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Interaction between equipment and Power Line Communication: 9-95 kHz

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Abstract: This paper presents detailed measurements of currents flowing between modern electronic devices in a domestic environment. The results shown in this paper cover the frequency range 9 to 95 kHz, being the frequency band dedicated to power-line communication by network operators. Large differences exist between different devices, even when they are of the same type. It is also shown that the voltage waveform and the emission by other equipment have a significant impact on the current flowing between a device and the grid. An important conclusion from the measurements is that the high-frequency currents mainly flow between neighbouring devices.

I. Introduction

THE research on voltage and current distortion has mainly been constrained to the frequency range up to 1 or 2 kHz. This paper presents some of the results from a set of measurements performed in a full-scale electric model of a house with a range of electronic equipment. The interaction between the devices in the frequency range 9-95 kHz is the main subject of this paper. The choice of the frequency range is identical to the frequency range allowed for power-line communication by the network operator.

II. Experimental Setup

A full-scale electric model of a house was built in the laboratory at EMC on SITE, Luleå University of Technology. The load consists of kitchen equipment, a heat pump, a flat-screen television and a range of lighting equipment. Measurements were performed to examine how these loads interact with each other and how they together and individually affect the impedance level for higher frequencies. Measurements were done on individual loads as well as on the total. Focus has been on conducted emission in form of the high frequency currents (9-95 kHz) produced by modern electronic equipment and the propagation of the high frequency signals injected by power-line communication. More information about the measurement set-up and additional results are presented in [3].

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III. Experimental Results

A. Emission by Electronic Equipment

During the first set of measurements, normal domestic equipment was connected to the experimental setup. No other electronic equipment was connected in the neighbourhood so that the waveform distortion observed would mainly be due to the load in the experimental setup. The current at the connection point was shown to be smaller than the current at the terminals of most equipment. Especially the group of four identical compact fluorescent lamps takes a high current between 35 and 40 kHz. The inductive cooker also takes a rather high current in this frequency range. However the current at the delivery point is much smaller. From this the conclusion is drawn that the main currents in this frequency band flow between equipment and not between equipment and the grid. This is an important difference with lower frequency ranges (below 2 kHz) where the main flow of waveform distortion (harmonics) takes place between equipment and the grid.

B. Grid-connected and Islanded Supply

The measured current flowing between a compact fluorescent lamp and the grid is shown in Fig. 1. In this case the measurement setup in the laboratory was supplied directly from the public grid. The current waveform shows a sharp rise and a slow decay, as has been reported by other authors as well.

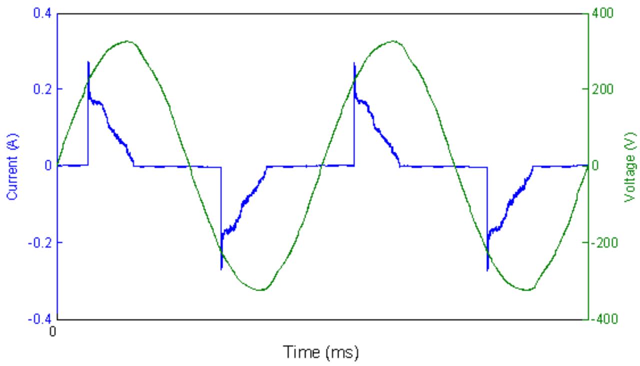

Fig. 1. Voltage (green) and current (blue) when a fluorescent lamp is supplied from the public grid. The horizontal scale is from zero to 40 ms.

The measurements have been repeated by supplying the laboratory setup from a small generator. Two generators were

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available for the tests: a modern 100-kVA generator used as a backup generator during maintenance in the distribution network; and an old 37-kVA generator. The measurement results are shown in Fig. 2 and Fig. 3. In all cases, no other equipment was connected to the laboratory set-up. However in the first case, supply from the public grid, other equipment was connected to the same 800 kVA transformer.

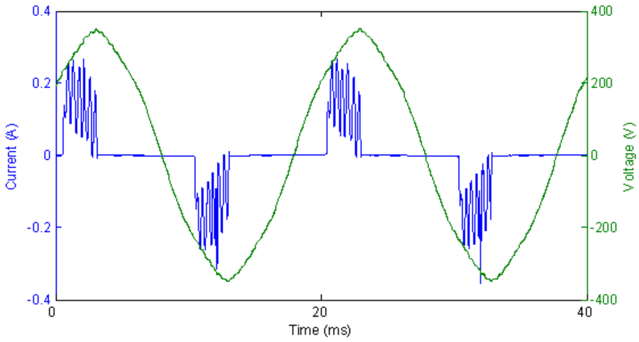

Fig. 2. Voltage (green) and current (blue) when a fluorescent lamp is supplied from a 100 kVA backup generator. The horizontal scale is from zero to 40 ms.

