HIGH-FREQUENCY COMPONENTS IN THE NEUTRAL AND PROTECTIVE EARTH CURRENTS DUE TO ELECTRONIC EQUIPMENT

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ABSTRACT

This paper addresses the issue of neutral and protective-earth currents in the frequency range 2 through 150 kHz. Both theoretical analysis and measurements will be presented. It is concluded that a large part of the high-frequency distortion in the phase currents closes via the neutral wire and impacts the terminal voltage for equipment in the other phases. The introduction of HF-harmonics is even more detrimental to the intention with three-phase systems to minimize the currents outside the phase conductors.

INTRODUCTION

The use of power electronics in domestic, commercial and industrial equipment has increased rapidly. There are several advantages with these power converters such as high power density, small losses and low weight. A disadvantage is however that they often generate high levels of harmonic emission [1].
International standards, e.g. EN 61800-3 (1996) and EN 61000-3-2 (2001), have been introduced to limit the harmonic currents produced by small and large equipment. Some types of equipment, noticeable electronic-driven ballast for fluorescent lamps and some advanced power-electronic driven electrical machines, are equipped with a so-called ”controlled rectifier” or ”active front-end” as interface. These interfaces produce only a small amount of distortion in the frequency band up to about 1 kHz.
However they produce instead waveform distortion at higher frequencies, typically at the switching frequency and at harmonics of the switching frequency. These so-called ”high-frequency harmonics” (HF-harmonics) may cause new problems and therefore need to be investigated.

LEAKAGE CURRENTS

The transport of energy as a current in the power grid (P in Figure 1) takes place at the power system frequency: 50 or 60 Hz in public grids, DC, 16 2/3 or 400 Hz in some special applications. Any other frequency component in the current is a form of conducted electromagnetic emission.
If the sum of the currents enclosed in the circle is not zero, some kind of leakage current exists. This leakage current leaves a device or system through an unwanted or unknown path. At the power-system frequency, the conductive part of this leakage current dominates. With increasing frequency, the radiating part of the leakage current increases, seen as electromagnetic radiated emission.

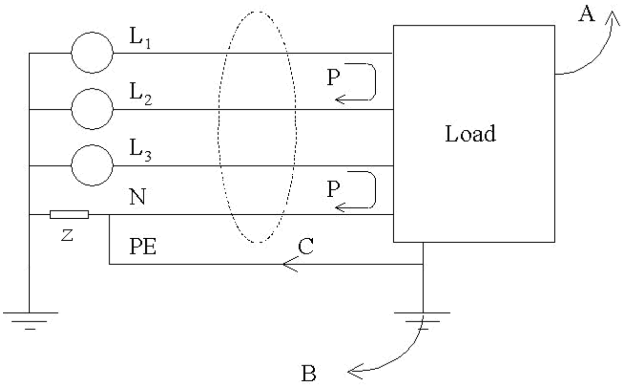

Figure 1. *The common-mode current shows up as three different types of electromagnetic emission: A-radiated emission, B-conducted emission in the form of stray currents, C-conducted emission through the protective earth*

This leakage current is also referred to as the common-mode (CM) current. The common-mode current shows up as three different types of electromagnetic emission:

- *Radiated emission:* (A in Figure 1). Radiated emission may interfere with radio communication or induce currents in neighbouring equipment that interfere with the correct operation of that equipment.
- *Conducted emission in the form of stray currents*: the part of the current that does not return through any of the metal conductors, but instead finds it way through water pipes, communications networks, the armouring of a building, etc. (B in Figure 1). The concern with stray currents is mainly their unpredictability (there should be no currents flowing outside the electricity wires) and the magnetic fields due to the large return loops.
- *Conducted emission through the protective earth:* (C in Figure 1). Currents through the protective earth (PE) may find a galvanic path to other devices connected to the same protective earth. According to the safety regulations, the PE wire is not allowed to carry current unless there is a fault in the power distribution system.

NEUTRAL CURRENTS

In a balanced three-phase power system with only power-system frequency in voltage and current, the current through the neutral wire is zero. Only an unbalance in current (a zero-sequence component) causes a neutral current. The load is normally spread over the three phases so that the neutral current is small; this also minimised the losses in the phase conductors.

The currents taken by electronic loads with switch mode power supply (SMPS), like almost all consumer electronics, is far from sinusoidal, resulting in a neutral current as high as $\sqrt{3}$ times the phase current, even when the load is equally divided over the three phases. This neutral current consists of the "zero sequence harmonics" (3, 9, 15 etc.) while the other odd harmonics are cancelled [1]. This high current could lead to thermally overloaded neutral and being a cause of stray currents, especially in the case of common neutral and PE wire.

