due to oscillations between parallel connected EMC-filters. It is shown that such oscillations may occur in the frequency range between 2 kHz to 150 kHz. Simulations and measurements have been carried out with different types of parallel connected power inlet filter, a common EMC Filter, and the circumstances giving oscillations have been highlighted.**

Keywords: Common mode voltage; conducted disturbances; electromagnetic compatibility; EMC Filter; oscillation and power quality.

I. List of abbreviations:

Conducted emission (CE);
Line impedance stabilizing network (LISN);
Equipment under test (EUT);
Common mode (CM);
Differential mode (DM);
Line (L);
Neutral (N);
Protective earth (PE);
High frequency (HF);
Uninterruptible power supply (UPS);
Switch mode power supply (SMPS).

II. Introduction

ALLMOST all electrical devices are equipped with a power inlet filter. The aim of this filter is to prevent high-frequency disturbances generated by the equipment from reaching the network. The presence of large numbers of such filters connected to the low-voltage network may introduce new phenomena, including resonances. This paper presents the possibility of common mode resonances in the frequency range 2-150 kHz due to the presence of these filters. The paper shows simulations, laboratory measurements and field measurements of this resonance condition.

The conducted emission (CE) test under laboratory conditions according to product standards and the consequences of impedance mismatch are briefly discussed in section III.

Financial support from Skellefteå Kraft Elnät AB, ABB and ELECTRA is gratefully acknowledged. C,M. Lundmark, S.K. Rönnberg E.O.A. Larsson and M.H.J. Bollen are with EMC-on-Site, Luleå University of Technology, 931 71, Skellefteå, M. Wahlberg are with Skellefteå Kraft Elnät AB, 931 24, Skellefteå, Sweden. (e-mail: martin.lundmark@ltu.se). M.H.J. Bollen is also with STRI AB, 771 80, Ludvika, Sweden.

In section IV this is followed by a description of the changed circumstances when an increasing number of devices are connected together during their practical application. By filter simulations in section V and laboratory measurements in section VI a test is done of what this changed circumstance could have on the common mode voltage. Field measurements made in a server room (section VII) are compared to the results from simulations and field measurements and further discussed in section VIII.

III. Standardized conducted emission tests

When designing any filter the impedance matching is of great importance. The insertion loss performance for EMC filters is assuming a 50-Ω source impedance and a 50-Ω load impedance.

The standardized CE test is carried out by placing a line impedance stabilizing network (LISN) between the utility grid and the equipment under test (EUT). Only one device at a time is tested.

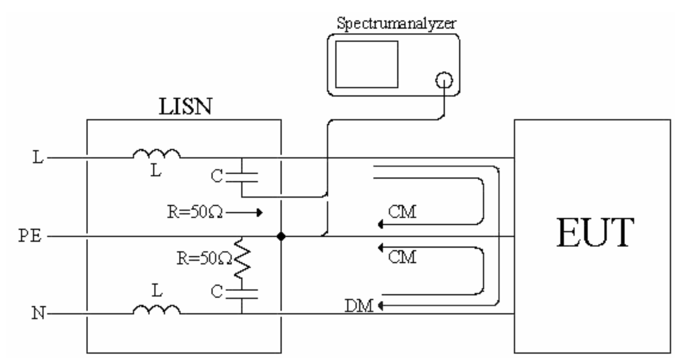

Fig. 1. Measurement of conducted emission using line impedance stabilizing network (LISN)

The LISN performs four functions: it allows ac power to supply the equipment; it suppresses incoming noise on the utility grid; it provides a defined line impedance (50-Ω) within the measurement range; and it provides a point for measuring the noise current across a 50-Ω resistor placed between phase and protective earth or between neutral and protective earth.

As the LISN creates a balanced supply and a new current path through the 50-Ω resistors (Fig. 1), it is no longer possible to distinguish between common mode (CM) and differential mode (DM) currents. The current value resulting from the test is the sum of CM and DM current. Efforts have been made to perform separation of the CM and the DM conducted noise [1] [2]. Such a separation would make it

978-1-4244-2235-7/09/$25.00

easier for the manufacturer to obtain emission below the limits by adjusting the EMC filter components.