The difference in voltage waveform between these two generators and the public supply is clearly visible by comparing these three figures. Where the public supply gives the most sinusoidal waveform, the new generator gives a waveform with an increase in peak voltage, and the old generators gives a waveform with reduces peak voltage (a flat top).

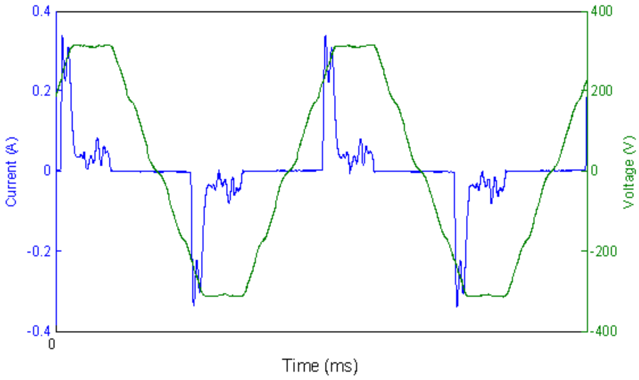

Fig. 3. Voltage (green) and current (blue) when a fluorescent lamp is supplied from a 37 kVA synchrononous generator. The horizontal scale is from zero to 40 ms.

The most striking difference between the three plots is the difference in current waveform. The 100-kVA generator results in an oscillating current, whereas the 37-kVA generator gives a high and a low peak with a superimposed oscillation. There is also a slight difference in the time the CFL draws current. There is a difference in size between the two generators and the public supply but the only load connected is an 11W CFL.

To visualize the time-frequency behaviour of the current taken by electronic load, the spectrogram was introduced in [1] and [2]. The spectrograms for voltage and current as shown before are shown in Fig. 4, Fig. 5, and Fig. 6. All three figures have the same horizontal scale (two cycles of the power-system frequency), the same vertical scale (9 to 95 kHz), and the same magnitude scale (the colours represent the same magnitude for each of the figures). However, the voltage and current diagrams have a different magnitude scale.

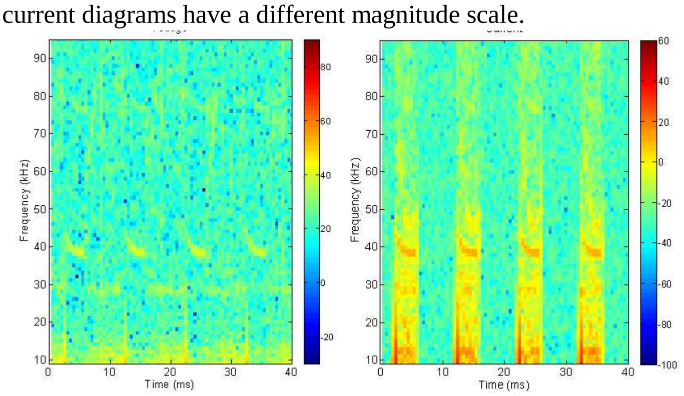

Fig. 4. Spectrogram of the voltage (left) and the current (right) when the lamp is supplied from the public grid.

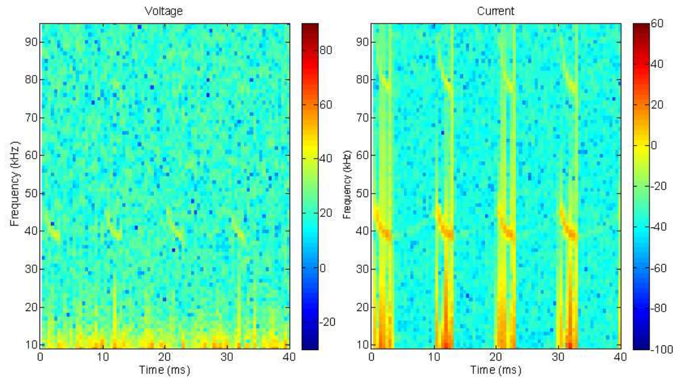

Fig. 5. Spectrogram of the voltage (left) and the current (right) when the lamp is supplied from the 100-kVA backup generator.

