INTERHARMONICS AND LIGHT FLICKER

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ABSTRACT

High levels of odd triplen harmonics and flicker of Compact Fluorescent Lamps (CFL) have been observed in networks. This paper addresses the possibility that these issues are related by the following phenomena. Inverter driven loads such as heat pumps generate odd harmonics that can be modulated by fluctuations in those loads, such as oscillating torque. Because the zero sequence impedance of the low voltage distribution network is much higher than for the other symmetric components of a three phase system, the impacts of odd triplen harmonics currents on the voltage are stronger than for the other harmonic currents. Modulating fluctuations may also come from the power network. This modulation causes interharmonics near odd harmonics, which cause voltage peak value fluctuations. In typical Compact Fluorescent Lamps (CFL) the link capacitance is dimensioned so small that the luminance varies with the voltage peak value fluctuations. Some related gaps in Electro Magnetic Compatibility standards are pointed out.

INTRODUCTION

This paper addresses two issues related to voltage quality that have recently appeared and that might be related:
- Levels of triplen harmonics, especially 15 and 21, that are near or higher than the objective values of standard or regulation. This has been observed at several different voltage levels in different countries.
- Reports of flicker by compact fluorescent lamps (CFL).

High levels of harmonics 15 and 21 were reported several years ago during a measurement campaign of high-voltage network in Bosnia and Herzegovina [1]. Increased levels of these harmonics were reported recently from measurements campaigns in Denmark [2], Sweden [3] and Germany. As most measurement campaigns concentrate on non-triplen odd harmonics (5, 7, 11, 13, etc) these levels may also be higher in other countries, but these high levels may have gone unnoticed.

Light flicker is a phenomenon for which well-defined standards exist, including IEC 61000-4-15, a rather complicated but widely-used way of calculating a voltage-quality index known as flicker-severity. The calculation is based on the assumption that light flicker occurs due to incandescent lamps exposed to voltage magnitude fluctuations. However, those lamps are being phased out in many countries and replaced by energy-efficient lamps. The flicker-severity index will no longer necessarily be a measure of the light flicker with those energy-efficient lamps.

Flicker due to interharmonics was reported by Mombauer et. al. [4]. The flicker of energy saving lamps is related to the fluctuations of the peak value of the voltage that typically appear in the frequency domain as fluctuating odd harmonics. Flicker due to interharmonics with both compact fluorescent lamps and fluorescent tube lamps was reported in 1997 by IEEE and Cigré/CIRED joint paper [5] and by Halpin et. al. [6].

The relation between interharmonics, fluctuating odd and triplen harmonics, fluctuations in voltage peak values and light flicker with CFLs and light emitting diode (LED) lamps will be explained in the paper. Recommendations will be made for the development of a new flicker severity index and for measurements for detection of interharmonics causing possible light flicker.

SENSITIVITY TO INTERHARMONICS

Energy saving lamps

Sensitivity of different types of energy saving lamps to voltage sags and fluctuations has been well reported in the literature. The luminance of different CFLs closely follows the DC-link voltage drop caused by a voltage sag on AC side [7]. Increasing the link capacitor reduces the sensitivity.

Reference [8] presents a comparison of several CFLs of different brands and an incandescent lamp for flicker under four common voltage disturbances: 1) square wave voltage modulation at different modulation frequencies, 2) single interharmonic voltage component at different frequencies, 3) phase angle jumps, and 4) dips and swells. All the CFLs are clearly sensitive to interharmonics close to an odd harmonic frequency, although less sensitive than to interharmonics near the fundamental frequency. Certain interharmonic voltages with magnitude slightly less than 1% of r.m.s. voltage are enough to cause disturbing light flicker. All the lamps were strongly and similarly affected by voltage dips and swells. CFLs were practically unaffected by the phase angle jumps that caused a considerable amount of flicker in the incandescent lamp.

Reference [9] investigated the flicker responses of an incandescent lamp, CFL and LED lamp to interharmonics. The LED lamp exhibited flicker response nearly similar to the CFL. It was not explained what kind of current control the tested LED lamp had. It can be expected that a good LED current control mitigates light flicker. The impact of voltage fluctuations on energy-saving lamps was also studied by [10, 11, 12], but only near the fundamental frequency. Both [10] and [11] concluded that CFLs and LED lamps are less sensitive to voltage fluctuations than incandescent lamps, but the studies presented in [12] indicate that this may be due to the measurement method used. Rectangular voltage variations and actual voltage variations (obtained from measurements) may cause more light flicker in CFLs and LED lamps than in incandescent lamps. More work is obviously needed, both measurements and modelling efforts.