HF-HARMONICS DUE TO SINGLE-PHASE LOADS

The SMPS, has besides a number of benefits, two basic drawbacks: the generation of harmonics of the power-system frequency, and the generation of so called "high-frequency harmonics" from the DC/DC converter in the output of the SMPS.

One of the solutions to reduce power-system frequency harmonics, active power factor correction (PFC), allows for a wide input voltage range, a displacement power factor close to 1.0 in combination with almost sinusoidal input current. An active PFC uses a switching element together with an inductor, a switched-mode boost converter, before the storage capacitor to force the current, like in a resistor, to follow the shape of the voltage.

These interfaces produce significantly less distortion in the frequency band up to about 1 kHz. However they produce instead waveform distortion at higher frequencies, among others at the switching frequency and at harmonics of the switching frequency.

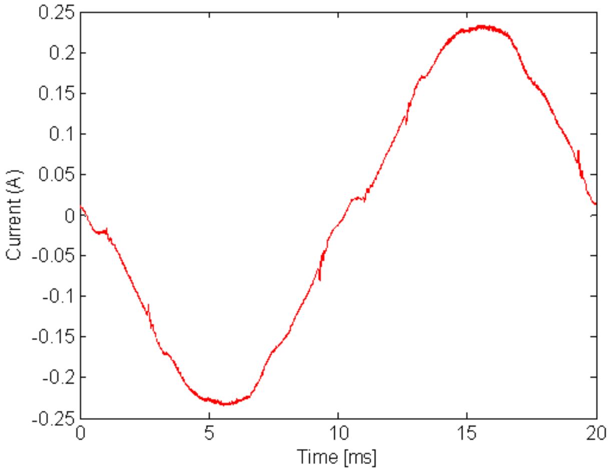

Figure 3. *The measured phase current for a HF - fluorescent lamp with active* PFC

The phase currents from a HF fluorescent lamp using a PFC solution including variable switching frequency, using hysteresis control, is shown in Figure 3.The current waveform includes two characteristic HF- components:

- A variable frequency with a peak at the power-system frequency's positive and negative maximum value [*hysteresis components*]
- Notches and oscillations close to the current zero crossing [*zero-crossing distortion*].

The hysteresis control switching frequency has the lowest frequency and highest intensity around current maximum and minimum. The switching frequency could also change between low and full load and being variable to minimize the EMC- filter [2]

The zero-crossing distortion occurs when there is a discontinuity in the current flow from the AC input. In a buck converter there is a usual period when the instantaneous AC input voltage is lower than the SMPS output voltage [3]. Also in a boost converter using active PFC, zero-crossing distortion is a common phenomenon [4]. Instability below the power system frequency has occurred when the PFC converter is connected to "certain types of AC sources including uninterruptible power supplies" [5]. Important parameters in that case are load, output capacitor and feedback gain [6]. Also fast-scale instability has been studied [7], [8], [9] showing the influence of parasitic capacitances and feedback gain. In the case of cascaded power electronic system, instability has occurred caused by impedance interaction [10]. Measurements on HF fluorescent lamps show the increase in these zero-crossing components with increasing number of lamps [11].

HARMONICS IN NEUTRAL AND PROTECTIVE EARTH

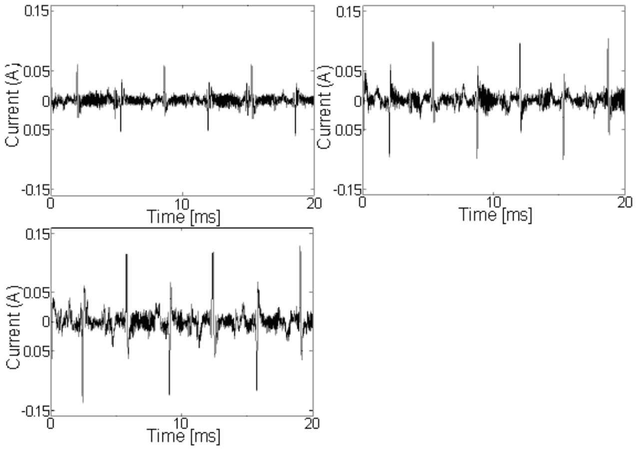

Figure 4. *Measured neutral current with one (top left) two (top right)) and three (bottom) HF fluorescent lamps per phase.*

Measurements have been performed on HF fluorescent lamps to study the HF- harmonic contents in the neutral wire. In the first set of measurements one, two and three lamps were connected per phase, and the neutral current was measured. A 2-kHz digital high-pass filter was used on the neutral current and the result is shown in Figure 4. The HF-harmonics consist of a series of hysteresis components (the spikes) and zero-crossing components (the noise bursts), with its origin in the three phase currents. At phase current maximum and minimum there is always a hysteresis component and also a simultaneous zero-crossing component contribution from the other two phases. The peaks, associated with the zero-crossing distortion, increase with the number of lamps. The hysteresis component increases with the number of lamps.

