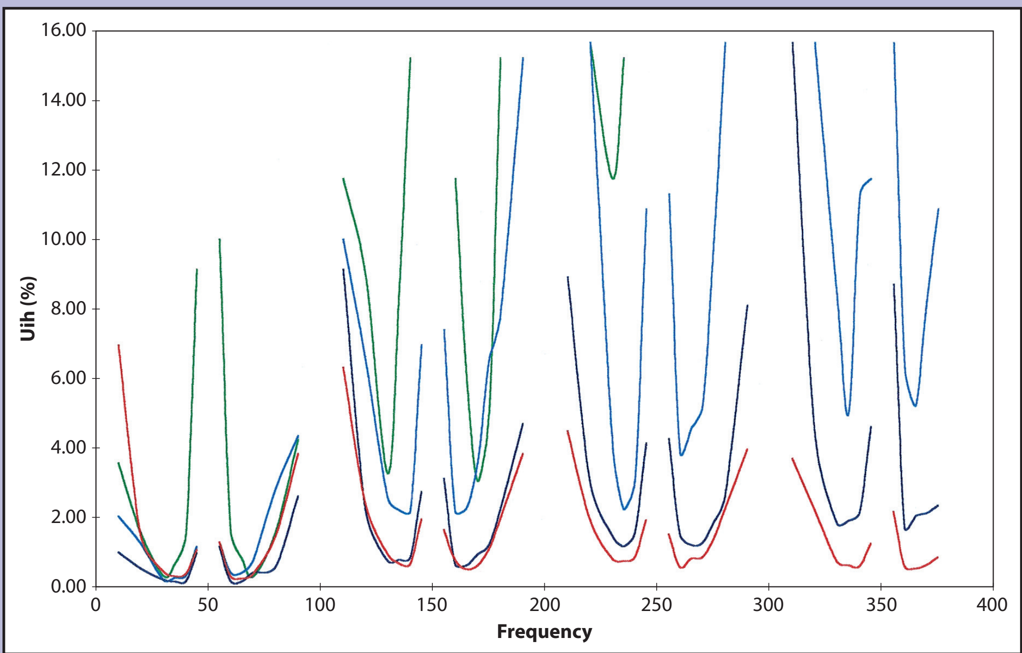
Case study

Leonardo ENERGY

Power Quality

Michèle De Witte
Laborelec
December 2007

Flicker problems in a steel plant caused by Interharmonics



european COPPER institute

Power Quality

Introduction

A steel manufacturing plant was experiencing a flicker problem. Lights in the office areas of the plant were often flickering, affecting productivity and creating an irritating nuisance for employees.

A Power Quality consultant was called in to investigate the case. He carried out measurements to gain a better understanding of the problem and to enable him to identify the source of the flicker phenomenon and the operating conditions in which it occurred. Once this information in hand, he was able to propose an appropriate solution.

1. Problem description

1.1 Flicker

Flicker is a particular deviation from the sinusoidal waveform of an electric voltage. It is usually experienced through the flickering of lights. Two types of flicker exist:

1) Normal flicker is caused by repeated rms voltage variations. It can be measured using a flickermeter[1].
2) Flicker provoked by interharmonic voltages[2]. An interharmonic voltage has a frequency that is a non-integer multiple of the fundamental frequency of 50 Hz. This kind of flicker cannot be measured by means of a normal flickermeter.

Not all interharmonic voltages necessarily cause visible flicker in all types of lighting equipment. Some equipment is more sensitive to certain interharmonic frequencies than others. Sensitivity curves for various types of equipment can be drawn based on experiments. An example representing the curves of fluorescent and compact fluorescent lamps is given in Figure 1.