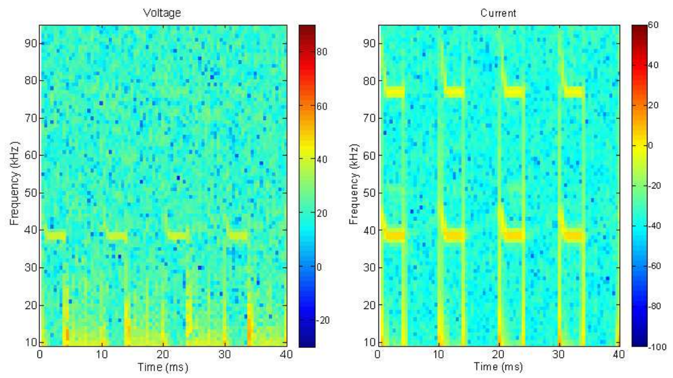

Fig. 6. Spectrogram of the voltage (left) and the current (right) when the lamp is supplied from a 37-kVA synchronous generator.

In all three cases, the high-frequency emission is present during part of the cycle only: this is when the diodes are conducting. There is no high-frequency emission when the diodes are not conducting.

The other simularity between the three spectrograms is that the 40-kHz switching frequency is present for all three. When supplied from a backup generator, especially for the 37-kVA case, the second harmonics (80 kHz) of the switch frequency also shows a strong presence.

Additional measurements are needed to find out if the differences in current waveform are due to the different source impedance or due to the different voltage waveform. When we assume a 20% impedance for the generators and 5% impedance for the distribution transformer, the source impedance is 30 to 100 times the grid impedance for the 100-kVA and 37-kVA transformer, respectively.

C. Devices influencing each other

Influence between devices was measured at many occasions. Several examples are shown in [3]. One of the most interesting and unexpected ones is illustrated in Fig. 7. A compact fluorescent lamp (CFL) is connected close to an induction cooker. The current to the CLF is measured for different states of the induction cooker, corresponding to different amounts of energy delivered to the cooking process. The figure shows that a neighbouring device can have a strong influence on the emission and that this influence does not have to be time-independent. A possible explanation for this behaviour is that the switching frequency of the induction cooker difference between different states. The emission, around the switching frequency, is absorbed by the capacitor in the EMC filter of the compact fluorescent lamp.

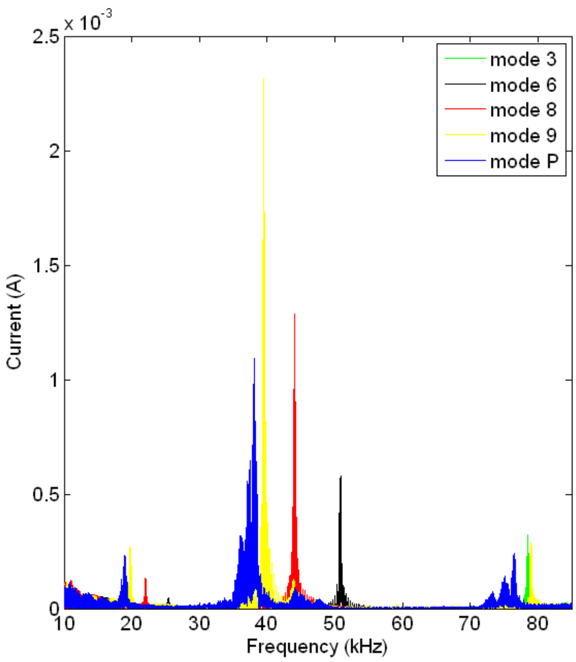

Fig. 7. Spectrum of the current taken by a compact fluorescent lamp close to an induction cooker. The different colors correspond to different states of the induction cooker. The horizontal scale is from 10 to 90 kHz.

D. Currents due to Power Line Communication

For a second set of measurements, a power-line communication (PLC) source is connected in a model of a neighbouring house close to of the delivery point. This neighbouring house did not contain any load in the experiments. The disturbance source (the PLC transmitter) has a frequency of 12.5 kHz and generates an rms voltage of about 7 Volt.

The presence of a power-line communication signal on the voltage resulted in high currents through several of the devices. These currents were significantly higher than the emission of the device or the current due to the emission from neighbouring devices.

Future immunity levels of equipment against distortion between 9 and 95 kHz should be based on the permitted levels of power-line communication signals.

E. Time-dependent impedance

Most modern household and office equipment contains a power-electronic converter as the interface with the grid. Therefore non-linear and time-dependent behaviour is expected. An example of non-linear behaviour was shown in the form of the increased current distortion at 18 kHz due to high voltage distortion at 12.5 kHz.