In the second set of measurements the current was measured for up to nine lamps connected to the same phase. The resulting neutral current was next estimated by assuming exactly one-third of 20 ms shift in time domain for the waveform in the other two phases. The neutral current was obtained by simply adding the three phase currents.
The results for one lamp per phase are shown in Figure 5. The blue, green and red curves are the phase currents (one measured, two obtaining by shifting the measured current), and the black curve is the (calculated) neutral current. The dominating third-harmonic components as well as the high-frequency components are clearly visible.

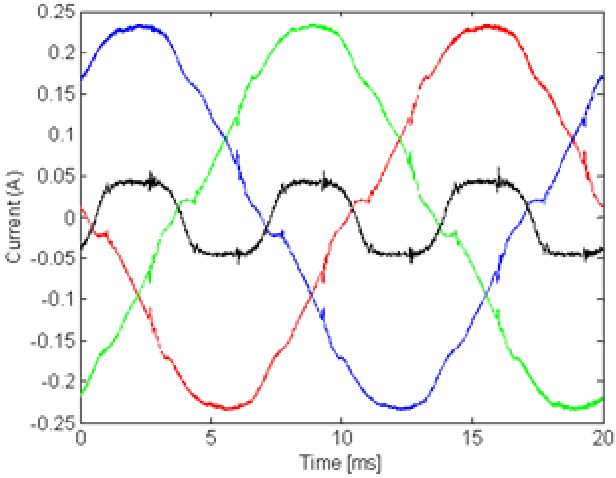

Figure 5. *The phase and neutral currents in the three-phase distribution system created from a single-phase current in Figure 3 (the red curve).*

By using a 2 kHz high-pass filter on the neutral current in Figure 5, it is possible to study the HF-harmonic separately as seen in Figure 6. The zero-sequence harmonics no longer dominate the current. The hysteresis components, are seen as a continuous ”noise” varying in amplitude. The notches and oscillations close to the phase current zero-crossing in each phase are seen as six damped ”peaks” in the 20 ms graph. All these peaks have almost the same maximum amplitude and are at least twice the noise amplitude. The rms value of the current, obtained over the 20 ms window in Figure 6, is equal to 17.4 mA.
Making a detail of the highest peaks in Figure 6, (not shown here) shows the damped peak to have about a 156 µs period time, a frequency close to 6.4 kHz. The positive peak is about 60 mA, and the negative peak is about 40 mA.

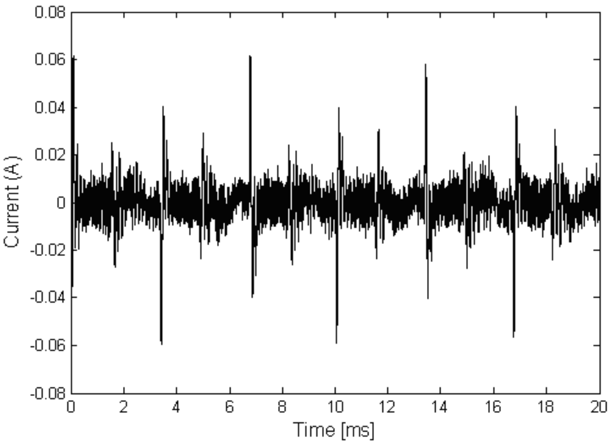

Figure 6. *Estimated neutral current in a three-phase system loaded with three HF fluorescent lamps. A 2-kHz digital high-pass filter has been applied.*