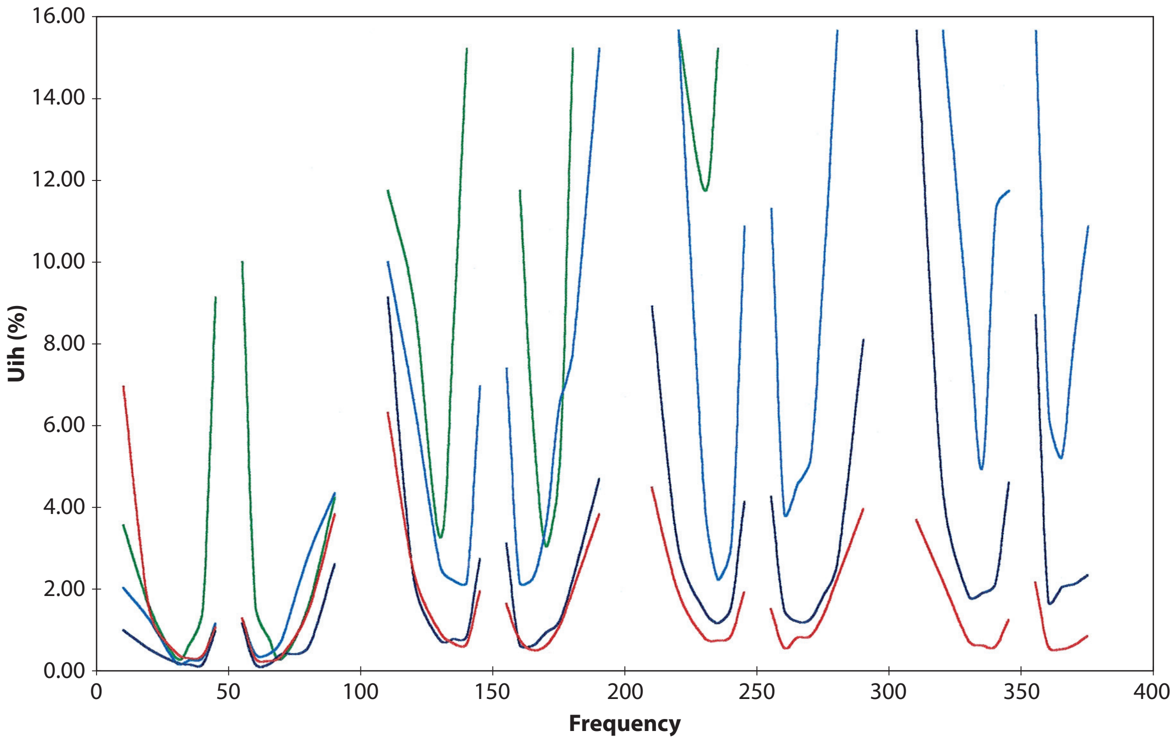


Figure 1: Sensitivity curves for various types of lighting equipment

[1] IEC 61000-4-15 – electromagnetic Compatibility (EMC) – Part 4: Testing and measurement techniques – Section 15: Flickermeter – Functional and design specifications

[2] "Light flicker caused by interharmonics"; 8th International Power Quality Applications Conference; 1998; Cape Town, South-Africa

1.2 Problems encountered

Normal flicker

The flickermeter indicated a relatively high level of normal flicker on the 30 kV bus bar. This flicker was traced and found to originate at loads at the higher voltage level (150 kV), which included an electric furnace. However it was demonstrated that this normal flicker measured on the 30 kV busbar resulted in a flicker that was hardly visible at the lower voltage to which the office lights were connected. Consequently, the normal flicker provoked by the electric furnace **could not be the sole reason for the flickering of the lights in the offices.**

Flicker by interharmonics

The 30 kV bus bar also connected a rolling mill. To improve the cosφ, capacitor banks and their corresponding filters are installed on the 30 kV net. **There were filters for the fifth, seventh, and eleventh harmonic currents.** These were passive filters that can be operated separately. **Such filters create a low-impedance circuit for one specific frequency, but also create anti-resonance at frequencies adjoining the tuning frequency.** This fact made it likely that the cause of the flicker problem was in the high interharmonic voltages provoked by the interaction between the rolling mill and the various filter passes. In other words, high harmonic impedance in the filters at frequencies that also show up in the current harmonics of the load proved to be the origin of this flicker problem.

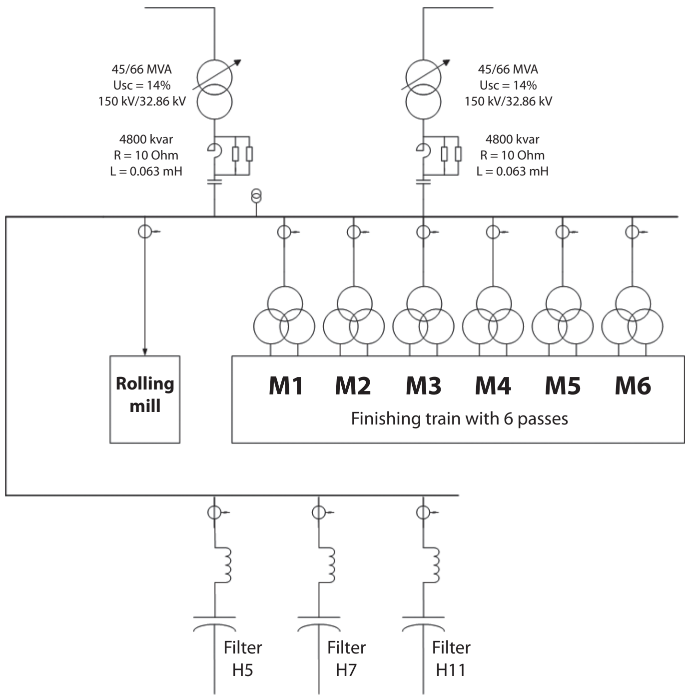


Figure 2: Electrical scheme of the in-stallation

2. Measurements and simulations

2.1 Theory

When a capacitor bank is installed to improve the power factor of the load, a combination of filters and inductors is often installed to attenuate certain harmonics. The filter creates a series resonance that attenuates a certain harmonic. The inductor, installed in series with the capacitor, creates a parallel resonance at a lower frequency than the filtered harmonic frequency. The combination of the series resonance from the filter and the parallel resonance obtained by the inductor, leads to the curve shown in the figure entitled Series + parallel resonance.