Note that the single-phase device will typically be unbalanced connected during its practical application. The standardized way for measuring emission does thus not necessarily predict the high-frequency currents as they will occur in practice. Among others, the impact of common-mode and differential-mode currents may be different.

If the impedance of the ac-mains or the impedance of the equipment under test (EUT) differs from 50-Ω the performance of the EMC filter will differ from its expected performance, as was shown in [3]

Another change in filter response occurs due to resonance phenomena associated with impedance mismatch between filter and supply [4] or between filter and EUT [5].

The mains cable between LISN and EUT, during the standardized conducted emission test, has a maximum length of 2 meters, depending on the particular standard documents. Experiments using an extra 2.5 m extension cord between LISN and EUT show that this extension cord has a 50-Ω impedance at low frequency, while at higher frequencies the impedance reaches almost 300-Ω [6]. Simulations have shown that a longer distance between the EUT and the LISN may impact the conducted emission by more than 10 dB [7].

IV. Common Mode Voltage, Current and Impedance

A. Power Inlet Filter

When a device is connected to the power grid during its practical application the circumstances are in many ways different from those during the standardized test. A single-phase device will typically be unbalanced connected. (Norway being the main exception.) In the practical application there is no LISN to suppress incoming noise from the grid and provide a defined impedance (50-Ω).

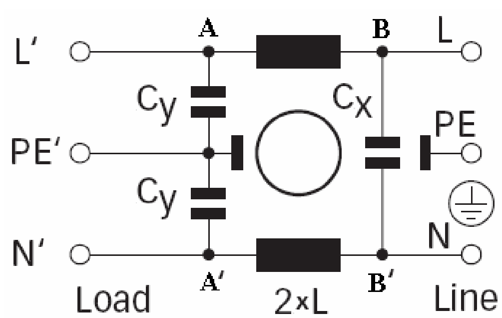

Fig. 2. Configuration of a power inlet filter.

A typical power inlet filter, a common EMC Filter, shown in Fig. 2, consists of a common- mode choke (2xL) in both line (L) and neutral (N) and a numbers of capacitors. One capacitor (C_X) is connected between L and N and two capacitors (C_Y) between L and protective earth (PE) as well as between N and PE. The windings in the common- mode choke are connected so that the magnetic fields produced by the load current (at fundamental frequency) cancel each other. The result is a relatively low inductance for the differential-mode current and a very high inductance for the common-mode current

B. Multiple Power Inlet Filters

When two filters are connected to the same outlet (as shown in Fig. 3) then each filter has an extra C_X capacitor (and a common- mode choke) connected in parallel with the grid impedance between phase and neutral.

When an increasing number of power inlet filters are connected to the grid, each filter will be connected to an increasing number of impedance elements in parallel, a situation a long way from the environment during the standardized test.

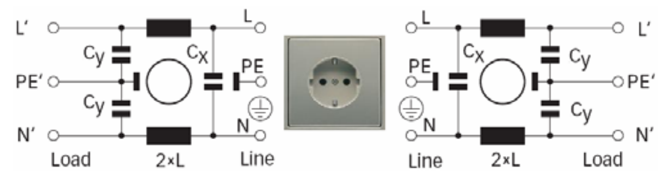

Fig. 3. Power inlet filters are connected in parallel with the power distribution network creating a sum of filter impedance different from 50-Ω.

C. Leakage current

One design parameter in power inlet filters is the leakage current to the PE. The leakage current is the current through the C_Y filter capacitor between L and PE, as shown in Fig. 2. To reduce the leakage current the capacitor is held small, typically 2.2 nF (leading to 160 µA leakage at 230 V, 50 Hz). The capacitor C_X is not limited by the leakage current.

