Electrical Power Quality and Utilisation, Magazine Vol. II, No. 1, 2006

Harmonic Analyses and Mitigation in Large Industrial Steel Plants
A Case Study

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Summary: **At its plant in the Dutch town of IJmuiden, steel-producer Corus has its own electricity network. For steel making electrical energy is needed, specially for the mill section, due to older techniques these installations produces more voltage distortion on the Corus network. This can cause equipment outages, and thus halt production. This paper presents an innovative solution to these problems, thereby limiting production losses and system mal operation and without exceeding of harmonic limits at the connection to the grid- operators network.**

Key words:
power quality, harmonics, resonance, non linear loads, filter, power electronics

1. INTRODUCTION

Several years ago, Corus began to experience increasing problems with its power supply quality. Electrical drives were tripping, clocks were running fast, PC supplies were burning out, lighting systems were malfunctioning and harmonic filters failed. On top of the damage to the equipment affected, these problems were accelerating the ageing of other components and in extreme cases interrupted steel production at a high cost. For a company whose production processes are normally continuous, unscheduled stoppages add high operational and production costs and are not accepted.
To understand these problems and provide mitigating solutions for these problems and how to prevent future problems associated with power quality, KEMA consultants and Corus engineers conducted a survey at the Corus electrical network. The developed approaches and analysis steps taken in this project can also be used as a general description to prevent problems with harmonics in other industrial grids.

2. GENERAL DESCRIPTION

Corus is an international steel manufacturing company, providing steel and aluminum products and services to customers worldwide. Corus has manufacturing operations in many countries with major plants located in the UK, The Netherlands, Germany, France, Norway and Belgium. From October 2003 Corus has been structured into four main divisions: Strip Products, Long Products, Aluminum and Distribution and Building Systems. Each of these has a number of business units within.

This case study is performed at the Corus Strip Products plant at IJmuiden, The Netherlands. This plant manufactures hot rolled, cold rolled and metallic-coated steels for many industries in a wide specification to European or other (inter)national standards. They include the automotive and transport industries, building and construction, consumer appliances and electronics, and general engineering.
For the process of manufacturing steel strips, iron ore, sinter, coke and limestone are combined into a blast furnace to make molten iron, which is refined into liquid steel by reducing its carbon content. Secondary steel making gives the steel exact physical properties by regulating its physical structure, temperature and compounds. The liquid steel is then casted continuously into slabs. Hot steel rolling (Figure 1) reduces the thickness of the strip and controls its finishing temperature, cooling rate, and coiling temperature, which, together with its physical properties, defines its mechanical properties.
Cold steel milling enhances the surface finish, shape and forming characteristics of the steel strip and reduces its thickness. The ductility lost in cold rolling is recovered by annealing, which also develops the mechanical properties. Temper rolling refines the shape, surface finish, and mechanical properties still further. Cold-rolled strip steel may then be coated with metallic elements, or alloys to protect it from corrosion. These elements include zinc, tin and aluminum. With an area of more than 750 hectares, Corus IJmuiden is the largest unified industrial complex in the Netherlands. On this site, the company has no less then 350 MW of electrical