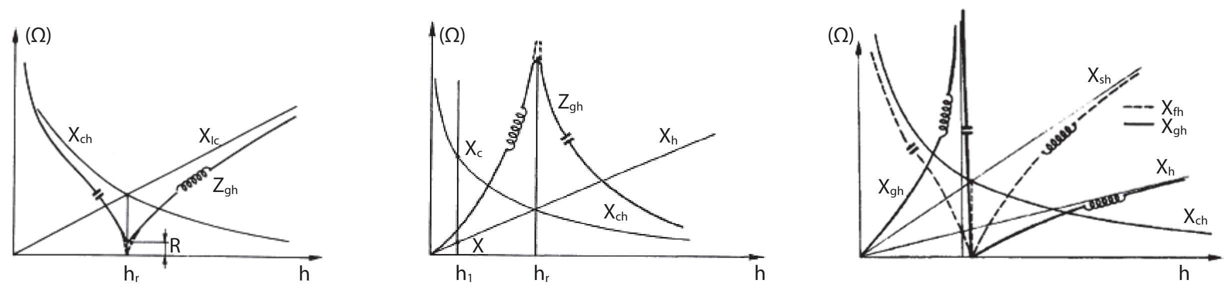


Figure 3: a) Series resonance b) Parallel resonance c) Series + parallel resonance

If several filters are installed, each tuned to another harmonic frequency, there is a cascade of these types of curves. There are several frequencies for which the harmonic impedance is (nearly) zero and several corresponding frequencies for which the impedance tends to infinity. An example of such a curve is shown in Figure 4.

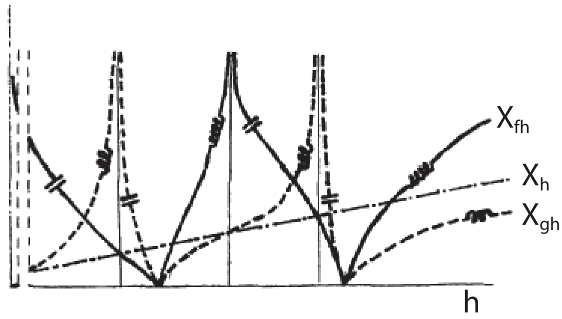


Figure 4 : Different filters in parallel

2.2 Network modelling and simulations

To verify the theory of the anti-resonances, a simulation of the network was set up to examine the harmonic impedance of the system. The simulation was carried out for three configurations:

1) Filters for h5, h7, and h11 switched on (hereafter called first filter configuration)
2) Filters for h5 and h7 switched on (second filter configuration)
3) Filter for h5 switched on (third filter configuration)

The principal results can be seen in the following graphs.

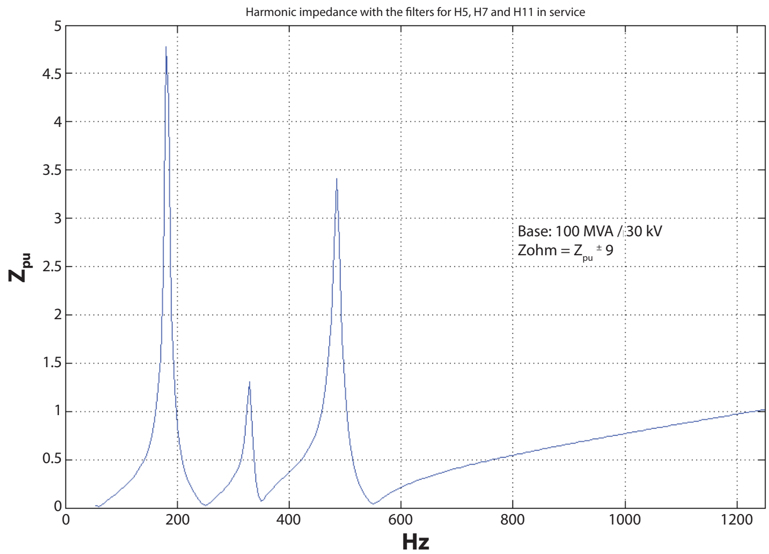


Figure 5: Harmonic impedance with three filters (h5, h7 and h11) switched on

The first graph (Figure 5) shows the harmonic impedance of the 30 kV bus bar when the three filters are switched on. One can observe that impedance is (nearly) zero at three frequencies: 250 Hz (h5), at 350 Hz (h7), and at 550 Hz (h11). These are the tuning frequencies of the filters. The filters behave as short-circuits for currents at these frequencies. An inherent characteristic of a tuning frequency is that it provokes an anti-resonance frequency just below the tuning frequency. In this case these anti-resonance frequencies are 180 Hz, 330 Hz, and 485 Hz respectively.

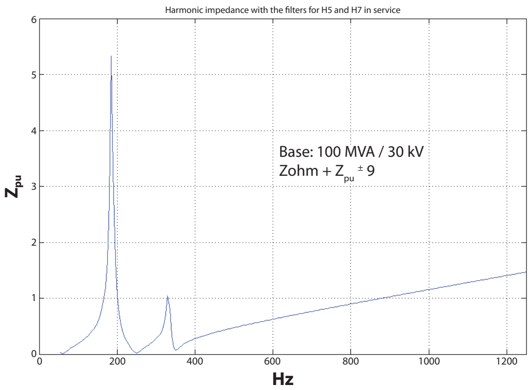


Figure 6: Harmonic impedance with one filter (h5) switched on

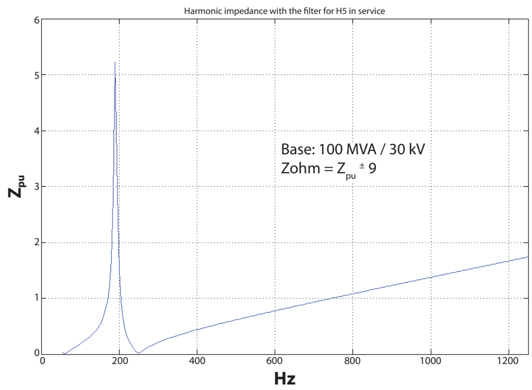


Figure 7: Harmonic impedance with two filters (h5 & h7) switched on

Figure 6 shows the harmonic impedance with two filters switched on. The anti-resonance frequencies in this case are 185 Hz and 330 Hz. This shows that the anti-resonance can shift depending upon the number of filters switched on.