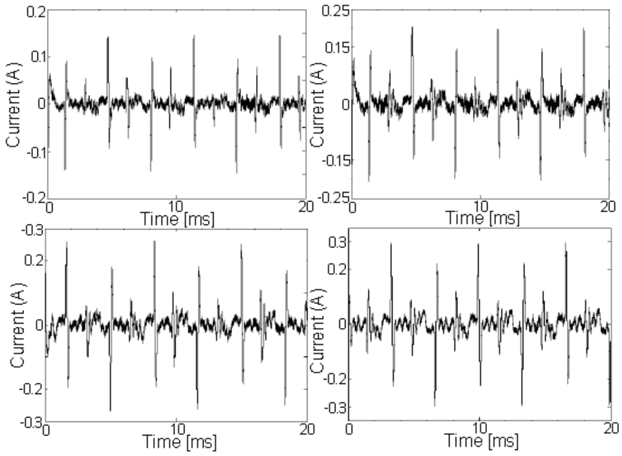

Figure 7. *Three HF-fluorescent lamps in each phase simulated in upper left, five at upper right, seven at lower left and nine HF fluorescent lamps at lower right.*

The estimated neutral currents for three, five and seven fluorescent lamps are shown in Figure 7. The trend from Figure 4 continues: the peaks associated with zero-crossing distortion increase in amplitude; the noise associated with hysteresis control reduces in amplitude.

The peak value increases from 10.2 mA to 60.6 mA (a ratio of 5.9) when the number of lamps per phase increases from one to nine. The increase is more or less linear up to 7 lamps, but shows a clear saturation after that. The oscillation frequency of the peaks decreases from 6.5 to 3.35 kHz.
These measurement results have next been used to estimate the neutral-to-earth voltage induced by the neutral current. A 2.5 mm^2 copper wire of 30 meters length has been assumed for the neutral. The results are shown in Figure 8.

The lower graph shows the voltage drop if only the resistance is taken into consideration.

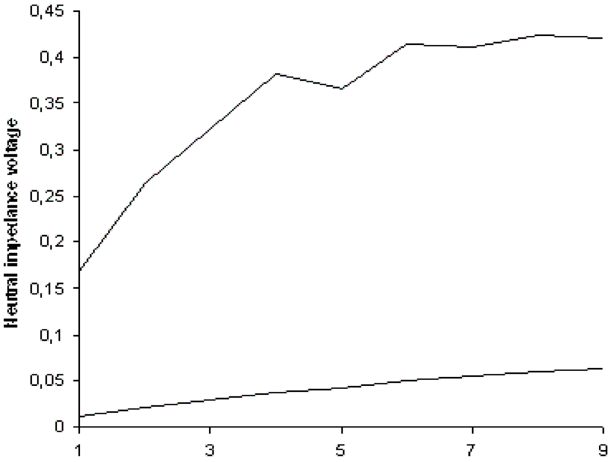

Figure 8. *Neutral peak voltage with increasing numbers of HF-fluorescent lamps; full complex impedance (upper graph) and resistance only (lower graph).*

The neutral-to-ground voltage is calculated by multiplying the peak current with the impedance for the resonance frequency. It is shown that already a small number of lamps can give a neutral-to-ground voltage of about 0.5 Volt. In this case increasing the number of lamps above 5 no longer increased the neutral-to-earth voltage. It is unclear if this is a general phenomenon. The voltage drop is mainly due to the inductive part, so that an increase in cross-section will not have much effect.

CROSS-COUPLING BETWEEN THE PHASES

The voltage over the terminals of a single-phase low-voltage device is the difference between the phase-to-earth voltage and the neutral-to-earth voltage, assuming the device is connected phase-to-neutral, as is almost always the case. The active PFC circuit in modern fluorescent lamps and other equipment aims at generating a current waveform that follows the (phase-to-neutral) voltage waveform. If the voltage is distorted, the current will be distorted in the same way.

The low-frequency distortion of the voltage is not impacted by the current taken by one individual device; so that there is no risk for any feedback. The situation is different for high-frequency distortion, especially for zero-crossing distortion, which is of relatively low frequency. It is shown in [11] that the current distortion of one device can already be the dominating impact on the voltage distortion. The zero-crossing distortion adds in the neutral voltage, as shown before, so that the risk of feedback not only exists for equipment in the same phase, but also for equipment connected to other phases.

A closer study is needed of the cross coupling between the phases and of the way in which high-frequency distortion in the voltage impacts the current waveform taken by an active PFC circuit.

CONCLUSIONS

A symmetrical three-phase system uses the wires optimally, with low losses and no current in the neutral. The introduction of harmonics leads to zero-sequence current in the neutral. Zero-sequence harmonics increase the capacity to create leakage and stray currents and increase the losses. The introduction of active PFC circuits introduces new types of (high-frequency) harmonics that add in the neutral wire. The risk of stray currents, radiated emission, and positive feedback loops needs to be seriously investigated.

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