Time-dependent behaviour was observed as well. An example is shown in Fig. 8. For this figure, the PLC source was connected on the grid-side of the delivery point. The figure shows the current measured at the terminals of a compact fluorescent lamp (CFL) and at the terminals of the PLC transmitter. The compact fluorescent lamp shows the typical spectrum of a 4-pulse (single-phase) diode rectifier with a small capacitor on dc side. During the 20-ms time window shown in the figure, the PLC transmitter generates two burst of 43 kHz signals, seen as the high-frequency ripple on the current trace. The current is highest when the diode rectifier in the CFL is conducting. As the PLC transmitter operates as a voltage source, the conclusion can be drawn that the total impedance seen by this source (i.e. for all equipment connected) drops to about 30% once the diode rectifier starts to conduct. This reduction in impedance is most likely due to the dc-side capacitor in the CFL.

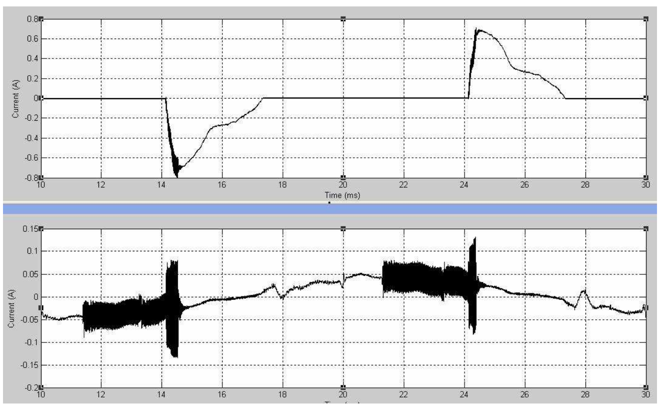

Fig. 8. Current drawn by a CFL 11 W (top) and by PLC disturbance source (bottom). The horizontal scale is from 10 to 30 ms.

F. Time-frequency behaviour

The spectrogram of the current taken by an LCD screen during one of the measurements is show in Fig. 9. The spectrogram was obtained while the 12.5-kHz source was emitting.

The large rectangular in the figure shows the actual spectrogram with time-axis horizontal and frequency axis vertical. To the left of the spectrogram the conventional spectrum (over the whole 200-ms window) is shown. Below and above the spectrogram the time-domain representation is reproduced: the original waveform below and the sliding-window rms above. The scale to the right relates the colours to a logarithmic (dB) magnitude scale.

The spectrogram in Fig. 9 shows that the 12.5 kHz component in the current is present continuously over the 200ms window. However the 25-kHz ”second harmonic” of is only present during short bursts every 10 ms. The 37.5 kHz ”third harmonic” shows a continuous as well as a pulsed character. Broadband spikes occur four times during the measurement windows, in groups of two. These may be related to the phase-shift keying in the PLC disturbance source. The component responsible for the low impedance path in this case is most likely the x-capacitor in the EMC-filter. This filter is expected to be connected to the grid as long as the appliances are plugged in. The appliance will draw high frequency current even though it does not draw current at the fundamental frequency. This is not the case with the CFL in the last section, when the lamp is turned off, no high frequency current will reach the lamp.

IV. Conclusions

A comparison between grid-connected and generator supply shows that this strongly influences the currents with a compact fluorescent lamp. No clear explanation for this is available at the moment, but this should be considered when relying on island operation of domestic or commercial load to guarantee the supply during maintenance or during a blackout.

For equipment connected to a “clean” supply, the currents in the frequency range 9 – 95 kHz flow mainly between neighbouring devices, not between the devices and the grid. The individual devices form a low-impedance path in this frequency range.

As a result of this, the emission in this frequency range will show much less spread over other customers than emission at lower frequencies. The impact of high-frequency distortion is likely to be limited to neighbouring equipment.

It is not possible to use standard emission models, as each device appears to be unique. The emission from different devices will thus add less at these frequencies than at lower frequencies. The resulting spectrum from a large number of devices will thus more likely be a rather flat continuous spectrum.

The emission and even the state of neighbouring equipment impact the current taken by a device. The emission measured by one device against a clean supply (like when using a "line impedance stabilizing network") is not a reliable prediction for the emission in a realistic environment.

Power line communication in the low-voltage network will result in significant currents through electronic devices due to the low impedance of the latter in the frequency range used by PLC (9-95 kHz). Future immunity requirements should be based on the permitted levels of PLC.