Figure 7 shows the harmonic impedance with only the filter for the fifth harmonic switched on. The anti-resonance lies at 190 Hz.

The difference of 10 Hz in the anti-resonance frequency can be significant. If any of the interharmonics produced by the rolling mill should coincide — or almost coincide — with one or more of these anti-resonance frequencies, this will result in rather high voltage components at these frequencies. This can cause flicker and its consequent nuisance. Thus, when setting anti-harmonic filters on or off, the harmonic impedance of the entire system changes and flicker can be provoked in one or more of the configurations. Attention must be drawn to the fact that the presence of other significant loads or other changes in the network configuration can also impact harmonic impedance and lead to flicker.

2.3 Measurements

During the first measurement campaign, the filter for the fifth harmonic was switched on while those for the seventh and the eleventh harmonics were off. Under normal operating conditions, the filter for the seventh harmonic would be on. When this filter was switched on, an immediate rise in the flicker level was observed. When this flicker was perceived, the filters also produced a severe and entirely abnormal noise. This confirmed the suspicion that the observed flicker originates from interharmonic voltages combined with an anti-resonance frequency of one or more passive filters.

Measurements were carried out with the rolling mill and various combinations of filters in service. The purpose was to see which of the configurations was provoking flicker.

3. Results

3.1 First measurement: 5th, 7th and 11th harmonic filters on

First we examined interharmonic content of the 30 kV supply voltage during a given period of functioning of the rolling mill and six passes (after the rolling mill, the steel plate goes through six different passes to further smooth the surface of the steel). Only the maximum values for each interharmonic were recorded. The analysis period is 500 seconds, and the interharmonics are calculated at 5 Hz steps.

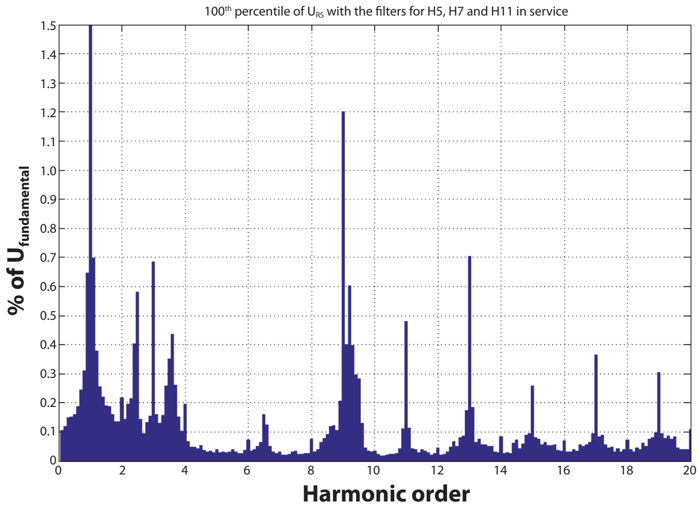


Figure 8: Voltage interharmonic spectrum in the first filter configuration (maximum values)

We can see that the resonances appear at the following frequencies:

- Rank 2,5 or 125 Hz
- Rank 3,6 or 180 Hz
- Rank 6,6 or 330 Hz
- Rank 9,2 or 460 Hz

Comparing these frequencies with the anti-resonance frequencies of the first filter configuration, we can see that two frequencies correspond: 180 Hz (or 185/190 Hz) and 330 Hz. A little slack is observed at the 485 Hz component, but the difference stays very small. There is consequently a serious risk of resonance at those frequencies. The corresponding evolution over time of the currents (50 Hz values) drawn by the rolling mill and the six passes, is shown in Figure 9.

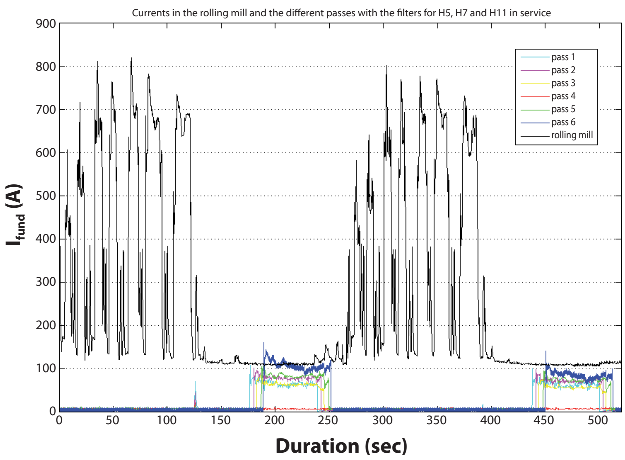


Figure 9: 50 Hz currents of the rolling mill and six passes – first filter configuration

The various passes that start up one after another can clearly be observed.