D. Resonances

The common- mode chokes (2xL) and the two capacitors (C_Y) between L and PE as well as between N and PE creating together two series, RLC, resonance circuits, including the resistive core losses in the chokes. These two resonance circuits could be supplied with common mode signals from the load side, from the line side or from both sides.

A common mode emission source (current or voltage) on the load side in Fig. 2 will apply a signal in the connecting point between the choke and the capacitor (A and A') in the two series resonance circuits. Similarly, a common mode emission source on the line side will apply a signal at the choke end of two series resonance circuits (B and B').

The source to the common mode emission on the load side, shown as a current $I_{CM}(f)$ in Fig. 4, is mainly a leakage of the switching frequency from the equipment connected to the grid.

When a power inlet filter is connected between the equipment and the grid as shown in Fig. 4, the $I_{CM}(f)$ is shunted back to the equipment. At higher frequencies the (2xL) impedance increase and the C_Y impedances decrease.

There will, of course be $I_{CM}(f)$ on both sides of the filter, because no filter is ideal. $I_{CM}(f)$ on the grid side of filter, is also a consequence if the grid is powered by uninterruptible power supply (UPS).

When two filters are connected to the same outlet (as shown in Fig. 3) the resonance circuit consists of two power inlet filter in series, each filter having a common mode source on the load side. When an increasing number of power inlet filters are connected to the grid, the result is a number of resonance circuits, all having their own common mode source on the load side. A common mode emission source on the line side wills, regardless there is one or a number of power inlet filter, meet resonance circuits.

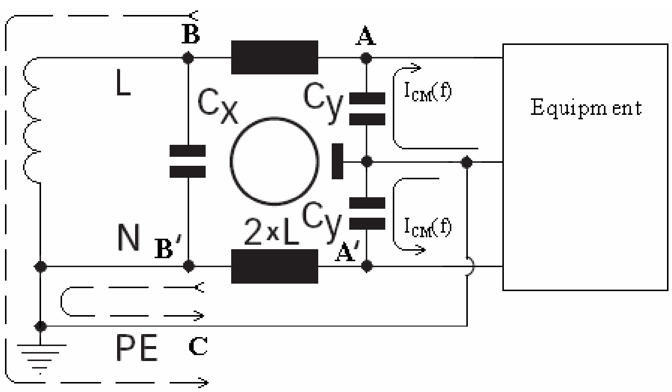

Fig. 4. Power inlet filters connected to the power distribution network. The upstream wiring impedance (loop impedance) is different from 50-Ω.

E. Loop impedance

The loop impedance is the upstream wiring impedance seen from the outlet to the feeding transformer. There are two loops in a grounded single phase outlet. One is the impedance loop between L and PE (L loop), (from B to C), in Fig. 4; the other is the impedance loop between N and PE (N loop), (from B' to C).

This loop impedance is of great importance for the chance of resonance in the power inlet filter. If the loop impedance is low enough at the resonance frequency no amplitude amplification will occur. The "low enough" value of the loop impedance will be studied by filter simulations in Section IV.

Comparing the L loop (from B to C) and the N loop (from B' to C) in Fig. 4, the L loop contains a transformer winding as well as fuses and extra wiring. The result is that the L loop will have higher impedance.

The L- and N- loop impedance is, for the chance of common mode resonance, operating in parallel.

The use of PEN- conductor, a common conductor for the PE and the N, gives further lower N loop impedance in comparing to the use of separate conductor for the PE and the N.

V. FILTER SIMULATIONS

A. Simulation model

Simulations have been performed, using the System EMC Simulator (EMEC) [10], to show the occurrence of resonances and to study the impact of the filter parameters on the resonances. The simulation model used to show the interaction between different filters is shown in Fig. 5. Two power inlet filters are connected in parallel and connected into a power outlet strip without a connection of the outlet strip to the power grid.

The absence of connection of the outlet strip to the power grid means that there is no loop impedance, as described in section III-E, between L and PE as well as between N and PE. The sensitivity for wiring loop impedance is than studied by introducing variable impedance between L and PE as well as between N and PE.