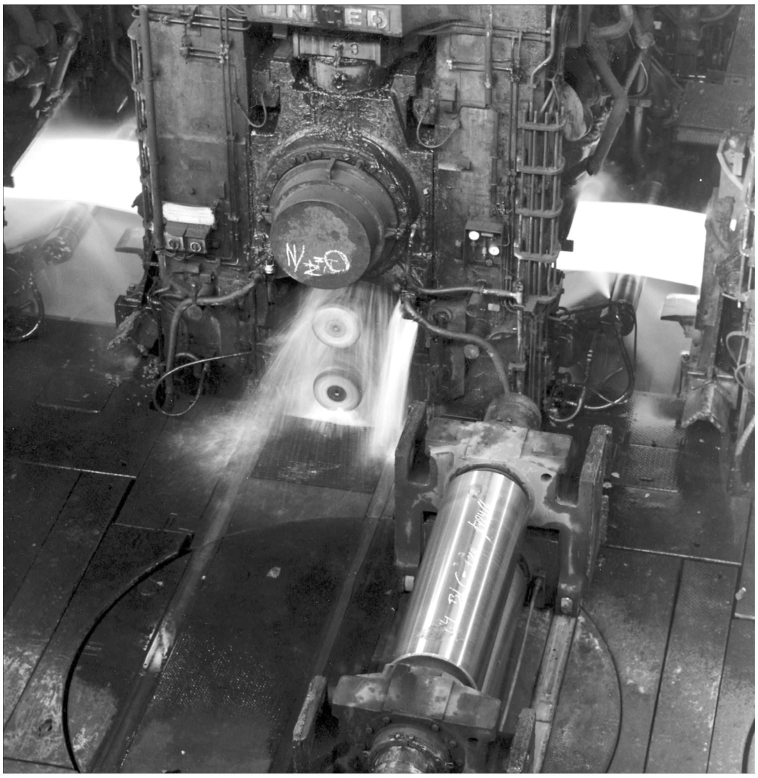


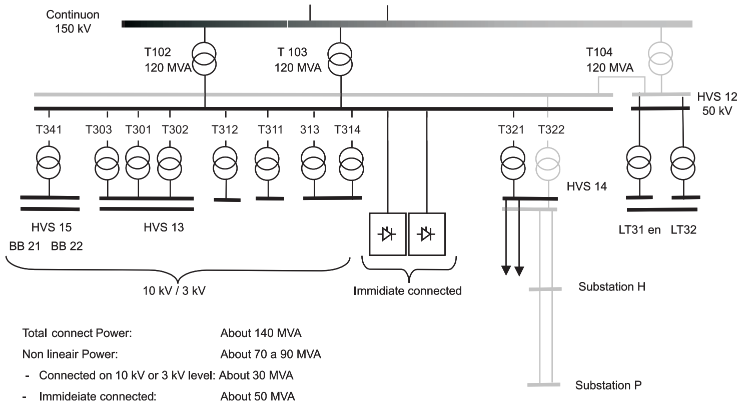
Fig. 1. Corus hot steel rolling process

power consumption. Corus is also connected to the 150 kV grid operated by Continuon. Within the Corus network, the voltage is reduced from 150 kV to 50 kV, then to 10 kV, and ultimately to 3 kV inside the manufacturing units. Transformers ensure that the voltage always remains at the appropriate level. However, to protect Corus's sensitive equipment, it is also important to ensure that power supplies within the plant are of the appropriate quality.

3. HARMONIC ANALYSES

The described power quality problems have occurred within the Northern part of the electrical installation of Corus. An overview of this grid is provided in Figure 2. Most of the

Fig. 2. Northern part of the Corus grid



problems have occurred at substation H and P. To analyze the power quality problems and propose mitigation options a number of consequent steps were taken. These general numbers of steps can be used for other problem related to similar problems.

3.1. Problem analyses

Within Corus's the grid and also at substations H and P, serious power quality problems were experienced under certain network configurations. Electrical drives were tripping, clocks were running faster, PC supplies were burning out, lighting systems were malfunctioning and harmonic filters failed. Furthermore accelerated ageing of other components, and in extreme cases interruption of the production, was experienced. For a company whose production processes are normally continuous, unscheduled stoppages adds enormously to costs and is not acceptable. During normal network configuration, as shown in the one-line diagram, of Figure 2, no problems occured at substations H and P. Here substations H and P are connected to the 150 kV network through transformers T322 and T104. The discussed power quality problems occurred during the maintenance configuration. Normally for reliability requirements, transformer T322 is connected to the black 50 kV bus bar at HVS 12, with a redundancy of two transformers (T102 and T103). The described power quality problems did occur when T322 was connected to the black bus bar, if T322 was connected to the grey bus bar, no problems happened.