When we now look at the content of the different harmonics in each of these 7 currents, we obtain the results given in Figure 10 to Figure 13 :

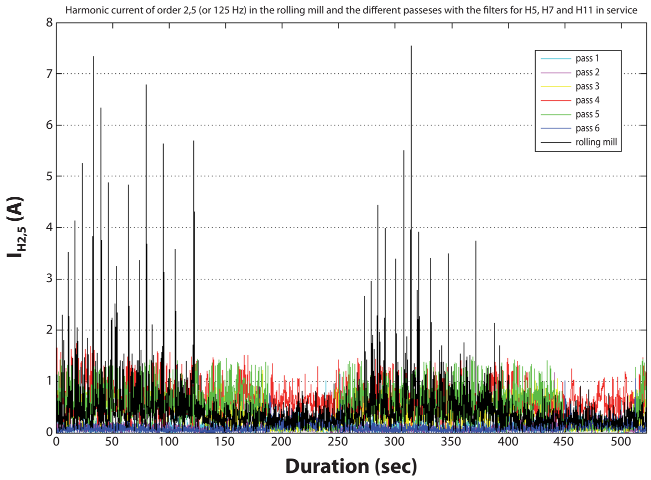


Figure 10: Interharmonic current at 125 Hz – first filter configuration

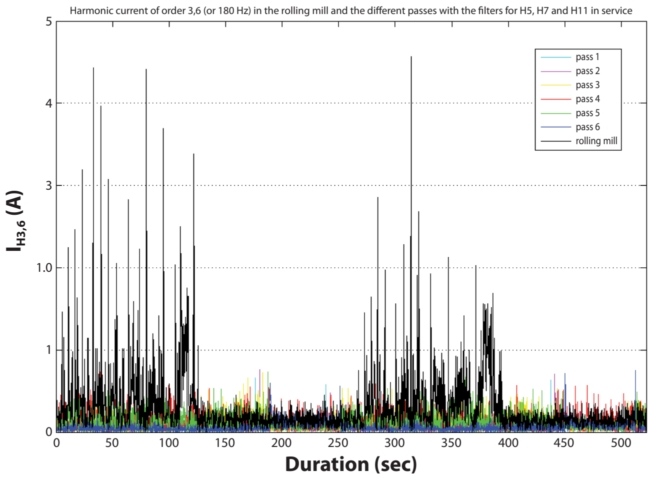


Figure 11: interharmonic current at 180 Hz – first filter configuration

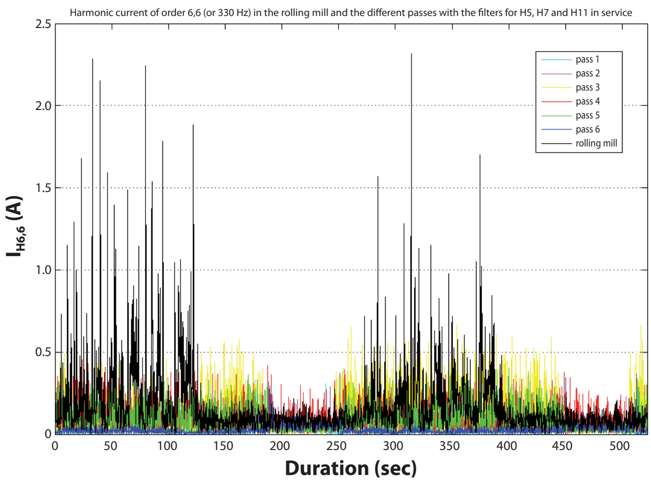


Figure 12: interharmonic current at 330 Hz – first filter configuration

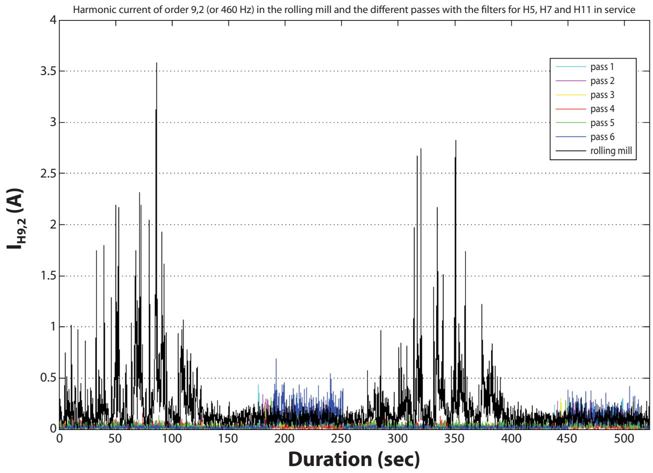


Figure 13: interharmonic current at 460 Hz – first filter configuration

Two major conclusions can be drawn from these figures:

- The rolling mill provokes by far the greatest part of the interharmonics
- The currents of the passes have higher interharmonics at 125 Hz and 330 Hz when they are not functioning than when they are in service!

Looking at the harmonic currents running through the various filters, the following can be observed:

- Along with the 50 Hz component, each filter obviously has a significant harmonic component corresponding to the tuning frequency it was designed for
- Each filter also has current components at other characteristic harmonic frequencies (rank11, rank13, etc.), mostly those higher than the tuning frequency (this is particularly true for higher tuning frequencies)
- Interharmonic currents can also be observed in the three filters:
  - o Rank 2,5
  - o Rank 3,6
  - o Rank 6,6
  - o Rank 9,2