The series resonance circuit, described in section III-D, consisting of capacitor C_Y in series with the (2xL) impedance, as seen in Fig. 4 also includes resistive losses in the inductor core and windings as seen as an added resistor in Fig. 5, where the resonance is damped.

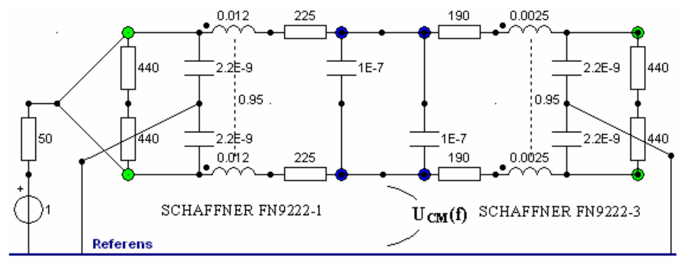

Fig. 5 The simulation of the common mode resonance is made by connecting two power inlet filters are in parallel with the power distribution network and measuring the common mode voltage U_{CM}(f) between N-PE. In figure the PE is named reference.

The component value for the common- mode choke (2xL) and for the capacitors ($C_{Y,}$ C_X) in the power inlet filter are often shown on the outside of the filters, but the resistive losses in the wiring and components are normally not specified. The losses in the choke core are the dominating losses and they are dependent on the frequency.

B. Measuring the resistive losses

To find the resistive losses, measurements has been made, at the point of common mode resonance for two types of power inlet filters, shown in Table 1.

TABLE I
CALCULATED EQUIVALENT RESISTANCE AT THE POINT OF RESONANCE AND THE RESONANCE FREQUENCY IN DIFFERENT POWER INLET FILTERS FROM TWO MANUFACTURES BASED ON MEASUREMENTS.

Schaffner FN9221-X	**Minimum R (Ω)**	**@ Frequency (kHz)**
1	451	19.7
3	380	33.6
6	143	81.5
10	115	146.5
Schulter 5120.00XX.0		
01	674	19.8
02	416	27.7
04	322	42.2
06	230	63.6
10	161	107.4

A sweep oscillator was connected between L/N (in parallel) and PE on the line side of the filter. The applied voltage and the loop current, at varying frequency, were measured, searching the frequency at which the impedance had its lowest value. An oscilloscope showed simultaneously that the applied voltage and the loop current were in phase. The quotient between the voltage and current then showed the total series resistance at the resonance frequency.

C. The simulations

The equivalent schema shown in Fig. 5 has been used to perform simulations for multiple filters.

The resistance at the resonance frequency, obtained from the above measurements, has been included as a frequency-independent resistance in the simulations. The impact of the resistance in a resonance circuit is small, beyond frequency close to the resonance frequency. The two 440-Ω resistors in series connected between L and N on the load side of the two power inlet filters represent a 60-W resistive load at 230V.

The oscillator connected to the left in Fig. 5 represents the common mode voltage generated internally in the device. The amplitude of this voltage is kept at 1 Volt so that the common-mode voltage on grid side of the filter, $U_{CM}(f)$ gives the transfer function of the common-mode voltage through the filter. For an ideal filter, the transfer is zero.

The common mode voltage at varying frequencies $U_{CM}(f)$ consists of two (identical) parts, the voltage L-PE and the voltage N-PE. By using a voltage source, it is possible to study the amplitude amplification at various frequencies.

Furthermore, by varying the loop impedance between L-PE respective N-PE the influence of the impedance on the amplitude amplification at resonance has been studied. This impedance has in this simulation been made frequency independent by using two resistors R5 respective R15.