3.2. Harmonic measurements (U/I)

Since the problems occur when T322 was connected to the black 50 kV bus bar of HVS 12, a measurement program was set up to establish the voltage wave shape, harmonic contents and harmonic levels at the low voltage side of transformer T322. For both situations (T322 connected to the black bus bar and connected to the grey bus bar) the voltage at HVS14 was measured and the current through transformer T322 (see Figure 3 and 4).
As can be seen from these figures, the voltage harmonics on the black bus bar have much higher values then the voltage harmonics on the grey bus bar for almost every harmonic order. Especially the 23rd and 25th harmonic numbers have very high values. This could indicate a parallel resonance scenario. The current through the transformer T322 has higher values for every harmonic order when connected to the grey bus bar. For both situations there are relative high harmonic values around the 23rd and 25th harmonic order.

This could indicate a series resonance scenario. Since the levels were so high, a voltage wave shape has been measured at an electrical wall outlet socket for conformation purposes. The wave shape is shown at Figure 5.

As can be seen in Figure 5, there are multiple zero crossings. Some equipment will switch off when such a voltage is applied. Next to the multiple zero crossings, it can also been seen that there is a classic resonance at the 23rd harmonic.

3.3. EN 50160 Requirements

To establish the maximum level of the distortion, Corus uses the limits provided in the EN50160. The voltage harmonics when transformer T322 was connected to the grey rail are within the limits of the EN50160. Contrary when transformer T322 was connected to the black bus bar, the voltage harmonic limits were exceeded from the 21st up to the 31st harmonic order and the 35th and 37th harmonic order. The THD level at the black bus was 13,3%, far above the limit of 8%, while the THD at the grey bus bar was only 3,7%.

3.4. Identify harmonic current sources

Within the Corus plant there are a number of electrical drives that produce harmonic current. About 70 to 90 MVA from the 140 MVA total connect power in the Northern grid of Corus are non-linear loads (about 60%). About 50 MVA is directly connected to the 50 kV bus bar and about 30 MVA at lower voltage levels (10 or 3 kV). Most of the drives have a 6 or 12 pulse characteristic design.

3.5. Mechanisms of series and parallel resonance

To describe the principle of resonance inside the Corus plant the equivalent network reactance at harmonic frequencies is used.

The principles are described here in terms of the Corus grid shunt capacitor and cable capacitances, and equivalent source and transformer impedances. Shunt capacitors and cable charging capacitances affect the system resonance dramatically. The charging capacitance associated with the HV cables and shunt capacitors are normally seen as an equivalent capacitance C in parallel with the system, while the network series impedance and transformer impedances, normally inductive, and are seen as an equivalent series reactance L. The load and resistance of the transformers and cables are seen as the equivalent R or damping in the system. When analyzing the resonance phenomenon in this network, characteristic harmonic currents generated from the drives and converters are considered.

Resonance phenomena are shown in Figure 6, and can be divided into the following:

— Parallel Resonance (Figure 6 (a)) of the parallel network capacitance Cp (cable charging capacitance and capacitor banks) and the supply inductance Lp (transformer leakage, generators, lines and cable). A parallel resonance is characterized as a

