A SIMPLE MODEL FOR INTERACTION BETWEEN EQUIPMENT AT A FREQUENCY OF SOME TENS OF KHZ

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ABSTRACT

This paper presents a simple model to explain the spread of high-frequency current between different devices and into the grid. The model is also used to show the aggregation between devices. The model is used to predict the amplitude modulation of the voltage and current ripple due to the small frequency differences between devices. The results from the model confirm earlier measurement results.

INTRODUCTION

Active power-factor-correction (APFC) is used with end-user equipment to limit the amount of harmonic distortion in the current. APFC is used with many electronic ballasts for fluorescent lamps. But also other equipment makes increasingly use of APFC as well [1]. The power-electronic switching used to achieve this leads to a current ripple with a frequency of typically some tens of kHz. An EMC filter, of CL or CLC form, is used to limit the amount of ripple injected into the grid.

With large numbers of devices connected at the same location, for example a lighting installation or a computer centre, the interaction between such devices becomes of interest. With increasing numbers of devices not only the total emission increases, but also the number of EMC filters connected to the grid. The situation is further complicated because of small differences in switching frequency even when devices are of the same manufacturer and type.

THE DEVICE MODEL

A typical configuration of a device equipped with APFC is shown in Figure 1. The four diodes and the capacitor C3 are the same as for a passive rectifier. The APFC circuit maintains the current through L2 such that the current at the grid interface follows the voltage waveform. The result is that the device behaves like a resistive load for the fundamental and lower-order harmonic frequencies.
The switching frequency used in the APFC circuit is visible in the grid current as well. To limit the high-frequency emission the device is equipped with an EMC filter (L1 and C1).

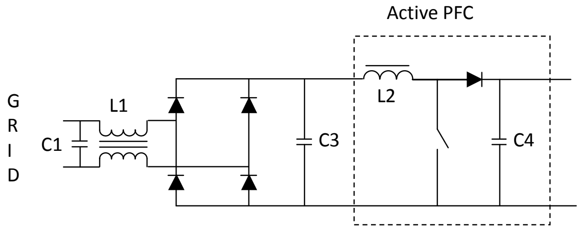

Figure 1. Electronic circuit at the grid connection for a device with active power-factor correction.

For the purpose of this paper, a simplified model of the device has been used. This model is shown in Figure 2. The device is modelled as an "internal emission" I_{L1} behind a capacitor C1. This is a combination of the current-source model often used for lower frequencies and a capacitor representing the way in which the grid impedance and voltage impact the emission.

The grid is modelled through a resistance R, as the resistance is dominating in low-voltage networks, especially close to the equipment. For higher frequency, R would be equal to the wave impedance.

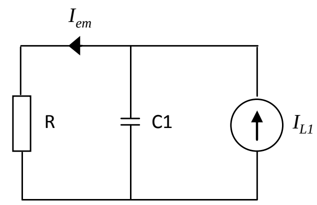

Figure 2. Simplified model of one device connected to the grid

PRIMARY AND SECONDARY EMISSION

One single device

The model for one single device connected to the grid is shown in Figure 2; I_{em} is the current flowing at the interface between the device and the grid, normally referred to as the emission of the device:

$$\bar{I}_{em} = \frac{1}{1+j\alpha}\bar{I}_{L1} \tag{1}$$

where $\alpha = \omega RC$. The voltage generated by the emitted device current I_{L1} is obtained from Ohm's law:

$$\bar{V} = \frac{R}{1+j\alpha}\bar{I}_{L1} \qquad (2)$$

From (1) it follows that the actual emission of the device depends on the impedance *R* of the grid and on the size of the capacitor on the grid-side of the filter.

Two devices

With two similar devices connected to the grid together, the situation becomes somewhat more complicated. Using the device model from Figure 2 gives the circuit in Figure 3. It is assumed that the two devices have the same capacitor C on grid-side of the EMC filter. All other inductance and capacitance in the grid is neglected here.