Some power line communicating remote control systems inject certain interharmonic frequencies such as 175 or 167 Hz. Energy saving lamp flicker has been observed during their usage. It can be shown mathematically that the addition of, for example, a 152 Hz voltage to a 50 Hz voltage results in a 2-Hz modulation in the peak voltage and therewith in a 2-Hz modulation of the DC-bus voltage inside of an energy-saving lamp.

Rectifiers, motors and generators

Zheo [13] analysed the sensitivity of low voltage loads to voltage fluctuations. The fluctuations increase the ripple, stress and losses in the DC-link capacitors of rectifiers and thus speed up their aging. In induction motors directly connected to the mains the voltage fluctuations increase stator and rotor r.m.s currents significantly. The induction motors of adjustable speed drives are affected rather similarly but less. The standard method for flicker measurement does not represent the equipment degradation by voltage fluctuations.

SOURCES OF INTERHARMONICS

Very little is known on sources of interharmonics in LV-networks (Low Voltage networks), but generally interharmonics levels are perceived to be low. The main sources used to be the higher voltage levels, if the large disturbance sources there were not isolated to their own buses. For example, it has been reported long ago that an arc furnace generated such interharmonics that make also fluorescent lamps and CFLs flicker severely and a Static Var System with harmonic filters worsened the fluorescent lamp flicker by generating more interharmonics (147Hz, 220 Hz and 380 Hz in a 60 Hz system) while removing the incandescent lamp flicker [14]. Now interharmonics are increasingly generated by equipment in the LV-network and its customers.

The impact of distributed photovoltaic (PV) power generation in an urban distribution network was studied within the PVupscale project [15]. It was concluded, among others, that 1) the PV systems were not the cause of flicker, 2) voltage interharmonic 3.5 (centred at 175 Hz) had low value, and 3) the levels of current harmonics stayed low except for 6 and 8. Thus this study and the known properties of PV generation give us no reason to suspect interharmonics from PV as a source of flicker of any types of lamps. Also the measurements presented in [16] gave no indications of interharmonics from PV.

Heat pumps are rotating loads so even small amount of mechanical unbalance or variable friction could cause interharmonics near the odd harmonic currents produced. According to [15] the odd harmonic emissions of many heat pumps are high especially on partial load operation and may cause voltage quality problems regarding harmonic levels in weak LV-networks where very many similar heat pumps are in the same network area [15].

When harmonics or interharmonics are coming from the same or an identical source, they cannot be considered independent from each other. The combined impact of each distortion source and each frequency component is much bigger than in the case when their sources are independent.

Several publications report interharmonics from wind turbines [18, 19]. A range of interharmonic frequencies is reported in [19] including those close to the third and fifth harmonic.

INITIAL SIMULATIONS

Fluctuation interaction between rectifiers in a single phase model

A simple simulation model was built to demonstrate how fluctuations in one load of one rectifier are transferred via the common AC-network to the DC-link voltage of the other rectifier. The supply impedance of the network is set so high that the two rectifier loads cause a flat topped voltage waveform, see Fig. 1. In the first rectifier a sinusoidal ideal current source was added in the DC side in parallel with the load in order to simulate load fluctuations. The frequency of this fluctuation was set to about 10 Hz. This causes 10 Hz fluctuation in the DC-link voltage of the rectifier which results in small fluctuations in the AC-voltage waveform peak at the modulating frequency. This fluctuation is hardly visible in Fig. 1 without zooming as in Fig. 2.

Also interharmonic voltages appear at the distance of the modulating frequency from the odd harmonic voltages that are caused by the current taken by the rectifiers. The total harmonic distortion is the AC-voltage was 7.34 % in the voltage of Fig. 1. The DC-link voltage of also the other rectifier fluctuates in a way that causes severe flicker of energy saving lamps using such fluctuating DC-link voltage. Fig. 3 shows the DC-link voltages of both rectifiers. Fig. 4 shows the FFT analysis (using Matlab SimPowerSystems FFT tool) of a 10 s long period of the AC-voltage partly shown in Fig. 1.

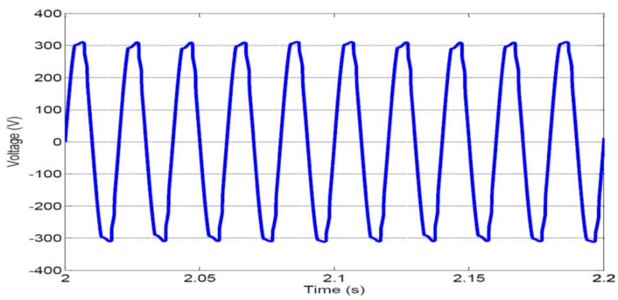

Fig. 1. The AC-voltage feeding the connected rectifiers is clipped at the peak with a barely visible fluctuation. Simulation.