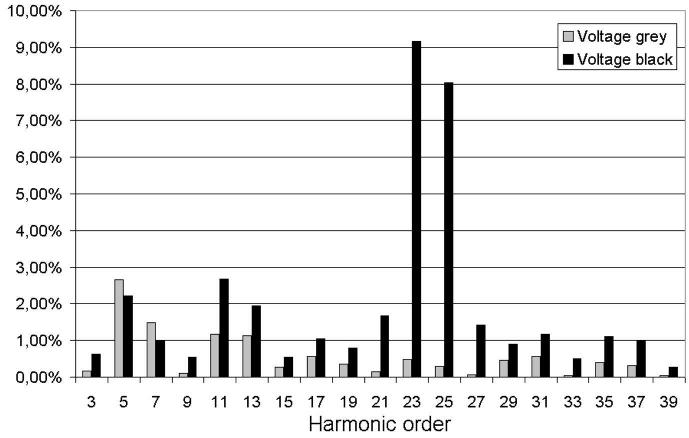


Fig. 3. Voltage harmonic spectrum

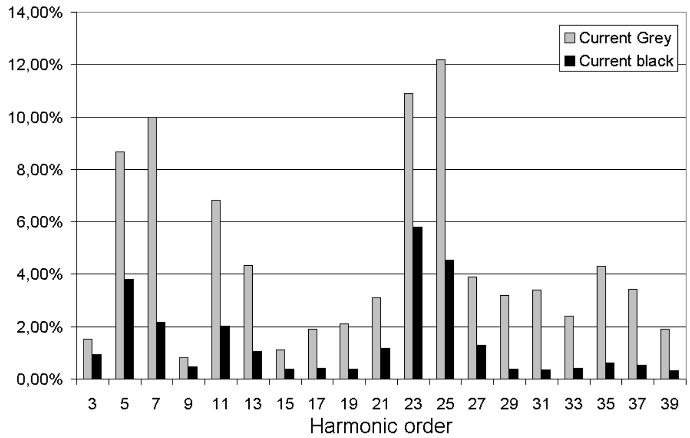


Fig. 4. Current harmonic spectrum

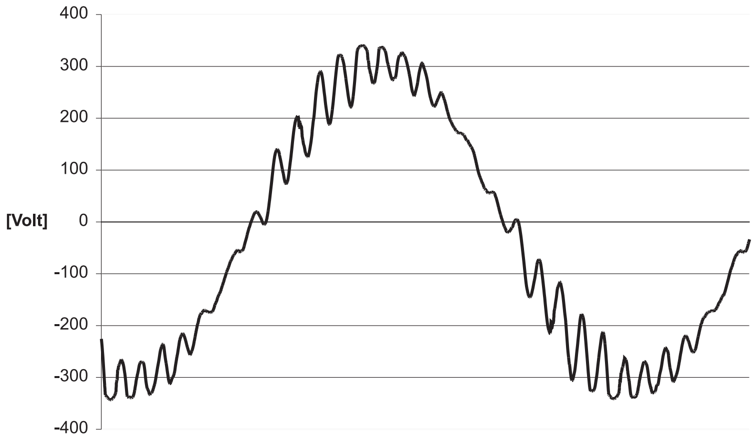


Fig. 5. Wave shape voltage

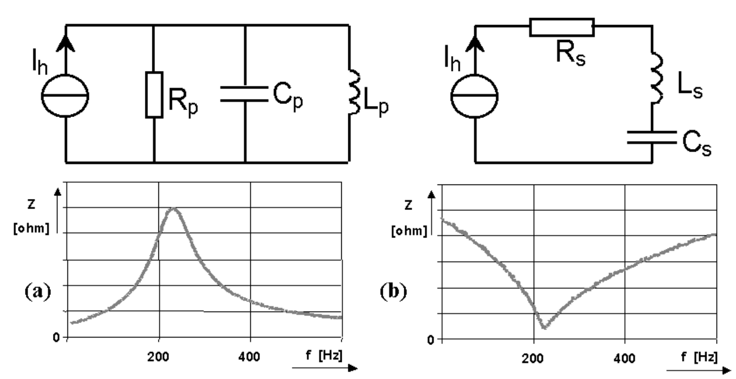


Fig. 6. Mechanisms of parallel (a) and series (b) resonance

high impedance to the flow of harmonic currents at the resonance frequency. This parallel resonance is initiated by distortion generated internally, i.e. within the load connection point. In this case a inrush current associated with the switching transformer or distorting converter load can be assumed to be the generating source current Ih. In this case the impedance at the resonance is high, resulting in higher voltage distortion at the Point of Common Coupling (PCC), or where the equipment and load is connected.

— Series Resonance (Figure 6 (b)) of the equivalent network capacitance Cs, and the supply reactance Ls, is resulting from externally generated or injected distortion from other parts of the system. A series resonance is characterized as low impedance for harmonic currents at the resonance frequency. In this case the background supply voltage distortion is the mechanism. In this case the impedance at the resonance is low, resulting in higher current distortion through the load, cable capacitance or capacitor bank installations.

In practice these two phenomenon are linked in one circuit and both increased levels in the voltage and current distortions are practically measured as shown in Figure 3 and Figure 4

3.6. Harmonic mitigation options

Reduction of the harmonics at the sources is also a possibility, however this would mean that most of the drives used have to be changed which is not an economical solution since the technical lifetime of these drives has not been reached yet.