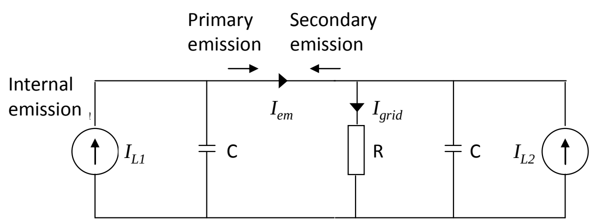

Figure 3. Simplified model for two devices connected to the grid.

The current flowing between device 1 (on the left) and the grid now consists of two components:

- ✓ The "*primary emission*": the part of the current driven by the internal emission of the device itself.
- ✓ The "*secondary emission*": the part of the current driven by the internal emission from the other device.

The (total) emission of device 1 is the sum of these two components:

$$\bar{I}_{em} = \frac{1+j\alpha}{1+2j\alpha}\bar{I}_{L1} - \frac{j\alpha}{1+2j\alpha}\bar{I}_{L2} \qquad (3)$$

The current flowing into the grid is the sum of the emission from device 1 and the emission from device 2:

$$\bar{I}_{grid} = \frac{1}{2j\alpha}\bar{I}_{L1} + \frac{1}{2j\alpha}\bar{I}_{L2} \qquad (4)$$

The voltage is equal to the grid current times the grid impedance *R*.

In practice the internal emission of the two devices will be slightly different (in amplitude and in frequency), even if the devices are of the same type, for example two fluorescent lamps with high-frequency ballast. Assume that both devices have an internal emission of the same amplitude I_L, but of slightly different frequency. Over a small frequency band, covering both frequencies, the amplitude of the total emission can be obtained from Parseval's theorem as the root sum square of the two components:

$$I_{em} = \sqrt{\frac{1+2\alpha^2}{1+4\alpha^2}}\, I_L \qquad (5)$$

For low frequencies, $\alpha \ll 1$, the interface current is equal to the internal emission; for high frequencies, the interface current is about 70% of the internal emission. The impact of the switching frequency or the capacitor size, on the interface current is small. The presence of a second device increases the emission of the first device

In the same way the amplitude of the total current (from the two devices) flowing into the grid is found from:

$$I_{grid} = \frac{\sqrt{2}}{\sqrt{1+4\alpha^2}}\, I_L \qquad (6)$$

The current at the interface of each individual device shows only limited frequency dependence whereas the current flowing into the grid decreases inversely proportional to the switching frequency.

Multiple devices

The calculations can be repeated for increasing numbers of devices. For *N* devices, with internal emission I_{Li} and capacitance *C*, connected to a grid with impedance *R*, the emission of one device is:

$$\bar{I}_{em} = \frac{1+(N-1)j\alpha}{1+Nj\alpha}\bar{I}_{L1} + \frac{j\alpha}{1+\mathrm{N}j\alpha}\sum_{\mathrm{i}=2}^{\mathrm{N}} \bar{\mathrm{I}}_{\mathrm{Li}} \qquad (7)$$

The amplitude of the current at the interface of an individual device is:

$$I_{em} = \sqrt{\frac{1+N(N-1)\alpha^2}{1+N^2\alpha^2}}\, I_L \qquad (8)$$

The total emission from one device is almost equal to the internal emission and independent of the number of devices, the switching frequency, the capacitor size and the grid impedance.

The total current flowing into the grid is obtained from the following expression:

$$\bar{I}_{grid} = \frac{1}{1+Nj\alpha}\sum_{i=1}^{N} \bar{I}_{Li} \qquad (9)$$

The amplitude of this current is:

$$I_{grid} = \frac{\sqrt{N}}{\sqrt{1+N^2\alpha^2}}\, I_L \qquad (10)$$

Whereas the emission from one device is constant, the emission of the total installation is, for higher frequencies, inversely proportional to the square-root of the number of devices. For low frequency the emission of the total installation is proportional to the square-root of the number of devices.