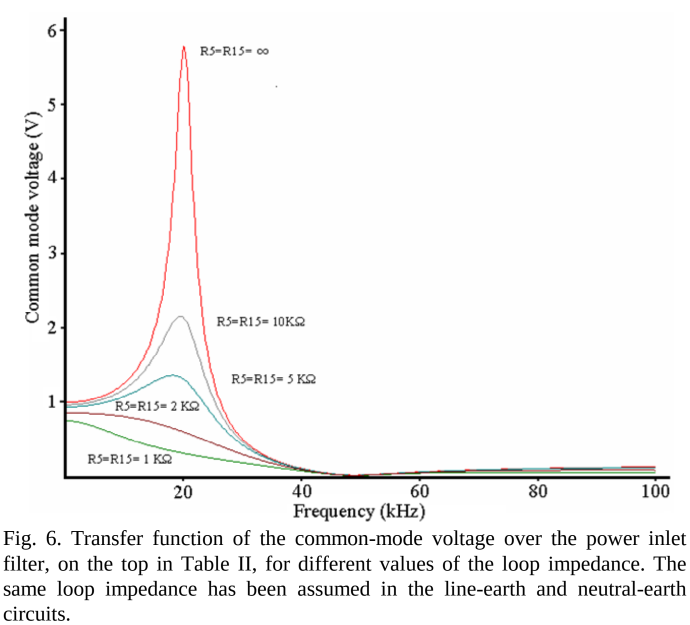

Fig. 6. Transfer function of the common-mode voltage over the power inlet filter, on the top in Table II, for different values of the loop impedance. The same loop impedance has been assumed in the line-earth and neutral-earth circuits.

The transfer function from the CM voltage generated internally in the equipment to the line-earth and line-neutral voltages is shown in Fig. 6; the two transfers are the same.

The resonance frequency when two filters (1A and 3A) are connected in parallel, with the two resistors representing the loop impedance (R5 and R15) infinite, is 20 kHz. The simulation also shows how the amplitude of the oscillations is strongly dependent on the loop impedance between L-PE (R5) respective N-PE (R15).

If the two resistors representing the loop impedance (R5 and R 15) are different in size, then there is a difference in the transfer function between the L loop (from B to C) and the N loop (from B' to C) in Fig. 4, but only below 10 kHz.

As mentioned before, the loop impedance in the line-earth circuit is normally higher than in the neutral-earth circuit. As a result the transfer to line-earth is more prone to amplification due to resonances.

VI. Laboratory Measurements

As a next step, two types of measurements were performed in the laboratory. The first to confirm the power inlet filter models and the simulations (one shown in Fig. 6), the second type of measurements to investigate the magnitude of impedance in the power grid between N-PE, and compare to the resistance value (R 15) in the simulations.

It was give priority to measure the N loop impedance (from B' to C, in Fig. 4) compared to L loop impedance (from B to C), as the investigation was to find the lowest possible value.

An overview of power inlet filter models confirmation and the simulations according four of the measured combinations is shown in Fig. 7, the measurements on the top (1A/3A) corresponds to the simulations in Fig. 6.

Table II
The Measured Common Mode Voltage $U_{CM}(F)$ Using Different Combinations of Power Inlet Filters.

Combinations of Schaffner FN9221-X filter	Resonance amplification U_2 / U_1	@ Frequency (kHz)
1A/3A	9.6	16.0
3A/1A	10.7	18.6
3A/6A	6.0	33.1
3A/10A	5.4	33.9

The resonance frequency in the simulations was 20 kHz when the two resistors (R5) and (R15) were infinite; the measured value was 16 kHz. The resonance frequency in the simulations is slowly decreased when the resistance is reduced and the amplitude peak disappears below 2 kΩ, the measured value was a confirmation of the impedance level (not showed here). Notice that the measurements show an amplification of 9.6 times, compared to 5.7 in the simulation, 1.6 times higher in the measurements. (When the relative amplitude is 1, the amplitude on the line side (U2) is the same as on the load side (U1)).

To investigate the magnitude of impedance in the power grid between N-PE, and compare to the value (R 15) in the simulations, a first attempt was a number of different measurements performed in real power distribution system.

Several measurements in different distribution systems were made, but the presence of the fundamental frequencies and its harmonics in the distribution system in the N-PE loop made the measurements complicated without special filtration. A complication factor is also that the impedance is influenced by the presence of other equipment connected to the grid.