In evaluating solutions to the resonance problems several mitigation options were considered. These were:

1. Detuning of the harmonic resonance frequency with passive components (C & L)
2. SVC (TCR and C) and STATCOM solutions
3. Splitting network into a high and low THD level grids

A summary of the first two options are provided in the Table 1.

Although the solutions described above will reduce the problem regarding the harmonics, the costs to invest were still too high. Therefore a remarkable solution has been found sufficient for the Corus production process by subdividing the grid into two separated grids with a high THD level and a low THD level grid. At the grid with low THD level all sensitive equipment for harmonics were connected. At the high THD level, all large harmonic sources and equipment that could handle these high THD levels were connected. Although the harmonic problems still exist, the process could still fulfill without losing production due to the resonance or harmonic problems. To subdivide the grid Corus only had to invest in a 10 kV cable, which was less then half of the cost for the other given solutions. The harmonic distortion at the PCC with the gridowner (150 kV) remains the same level as before the studies.

4. Plant and grid expansion

For a couple of years the split-network solution, where the grid is separated into high- and low THD level grids, has operating successfully. The steel production process has not been stopped due to harmonic or resonance problems. Equipment did fulfill the expectations and did not fail and the financial damages due to lack of power quality at the several locations in the plant were minimized.

Corus recently decided to add a Near Infra Red (NIR) installation to its facilities. This special steel coating installation is made of 12 different units (10 units having a rating of

Table 1. Summary of solutions to the resonance problems

Option	C bank + filter	SVC (TCR + C)	STATCOM	STATCOM + C
Rating (MVAr)	30 – 50	35 – 60	5 – 10	55 – 60
Filtering	+/-	+/-	+	++
Detuning	+/-	+	+	++
Effectivity	Limited	Sufficient	Good	Excellent
Flexibility	--	+/-	++	++

800 kVA and 2 units of 400 kVA) and can be seen as a large infrared lighting equipment witch can be dimmed. To control the NIR dimmers are used to control the voltage. Sadly the dimmers produce a large amount of harmonic currents. The NIR installation produces a maximum THD(I) level of 30% at a total rating of almost 9 MVA. The NIR installation is subdivided into 4 sections and the voltage supply will be at the Low voltage level of 400 V (Table 2).

Normally the NIR installation would be connected by transformers into the high THD level grid, however since the geographical location of the NIR installation is not in the neighborhood of a connection point to the High THD level grid, it had to be connected to the low THD level grid. The NIR installation had to be connected to the grid with low THD level.

With a THD(I) level of 30%, the NIR installation was expected to cause considerable harmonic distortion in the 10 kV grid. Without countermeasures, the power supply to the rest of the complex would be vulnerable. The goal to connect this installation into the low THD level grid was to connect it without exceeding the limits as provided in the Dutch Grid code [2] (based on the EN50160 [1] standard). Furthermore provision for future upgrades and installation of equipment can also produce some harmonics on the grid. To prevent potential resonance on the 23rd harmonic, it was tried to reduce the 23rd harmonic as far as possible.

Next to the technical issues, the solution should be as cheap as possible. Since the NIR installation had to be connected from 400 V grid to the 10 kV grid, the cheapest way to fulfill the requirement was by the choice of the type of transformer configurations. In this case the following steps were identified:

1. Voltage background measurement in the current situation without NIR and comparison with the standards.
2. Develop equivalent circuit within Matlab/Simulink (including verification).
3. Simulation of different transformers configurations to connect the NIR.
4. Select most cost-effective transformer configuration.
5. Develop an acceptable specification for the transformer.
6. Develop guidelines for further installation connected to the network.

4.1. Measurement of the background harmonic level

To establish the influence of the NIR installation on the 10 kV network of Corus, Figure 7 shows were the NIR installation had to be connected onto the 10 kV grid. Since most of the other sensitive equipment is placed at the 10 kV bus bar of HVS 14 the THD level and all harmonic levels were measurement at this bus bar.