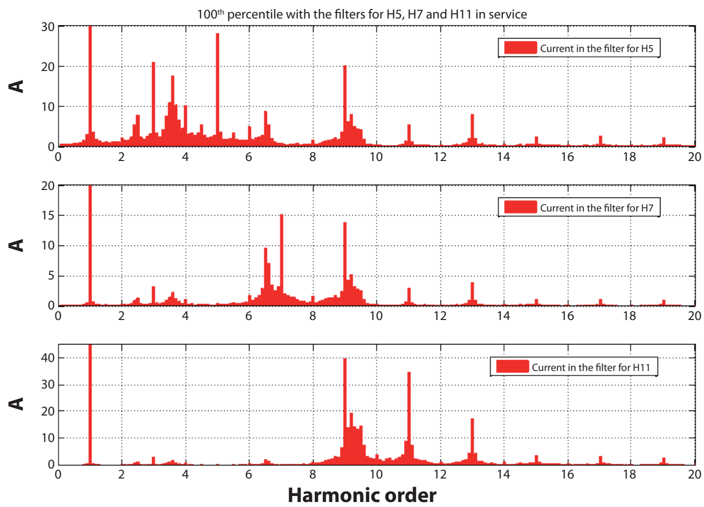


Figure 14: interharmonic currents in the three filters – first filter configuration

3.2 Second measurement: 5th and 7th harmonic filters on

Again, we first examined the interharmonic voltages during a given period of functioning of the rolling mill and the six passes. The analysis period was 750 seconds this time.

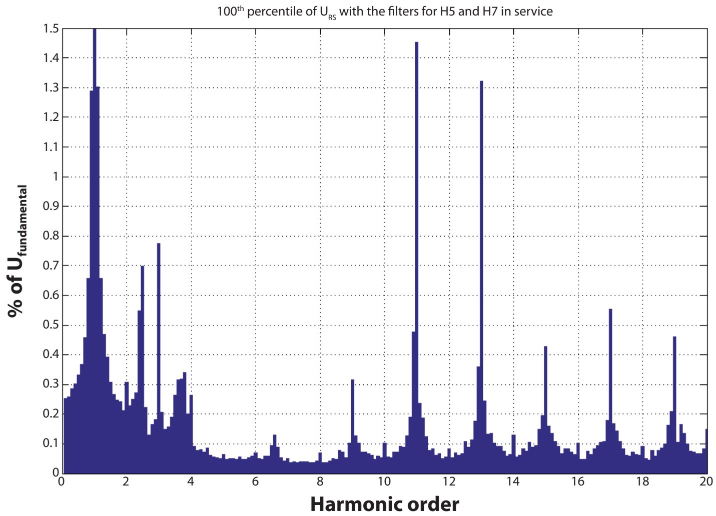


Figure 15: voltage interharmonic spectrum in the second filter configuration (maximum values)

The resonances appear on the following frequencies:

- Rank 2,5 or 125 Hz
- Rank 3,6 or 180 Hz
- Rank 6,6 or 330 Hz

Rank 9.2 was not taken into account this time, since there is no anti-resonance impedance expected for this rank. Regardless of the impact of this interharmonic, it will be smaller than in the first filter configuration.

The corresponding evolution over time of the currents (50 Hz values) of the rolling mill and the different passes is as follows:

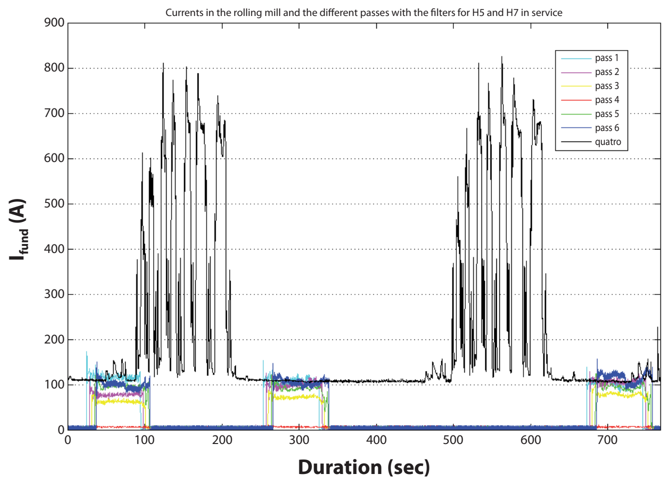


Figure 16: 50 Hz currents of the rolling mill and six passes – second filter configuration

Again, the various passes that start up one after another can clearly be observed.

When examining the content of the harmonics in each of the seven currents, the observations are similar, as in the first measurement:

- **The rolling mill provokes by far the greatest part of the interharmonics**
- **The currents of the passes have higher interharmonics at 125 Hz and 330 Hz when they are not functioning than when they are in service**

Looking at the harmonic currents running through the various filters, the following can be observed:

- The eleventh harmonic is higher in the two remaining filters of this configuration (this is obvious since the filter for h11 is not in service)
- The ninth harmonic is much lower than in the first configuration
- The interharmonics of rank 9.2 have disappeared

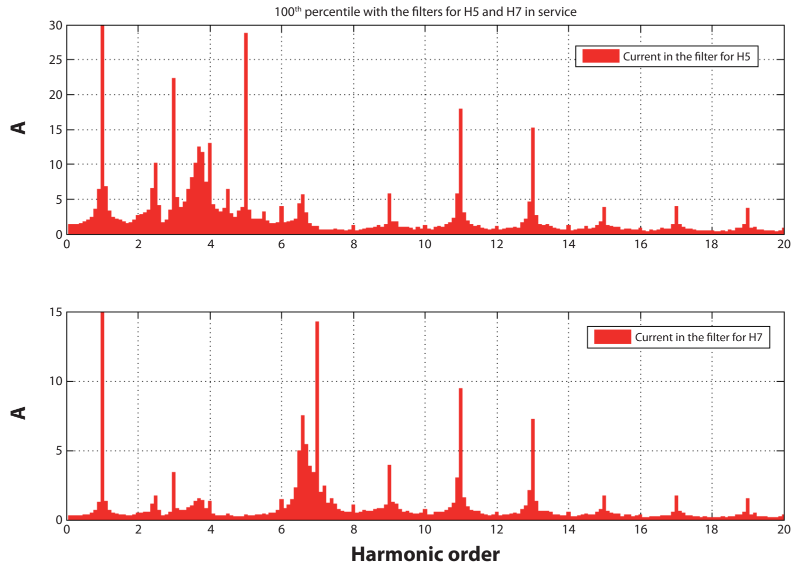


Figure 17: Interharmonic currents in the three filters – second filter configuration