New measurements were made this time using cables not connected to the grid, having reasonable dimensions and lengths corresponding to low voltage distributions. The connection between the cables was made short giving lowest possible inductance.

The expectation is that this will give lowest possible value of N-PE loop impedance. In other words, the N-PE loop impedance in an installation should always be higher than the measured value in these measurements.

The result of some of those measurements including three combinations of cables is shown in Fig. 7 having impedance exceeding 100-Ω beyond 90 kHz and having peaks above 350-Ω at a cable length of 310 m (a loop length of 620 m).

Reasonably, the N-PE loop impedance value in an installation should due to branching and numbers of parallel cables and outlets, are noticeable higher.

In reality there will be a number of power inlet filters, often hundreds, all having its own CM current source, in outlets and via hundreds of meters cables connected in parallel to the grid.

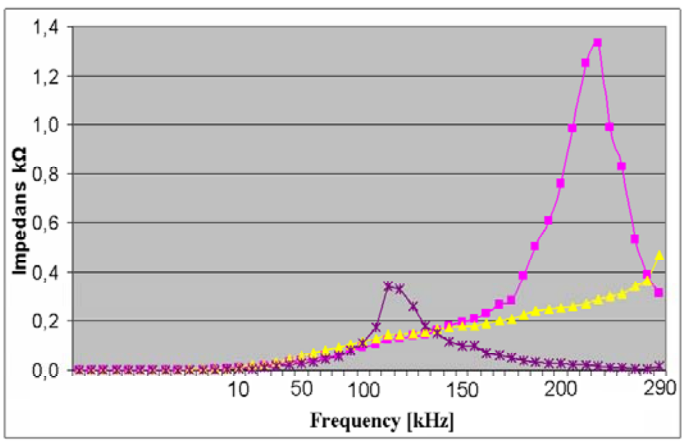

Fig. 7. Measured cable loop impedance between N-PE for three combinations of cables Yellow (triangels) 97 m N1XE-U 5G16 Magenta (squers) 213 m N1XE-U 5G10 Blue (stars) 50 m EKLK 3G1.5 + 213 m N1XE-U 5G10 + 97 m N1XE-U 5G16

VII. HIGH COMMON MODE VOLTAGE IN SERVER ROOM

As a final step, measurements have been performed in the electrical installation of a server room. High-amplitude oscillations between the neutral and the protective earth conductor were observed on the load-side of a 50 kVA uninterruptible power supply (UPS) feeding servers and modems. The server room had several communications failures on a specific communication line. When the ungrounded modem was powered from other sources than the UPS, there is no interruption.

Measurements on the phase voltage made with a HIOKI 8855 MEMORY HiCORDER and a HIOKI 9322 differential probe are shown in Fig. 8 is using two references, the neutral on the upper left (the modem power input, differential voltage) and the protective earth in the other graph. The fundamental-frequency voltage is attenuated 26 dB (20 times) in all cases.

A comparison of the two upper graphs in Fig. 8 shows a difference in high frequency (HF) harmonics amplitude. The highest L-N ”peaks” to the left are about 6 V, while the highest L-PE ”peaks” are approximately 20 V, three times as high. The right graph shows 6 peaks in one period (20ms), while the peaks are more ”hidden” and difficult to count in the L-N voltage to the upper left.

The CM voltage lower left, calculated from the measured L-N and L-PE voltage, down left in Fig. 8 shows several 10-V ”spikes”, and some of them reach 15 V. Comparing the common mode voltage (down left) with the L-PE (upper right) shows almost the same HF harmonics amplitude, L and N are together moving in amplitude using PE as a reference.