Table 2. Sections NIR Installation

Section	A	B	C	D
Number of units	3	3	4	2
Rating	2400 kVA	2400 kVA	3200 kVA	800 kVA

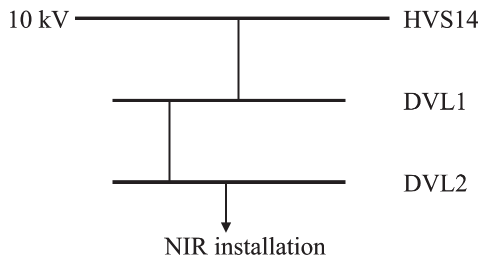


Fig. 7. Connection of the NIR installation into the 10 kV network

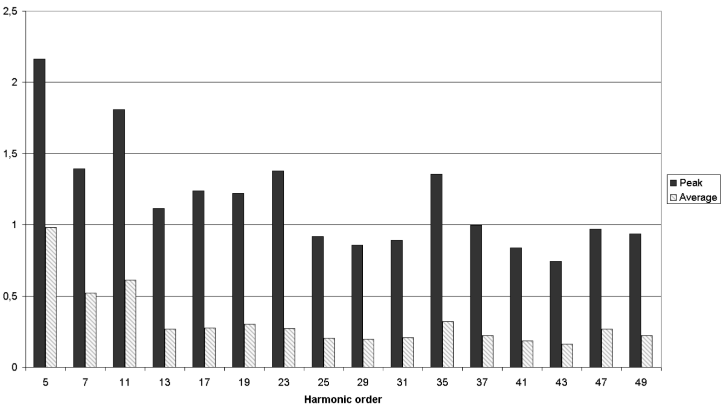


Fig. 8. Measurement harmonic order on 10 kV bus bar HVS 14

During a few hours with continuous process each 3 seconds a measurement was recorded (peak value). These values are shown in Figure 8 (including a 10 minutes average value).

4.2. Development of harmonic models

Next step in this methodology is to set up models and to perform simulations to establish what the influence of the connection of the NIR installation would have on the harmonic contents on the point of common coupling at 10 kV. We have set up three models into Matlab/Simulink:

— A model of the existing 10 kV grid (including harmonics).
— A model of the NIR installation (including harmonics at 0,4 kV).
— Models of the transformers needed to connect the NIR installation (0,4 kV) to the 10 kV grids.

To model the existing 10 kV grid the harmonic sources as provided in the section about harmonic analyses mitigation were used. This model was taken as crucial and adjusted until it fitted according the measuring results.

To model the NIR installation information, the NIR model was created with manufacturer input data. Since the information provided by the NIR manufacturer was very limited, a worst-case model, meaning the harmonic sources contain harmonics according the theory of a 6-pulse converter was used.
The dry type transformers to connect the NIR to the 10 kV network, were modeled according to reference 3 including the frequency dependency of the resistance in the transformer.

4.3. Different transformer configurations

To reduce the harmonic contents caused by the NIR installation, at the 10 kV bus bar HVS14, several transformer configurations were considered. Figure 9 shows the results of an simulation were the NIR installation is connected with two Yyd transformers compared with a solution were a phase shift is made within the transformer, one with +7,5 degree and one transformer with –7,5 degree. As can seen the transformer with the phase shifting will result in a lower THD level, since the 11th, 13th, 35th and 37th harmonics are much lower compared with the transformer without phase shifting.