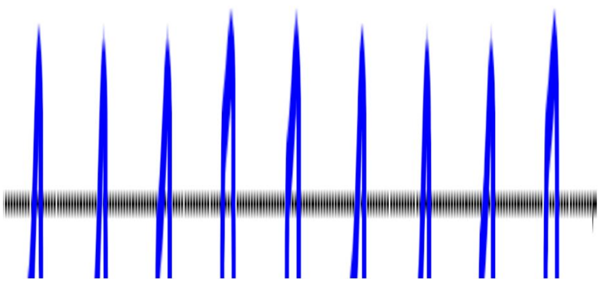

Fig. 2. Zoom of Fig. 1. The horizontal line is at 300 V.

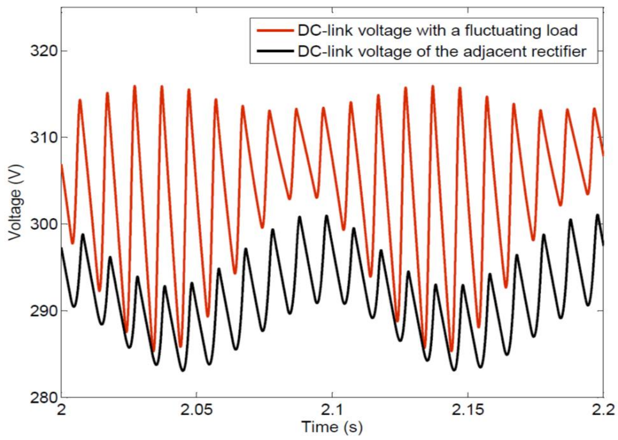

Fig. 3. Rectifiers connected via a weak single phase AC-network. Simulation.

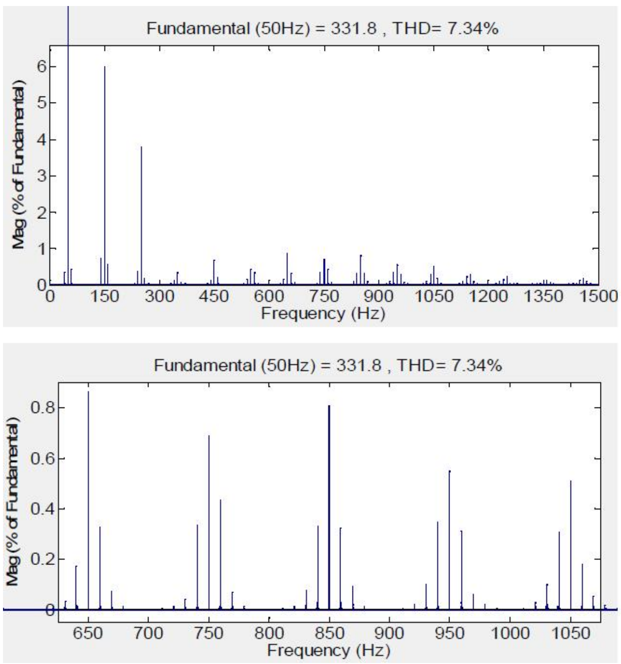

Fig. 4. FFT of the AC-voltage over a 10 s long period. Thus frequency resolution is 10 Hz. Simulation.

Three phase system

The single phase setup described above is multiplied to each phase. Also transformers are added to every rectifier. The relatively high zero sequence impedance of three phase LV distribution network and weak neutral conductor at the customer premises contribute to the issue. The fluctuation of the DC-link voltage is high in the rectifiers in phases L1 and L3, but not in phase L2. See Fig. 5 and 6. The reasons have not yet been analyzed.

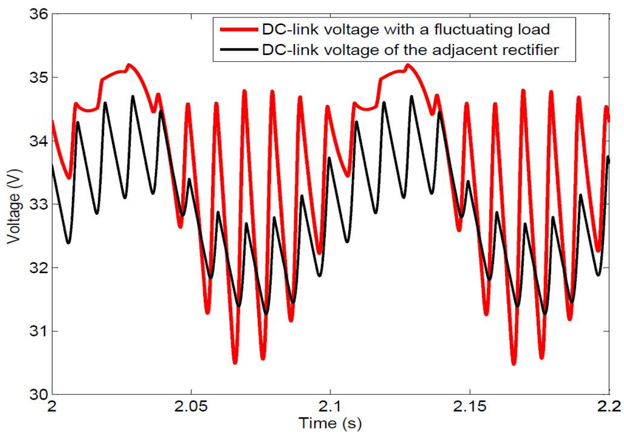

Fig. 5. DC-link voltage of the rectifier with fluctuating load and the DC-link voltage of an adjacent rectifier. Both are in the phase L1. Simulation.