BEHAVIOUR IN TIME DOMAIN

The expressions shown in the previous section all hold in frequency domain. In time domain we assume that the internal emission is a sinusoidal waveform. For one device both the current and the voltage are, under that assumption, also a single-frequency sine wave.

Two devices

For two devices, with slightly different frequencies of the internal emission, voltage and current consist of two sine waves with slightly different frequencies.

The emission by one device is given by the following expression:

$$i_{em}(t) = \frac{\sqrt{1+\alpha^2}}{\sqrt{1+4\alpha^2}} I_L \cos(\omega_1 t + \phi_1) + \frac{\alpha}{\sqrt{1+4\alpha^2}} I_L \cos(\omega_2 t + \phi_2) \quad (11)$$

Due to the two slightly different frequencies, the result will be an amplitude-modulated sine wave. The maximum amplitude of this sine wave is:

$$I_{em,max} = \frac{\sqrt{1+\alpha^2}+\alpha}{\sqrt{1+4\alpha^2}} I_L \quad (12)$$

And the minimum is:

$$I_{em,min} = \frac{\sqrt{1+\alpha^2}-\alpha}{\sqrt{1+4\alpha^2}} I_L \quad (13)$$

In the same wave it can be shown that the current flowing into the grid is an amplitude-modulated sinewave with minimum zero and maximum

$$I_{grid,max} = \frac{2}{\sqrt{1+4\alpha^2}} I_L \quad (14)$$

Multiple devices

With multiple devices, the voltage and current amplitude are modulated with a multitude of modulation frequencies. In the same way as before, the maximum and minimum amplitudes can be calculated. The maximum current from one device is:

$$I_{em,max} = \frac{\sqrt{1+(N-1)^2\alpha^2}+(N-1)\alpha}{\sqrt{1+N^2\alpha^2}} I_L \quad (15)$$

The minimum amplitude goes to zero for increasing numbers of devices.

The maximum current into the grid is equal to:

$$I_{grid,max} = \frac{N}{\sqrt{1+N^2\alpha^2}} I_L \quad (16)$$

NUMERICAL EXAMPLE

To illustrate the interaction between different devices, consider the following numerical example:

- ✓ R=50 Ω
- ✓ C=220 nF
- ✓ ω=2π x 40 kHz

Using the expressions in the previous sections, we find that for one device the emission is equal to 0.34xI_L (with I_L the internal emission). Connecting a second device close to the first device increases the emission for each device to 0.72xI_L, but the total current from the installation into the grid reduces to 0.25 xI_L. The emission per device increases but the total emission of the installation becomes less.

In time domain the currents are amplitude modulated. The current from one device varies between 0.03xI_L and 1.02xI_L. The current from both devices together varies between zero and 0.36xI_L. Although the current into the grid is less for two devices than for one device in the frequency domain, its highest amplitude in time domain has slightly increased.

For multiple devices the currents have been calculated as a function of the number of devices. The results are shown in Figure 4 for the current from one device and in Figure 5 for the total current.

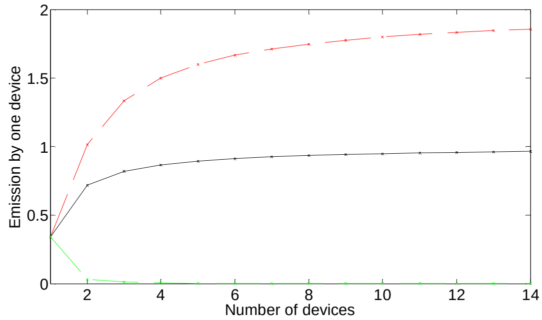

Figure 4. Emission by one device as a function of the total number of devices in the installation; top-to-bottom: highest amplitude in time domain; value in frequency domain; lowest amplitude in time domain.