3.3 Third measurement: 5th harmonic filter on

We examined the interharmonic voltages during a given period of functioning of the rolling mill and the six passes for the third time. The analysis period was again 750 seconds.

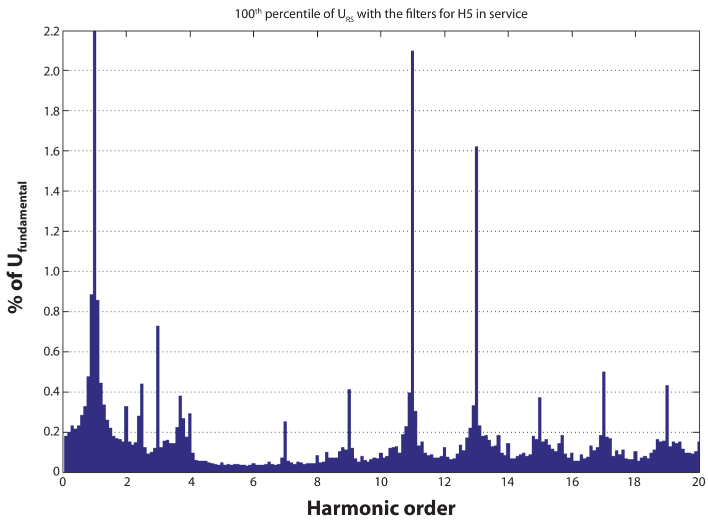


Figure 18: voltage interharmonic spectrum in the third filter configuration (maximum values)

The resonances appear at the following frequencies:

- Rank 2,5 or 125 Hz
- Rank 3,6 or 180 Hz

The resonance for rank 6,6 has almost completely disappeared.

The corresponding time evolution of the currents (50 Hz values) of the rolling mill and the six passes is as follows:

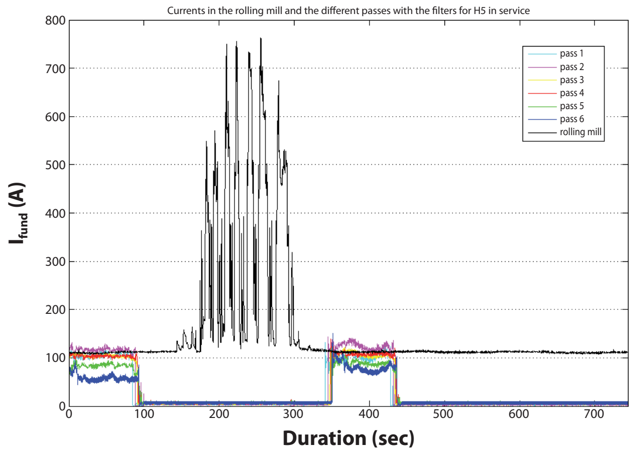


Figure 19: 50 Hz currents of the rolling mill and six passes – third filter configuration

Again, the various passes that start up one after another can clearly be observed. When again examining the content of the harmonics in each of the seven currents, observations are similar to those in the first measurement:

- The rolling mill still produces interharmonics of rank 2.5 and 3.6
- The passes provoke mainly interharmonics of rank 3.6

4. Lines of enquiry

Based on these measurement results, one can start seeking the origin of the interharmonic currents. A new measurement campaign was carried out to record an incident. The aim was to determine where the interharmonics come from and how they provoked the incident.

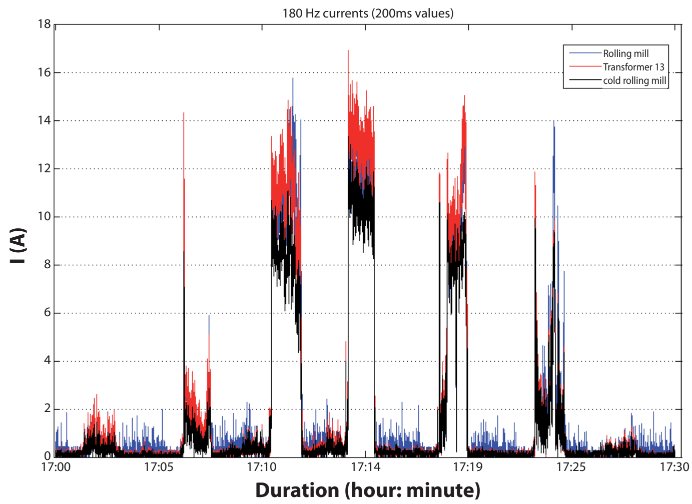


Figure 20: 180 Hz currents in the main rolling mill, a cold rolling mill, and their feeding transformer