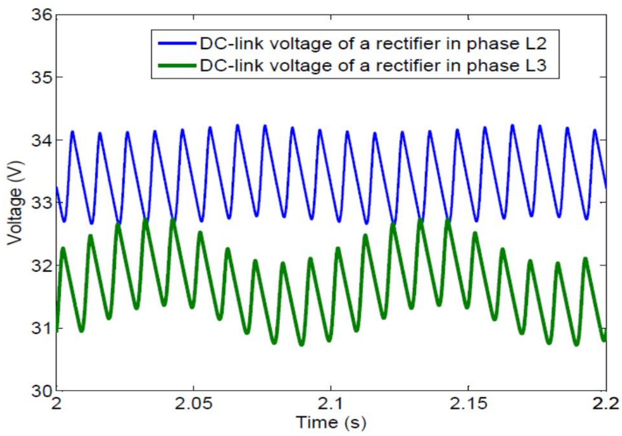

Fig. 6. DC-link voltages of rectifiers in the other phases. Rectifier in L3 fluctuates much more also in this simulation where it is in the network further away from the fluctuating load than the rectifier in L2. Simulation.

The odd triplen harmonic voltages (H3, H9, H15 and H21) and their sidebands are relatively big in the AC-voltages that supply the rectifiers, see Fig. 7. The sidebands and the 5th harmonic H5 are attenuated from phase L1 load to L3 at the kWh-meter, but the DC-link voltages of the phase L3 rectifiers fluctuate as shown in the Fig. 6. The other odd harmonics are not significantly attenuated. Odd harmonics and the voltage peak values in a peak clipped voltage waveform have a close connection with each other. Thus it can be expected that fluctuating odd harmonics in the AC-voltage may contribute somewhat more than other fluctuating harmonics to the DC-link voltages of the rectifiers. The only connection confirmed so far by the initial simulations was that the high zero sequence impedance contributes to these issues.

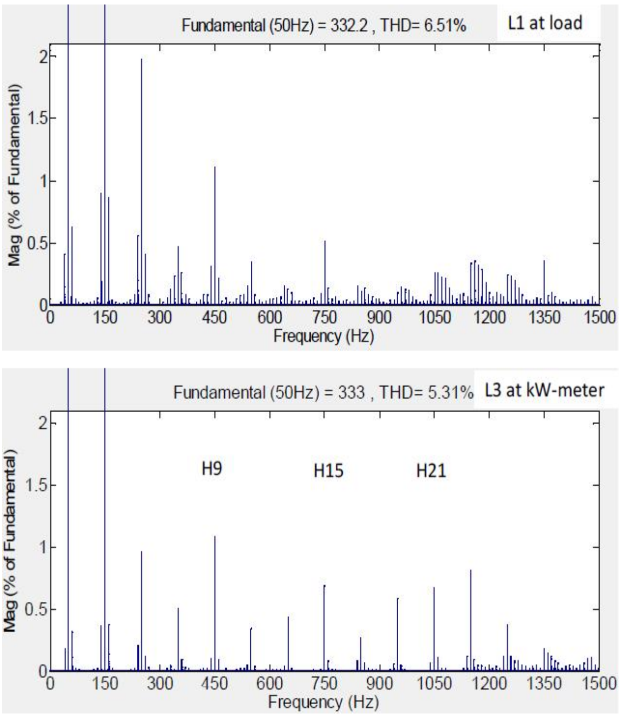

Fig. 7. FFT of the AC-voltage over a 10 s long period upper at the fluctuating load in phase L1 and lower in phase L3 at the customer connection point. Simulation.

A more thorough study including both measurement and simulations is needed to understand to what extent and how this happens. The simulation results supported the observation from field tests that these voltage quality challenges tend to appear in situations where very many similar appliances are connected to the LV-network. The simulations also revealed that even the common simple nonlinear loads have so complex interactions via the LV-network that simulation studies are needed to understand them.