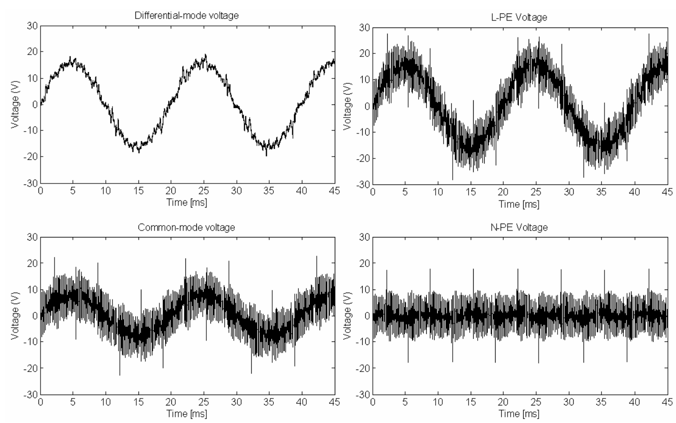

Fig. 8. The phase and neutral voltage in a server room measured with different references. The differential (L-N) voltage on the upper left, L-PE voltage on the upper right and the N-PE voltage lower right. Common mode voltage, to the lower left, is calculated from the measured L-N and L-PE voltage. The fundamental frequency voltage is attenuated 20 times in all cases.

This high-frequency common-mode voltage in respect to PE is feeding the ungrounded modem through the power inlet from the line side. When the power supply in moving in potential in respect to PE (and the building), these high-frequency common-mode ”spikes” could be added on the digital communication signal, causing communications failures,

The owner’s easiest solution is to power the modem through an extra UPS or a power outlet in the server room beside the 50 kVA UPS system, than there was no interruption in the communication.

Measurements of phase neutral and phase ground in the power outlet in the server room that was used to power the modem when there was no interruption in the communication shows low levels of HF harmonics (not shown here).

VIII. DISCUSSION

The simulations and laboratory measurements have been made to find the reason to the high amplitude of HF harmonics in the electrical installation of a server room feed by a 50 kVA UPS system.

The server room had communications failures on a specific communication line, the only line in the server room using an ungrounded modem. It is possible that the HF harmonics CM voltage in combination with the ungrounded modem power input is enough to disturb the communication modem.

It was an interruption in the communication that showed that something was wrong. The owner's solution, using a separate UPS system for the modem, is perhaps fast and easy but only create a lower level of disturbances for a part of the server room, leaving the rest at a high level.

But, the server room is a place where it not should be high levels of disturbances. And if there are high levels, the reason has to be investigated.

The distance between the 50 kVA UPS system, the servers and the modems is physically short but there are many meters of wiring, branching, outlet strips, power inlet filters and switch mode power supply (SMPS). The specified test conditions in laboratory have not to be fulfilled in these types of installations. In other words, the impedance levels at the point of the power inlet filter is probably not as in the specified test conditions, and this causes her high CM voltage.

In laboratory measurements each filter has 50-Ω between L-PE respective N-PE. In the server room hundreds of power inlet filters share the feeding impedance, in other words the impedance level on each filter is different, is varying at varying frequency.

Simulations and laboratory measurements has showed the necessary impedance levels between N-PE respective N-PE when two filters in parallel that curses increased amplitude, a common mode resonance. This impedance level is than compared to laboratory measurements of the impedance levels between N-PE respective N-PE in cables.

Although this simulations and measurements on filters only refer to a limited numbers, and the wire measurements included no branching, the result shows the possibility of common mode resonances, if there are many meters of wiring, branching, outlet strips, power inlet filters etc.

The source (the HF voltage or current generator), to the high common mode voltage shown in Fig 8, is most likely the 50 kVA UPS system, and if that's the case, the question is, is this common in UPS system, or has this UPS a fault.

What is our knowledge about the electrical environment in server rooms? Is this high-amplitude CM voltage between the neutral and the protective earth conductor common, in this type of installation? Who has made measurements? Is it a problem at all?

Or, is there a problem, and there is a need of limitation in the numbers of SMPS that can be used together [8], [9] in server rooms and other equivalent places, a limitations in the length of the wiring branching, outlet strips, power inlet filters etc?

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