As shown in Figure 20, the 180 Hz component is clearly present in the currents of the feeding transformer (called transformer 13 in the figure), the rolling mill, and in a cold rolling mill that is also connected to this transformer. It is consequently certain that this 180 Hz current is linked to the loads connected to this transformer. Looking into detail at the six passes, it appears that passes 1, 2, and 6 also provoke this 180 Hz component, while the other three passes do not, as shown in the following figure:

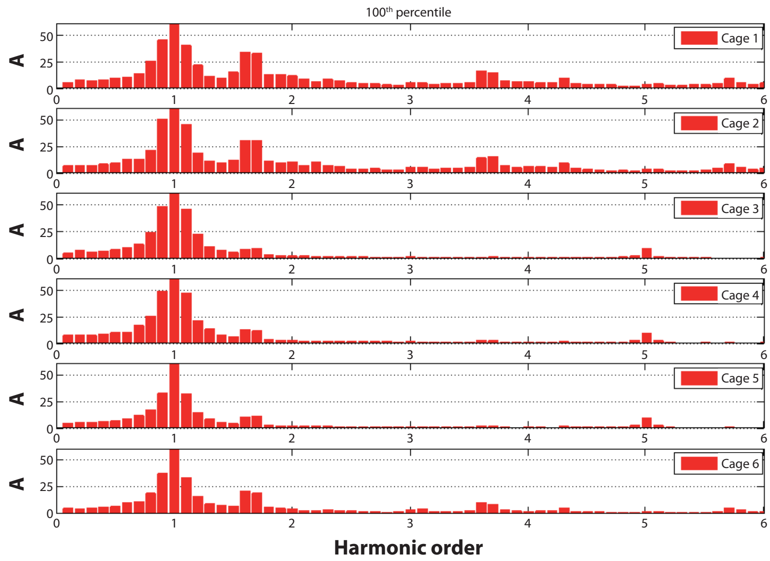


Figure 21: maximum of the 180 Hz component of the current in the passes

The final conclusion was that passes 1, 2, and 6 provoke the interharmonic currents. The 180 Hz component is present in those three passes, and only when they are functioning. The 180 Hz component is also present in the main rolling mill (and also in a cold rolling mill), but without correlation with the functioning of this mill.

Note: in Figure 22, the transformer current was measured at the high voltage side (primary voltage).

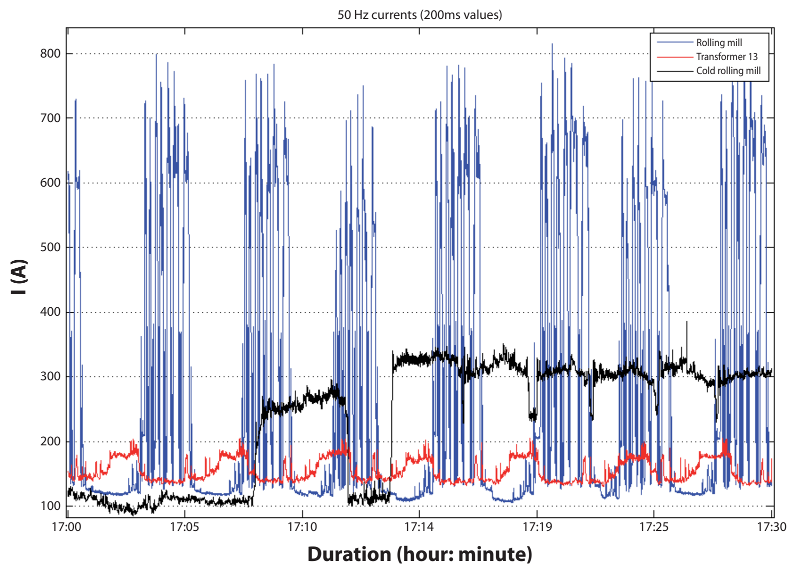


Figure 22: 50 Hz currents in the main rolling mill, a cold rolling mill, and their feeding transformer

5. Conclusions and solutions

5.1 Conclusions

The measurements clearly show the presence of interharmonics on the voltages as well as on the currents. Their frequencies are 125 Hz (rank 2.5), 180 Hz (rank 3.6), 330 Hz (rank 6.6), and 460 Hz (rank 9.2).

Those four interharmonics are produced by the rolling mill and its passes.

The three filters create high harmonic impedance for the frequencies 180 Hz, 330 Hz, and 485 Hz respectively. These are the anti-resonances of the tuning frequencies of the filters.

The levels of the various interharmonics are high enough to provoke perceptible flicker.

Whether the filter for h11 is in service or not, the interharmonics in the two other filters remain at the same level. However, they do not present a danger to the filters themselves.

5.2 Solutions

In so far as the presence of interharmonics on the voltage is not affecting the state of the equipment connected to the 30 kV busbar, the easiest solutions to this flicker problem are either changing the lighting devices, or feeding them via another transformer (separation of the electrical circuits).

If malfunctioning or even damage is observed on the equipment connected to the 30 kV busbar, other solutions must be investigated. Those can include:

- A deep study of the mechanism inside the drives that lies at the origin of the interharmonic currents (e.g. a study of the regulation loop/of the closed loop of the drive control), in order to eliminate them
- Detuning the filters, with the risk of affecting their efficiency in filtering the harmonics

The malfunctioning mentioned above can for instance be a vibration problem, which can provoke the detachment of connections and consequently filter damage. It is a good idea to check the connections regularly.