FIELD MEASUREMENTS AND EXPERIENCE

Recent measurements performed in Denmark did however indicate PV installations as a source of interharmonics. Some of the measurements are shown in Fig. 8, where the curves indicate different interharmonics subgroups. Most remain at a very low level, but some of them show a clear increase whenever the solar panels are producing power. The emission level remains rather constant as long as the panels are active. The dominant interharmonics emission is in the bands centred around 75 Hz, 25 Hz, 125 Hz and 175 Hz (top to bottom in the Fig. 8).

No complaints were received about flicker at the location where these measurements were performed. This might be due to the interharmonics frequencies not being close to the third harmonic or due to the amplitudes being too low to cause any observable flicker. Note that even the highest levels in Fig. 8 are only 0.17% of nominal voltage.

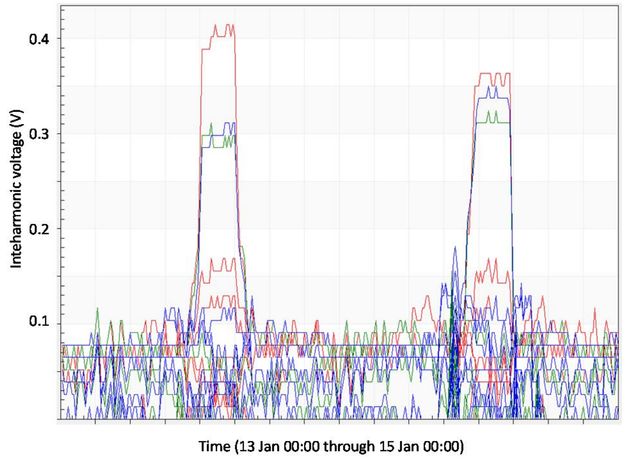

Fig. 8. Interharmonic voltages due to PV installations measured in a low-voltage network.

In Finland some power quality experts have witnessed CFL flicker in connection of using in the same customer premises either a certain vacuum cleaner or a certain laser-printer. Also in Sweden light flicker was observer with a fluorescent lamp in combination with a laser printer. However in none of those cases were detailed measurements done to study the impact of any interharmonics voltages. The flicker in association with laser printers may be due to minor voltage dips (individual rapid voltage changes).

Several cases of flicker in association with energy-saving lamps were also reported from Denmark, but in none of the cases were interharmonics measurements performed.

DISCUSSION

We identified potential gaps in the EMC standards, where it concerns interharmonics as well as flicker. There may be a relation between the two that will be completely missed because of these gaps.

The flicker standard (IEC 61000-4-15) is completely based on the classical standard 60-watt incandescent lamp. This one is rather quickly being replaced by other lamp types, which are differently sensitive to voltage magnitude and peak value fluctuations. A complete overhaul of the flicker standards is needed. Also more systematic studies are needed to measure and explain the relations between voltage fluctuations and light flicker for modern lamps.

There are clear indications, both theoretically and from measurements that certain interharmonics cause light flicker with energy-saving lamps such as LED lamps and CFLs, which is not captured by the flickermeter algorithm at all. 1) The flickermeter algorithm behaves according to standard 60 W incandescent lamps that are immune to frequency components above 100 Hz. Especially interharmonics close to odd harmonics, such as 150 Hz in a 50-Hz system, have been shown to cause light flicker in energy saving lamps. 2) In the flickermeter algorithm and the incandescent lamp the flicker is related to the fluctuations of the r.m.s. value of the voltage, while the flicker on energy saving lamps is rather closely related to the fluctuations of the voltage peak value. Linear lamp simulation model in the flickermeter algorithm cannot adequately represent this nonlinear behaviour. All this calls for additional measurements, simulations and theoretical studies.

The flicker sensitivity of energy saving lamps to real network voltages varies very much depending on the design of the particular lamp. Such design decisions include DC-link capacitor size and design of the LED current control. Thus it is necessary to include, in the design requirements of energy saving lamps, immunity to voltage fluctuations. Especially the immunity to fluctuations of the peak value of the voltage waveform must be addressed. The new flickermeter algorithm could then be developed based on those immunity requirements.

The standard method for measuring interharmonics (resulting in harmonic and interharmonics subgroups) gives insufficient frequency resolution to detect interharmonics that might potentially cause light flicker. Systematic measurement campaigns for interharmonic emission are needed, where measurement and analysis methods should be used that go beyond the standard methods. The results from such campaigns, together with the earlier-mentioned studies on the relation between interharmonics and light flicker, should be used as input to new standardization for both flicker and interharmonics.

CONLUSIONS

Neither flicker nor interharmonics receive the attention they deserve in power-quality research, development and measurements. Especially the relations between interharmonics and flicker deserve much more attention.

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