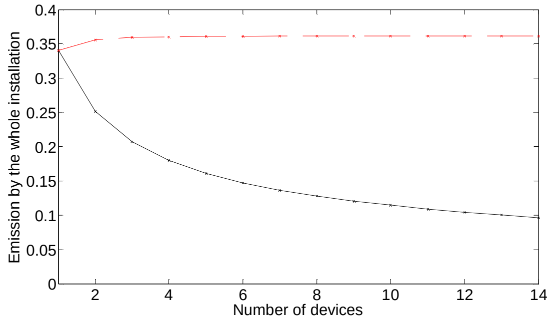

Figure 5. Emission by a complete installation as a function of the number of devices in the installation; highest amplitude in time domain (top); value in frequency domain (bottom).

The emission by one device is shown in Figure 4. The black (solid) curve indicates the emission in frequency domain. This increases with the number of devices and reached a value equal to the internal emission for a large number of devices. In time domain the amplitude varies between a minimum value (decreasing to a small value with increasing number of devices) and a maximum value (increasing towards twice the internal emission).

The emission from the total installation, shown in Figure 5, behaves completely differently. In frequency domain it decreases with the number of devices. For 10 devices, the total emission is only one third of the emission from one single device connected to the grid. Note that the total emission of the installation decreases, the "total emission per device" decreases even faster.

In time domain the highest amplitude of the emission from the total installation remains more or less the same at a value slightly above the emission from one single device connected to the grid.

MEASUREMENT

Measurements were performed in the laboratory of Luleå University of Technology on installations consisting on multiple fluorescent lamps with high-frequency ballasts. These ballasts are equipped with active power-factor correction using a switching frequency around 45 kHz. Measurements for an installation with two lamps are shown in Figure 6.

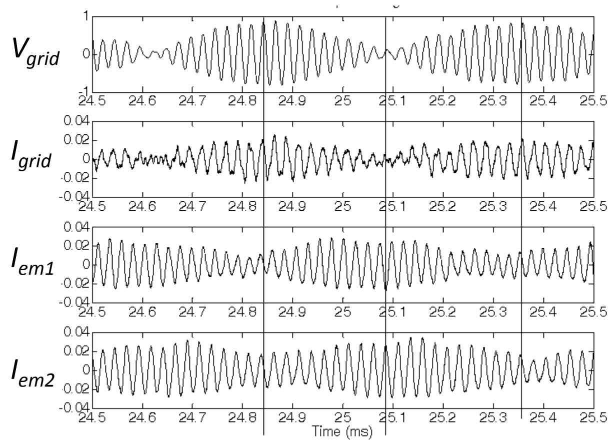

Figure 6. Measured voltages and currents from an installation consisting of two fluorescent lamps. Top to bottom: voltage at the connection to the grid; current from the total installation into the grid; current at the interface of lamp 1; current at the interface of lamp 2.

The observed behaviour corresponds well with the results predicted from the simple model presented in this paper. The voltage amplitude varies between a maximum value and zero; the current amplitude varies between a maximum and a minimum value; the maximum amplitude of the voltage occurs close in time to the minimum amplitude in current. The latter follows from the expressions for ϕ_1 and ϕ_2 in (11).

The general behaviour shown in Figure 4 and Figure 5 corresponds with the results from measurements at installations with multiple devices [2,3,4]. The model calculations show that the observed behaviour can be explained from the increase of the amount of capacitance with increasing number of devices.

CONCLUSIONS

A simple model is presented to estimate the emission from an installation with multiple devices equipped with active power-factor correction. It is shown that the secondary emission (current flowing at the interface between a device and the grid due to a disturbance source elsewhere) cannot be neglected. It is further shown that the emission from one devices increases when more devices are connected to an installation, whereas at the same time the total emission from the installation becomes less.

In time domain the current amplitudes are be modulated due to slight differences in switching frequency between individual devices. The highest current amplitude for each device will increase with the number of devices. The highest amplitude of the total current from the installation remains about the same.

It is also concluded from the calculations that all currents (in frequency as well as in time domain) increase towards a maximum value that is not exceeded even for very large installations. For example the current at the interface of a device never exceeds twice the internal emission.

A next step is a quantitative comparison between this simple model and measurements, to determine the accuracy of this model. Some measurements results are presented in two companion papers [3,4].

ACKNOWLEDGEMENTS

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