Equipment with a diode rectifier shows non-linear as well as time-dependent behaviour. The impedance of the device is lowest when the diodes are conducting, so that the current amplitude may be significantly higher than would be concluded from looking at the spectrum only. The non-linear character of the device results in additional frequencies being generated. The spectrogram (time-frequency-domain representation) is a suitable tool for studying these phenomena.

V. References

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[3] S. Rönnberg, M. Wahlberg, M. Bollen, A. Larsson, M. Lundmark, Measurements of interaction between equipment in the frequency range 9 to 95 kHz, Int Conf on Electricity Distribution (CIRED), Prague, June 2009.

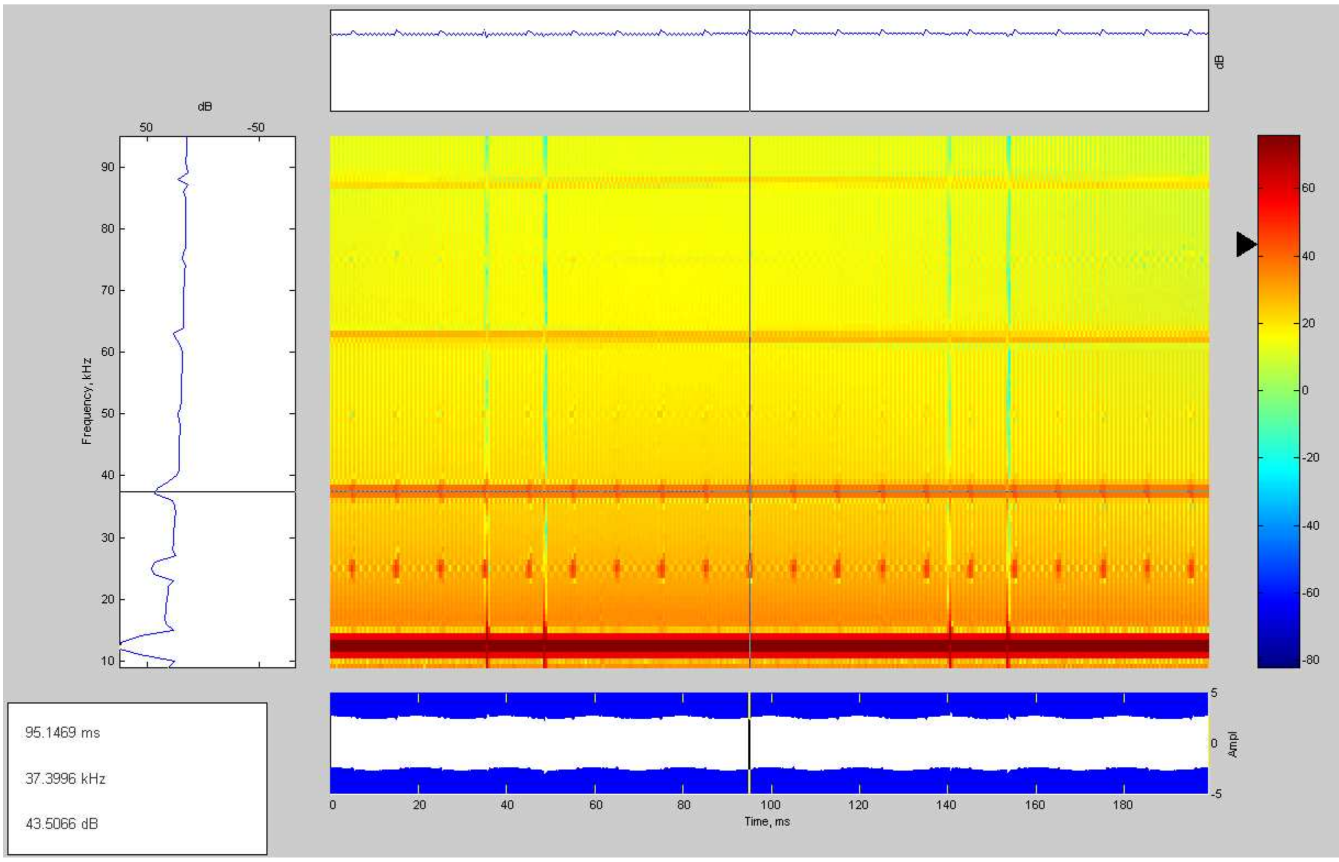

Fig. 9. Time-frequency representation of the current taken by an LCD screen while the PLC is transmitting.