Fig. 9. Results simulation Yyd versus Zyd (phase shift) configuration

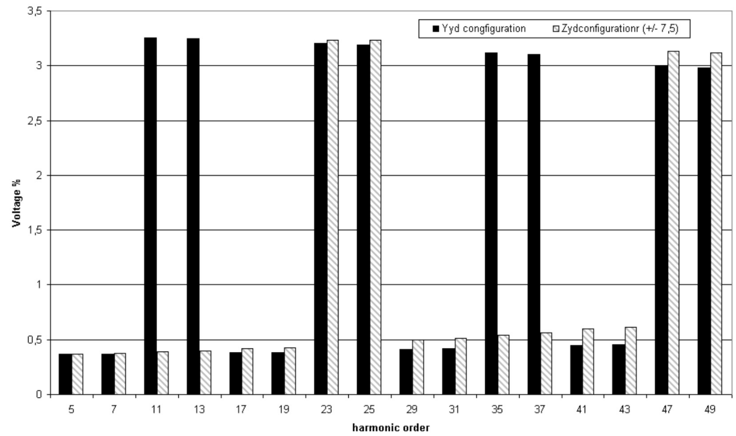
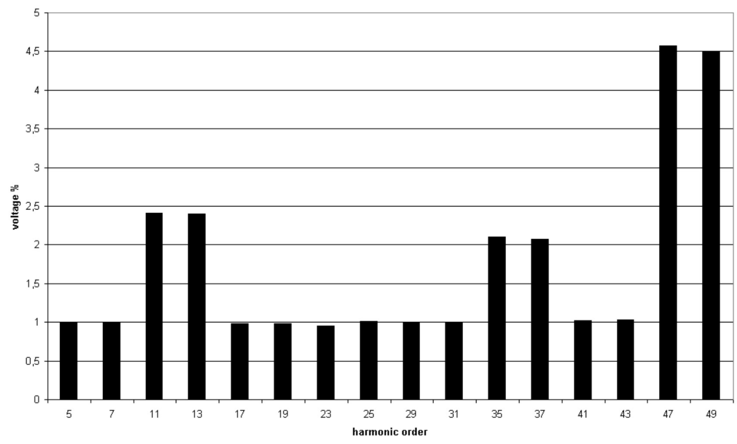


Fig. 10. Results simulation one Yyd and two Zyd (phase shift) configuration



Still the solution with two-phase shifting transformer was not adequate. The level of the 23rd harmonic was still not acceptable.
To reduce the 23rd harmonic the NIR installation was connected to the 10 kV grid with 3 transformers. 2 transformers were having a phase shift of plus or minus 7,5 degree, while the third transformer was an Yyd transformer. As can seen from figure 10, this resulted in a reduced 23rd harmonic.
Although the 47th and 49th harmonics are still high, it is expected that these high values will be much lower in reality, since the resistance in the network will damp them. All simulations were performed with the NIR at full load and at a loading were some units were switched off. For the case with 3 transformers, the highest values were achieved when the NIR installation is at full load.

4.4. Select transformer configuration

Based on the results it was decided to use 3 transformers were two will have a phase shift. Although these two transformers are about 10-15% more expensive compared with a transformer without phase shifting, this solution was still the most acceptable solution to Corus.

4.5. Specification of the transformer

To make sure the transformers fulfill the requirements of harmonic loading, the harmonic loading for each transformer was calculated. This harmonic content was provided within the specification of the transformer to the manufacturer [3]. The manufacturer was asked to establish the influence of the harmonics on the losses, cooling and life expectation of the transformer.

4.6. Guidelines for further installations

Growth of the Corus production plant can be expected in the future. It is almost sure that future equipment will produce more harmonics. To make sure the installation in the future can handle these harmonics, Corus has set up guidelines for manufacturers what the maximum amount of harmonic produced by equipment might be. In case the equipment produces higher harmonic content than the limits given in the guidelines, the manufacturer is asked to reduce the harmonics. This way Corus makes sure that harmonic sources have to reduce their own harmonic pollution.

5. SUMMARY AND CONCLUSIONS

Loss of production at the Corus steelplant due to harmonic and resonance problems in the electrical grids has occurred. Within this paper a general approach has been provided how the problems can be solved by technical solutions. However since the costs to reduce the problems were high for a production plant were the core business is not electricity, a cost-effective solution was described to split the network into a high THD level grid and a low THD level grid. The costs were less then half compared to the costs necessary to reduce all harmonics or resonance.

For several years this solution was adequate, however when an upgrading of the production plant was necessary harmonic sources had to be connected with the low THD level grid. Based on simulations it was shown that if no action was taken to reduce the harmonic distortion, the THD level of the LV grid would be to high, causing again problems (outages) for the production plant. Due to modeling and simulation it was found that the THD level can be reduced by using a phase shifting transformer. Although the transformer are about 10-15% higher in costs then regular transformer, they make sure that the THD level and resonance frequency are within the limits as given in the EN 50160.

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