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MASTER THESIS

Electric power quality in low voltage grid

Office buildings and rural substation

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Abstract

The modern society uses more and more electronic devices needed to being able to function together. This put higher demands on the electrical grid together with that the typical load have changed from the past. Therefore utility companies are obliged to keep the voltage within certain limits for this to function. What exact these limits have been have not always been clear since they have not been gathered in one single document.

This thesis is a cooperation with Kraftringen who also has been the initiator. Kraftringen would like to become more proactive in their work regarding electric power quality. For becoming more proactive continuously measurements have to be done but the locations have to be carefully selected in the beginning to get a wider perspective of the grid.

Energy markets inspectorate (EI) is supervisory of the electric power quality in Sweden and since 2011 they have published a code of statutes (EIFS 2011:2 later 2013:1) intended to summarize limits on voltage. Some of the electrical power quality aspects are not mentioned in EIFS 2013:1 and standards have to be used to find limited values. Flicker and interharmonics are not mentioned in EIFS 2013:1 and for values on flicker the standard SS-EN 50160 has to be used and for interharmonics the standard SS-EN 61000-2-2 state limit values. Besides all this there are standards with stricter limits than EIFS 2013:1 e.g. for total harmonic distortion on voltage were SS-EN 61000-2-2 suggest 6 % instead of 8 %.

Three different field studies have been conducted in order to get some perception of the present situation regarding electric power quality. Two measurements were conducted on a typical office building because they represents a large part of the typical load in Lund. The third measurement was conducted on a substation in a rural area to get a perception of the situation outside urban areas.

These measurements shown that the overall electric power quality was within given limits according to EIFS 2013:1 and different standards. However, conducted measurements shown some interesting results. Both the typical office buildings have a slightly capacitive power factor which results in that the voltage inside the building is going to be slightly higher than at the substation. Since the voltage level at the measured urban substation was above nominal voltage level with about 2-5 % this could be problematic. Another eventual problem with a load with a capacitive power factor is resonance with the inductive parts of the grid like transformers leading to magnified harmonic levels.

It is suggested that Kraftringen expand their number of permanent electric power quality measurement locations to get a better overview of the present situation. The best suited locations to start with are such that have received complaints earlier, preferably measured on the low voltage side of the transformer for also register the amount of zero sequence harmonics. Next step in the measurement expansion would be substations known to be under higher load than others or substations with a PEN-conductor in a smaller area than the phase conductors, supplying a typical office load with high amounts of third harmonics and unbalance. From this it would be appropriate to spread out the measurement locations geographically to better get to know the grids behaviour.

Sammanfattning

Det moderna samhället använder allt mer elektronisk utrustning vilken måste fungera tillsammans. Detta ställer allt högre krav på elnätet samtidigt som den typiska lasten har förändrats med åren. Elnätsbolagen är därför skyldiga att hålla spänningen inom givna gränser för att detta ska fungera. Värdena på dessa givna gränser har inte alltid varit självklart då de inte varit samlade i ett dokument.

Detta examensarbete är ett samarbete med Kraftringen som också varit initiativtagare. Kraftringen har som mål att bli mer proaktiva i deras arbete rörande elkvaliten. För att bli mer proaktiva behöver kontinuerliga elkvalitetsmätningar upprättas men lokaliseringen av mätpositionerna måste vara noggrant utvalda i början för att ge en bredare bild över elnätet.

Energimarknadsinspektionen (EI) är tillsynsmyndighet för elkvaliten i Sverige och har sedan 2011 gett ut en författningssamling (EIFS 2011:2 senare 2013:1) som är tänkt att sammanfatta gränsvärdena för spänning. Det finns vissa elkvalitetsaspekter som inte nämns i EIFS 2013:1 och standarder behöver tillgripas för att klargöra gränsvärden. Flimmer och mellantoner nämns inte i EIFS 2013:1 och för gränsvärden rörande flimmer får standarden SS-EN 50160 användas och för mellantoner får standarden SS-EN 61000-2-2 användas. Utöver detta så finns det standarder som anger striktare gränsvärden än EIFS 2013:1, som exempel kan totala övertonshalten för spänning nämnas där SS-EN 61000-2-2 anger 6 % istället för 8 %.

Tre olika fältstudier har genomförts för att på så vis skapa någon form av nulägesbild av elkvaliten. Två av mätningarna genomfördes på typiska kontorsbyggnader då de representerar en stor del av lasten i Lund. Den tredje mätningen genomfördes på en nätstation i en lantlig miljö för att skapa en bild av elkvaliten utanför stadsområden.

Mätningarna visar att elkvaliten överlag är inom givna gränsvärden enligt EIFS 2013:1 och olika standarder. Dock så visar mätningarna på andra intressanta resultat. Båda de typiska kontorsbyggnaderna hade en svagt kapacitv effektfaktor vilket kommer resultera i att spänningen i byggnaderna kommer vara något högre än i nätstationen. Då spänningsnivån var över den nominella under båda mätningarna i stadsmiljö på mellan 2-5 % så kan detta bli problematiskt. Ett annat potentiellt problem med en last med kapacitv effektfaktor är resonans med de induktiva delarna av elnätet så som transformatorer vilket leder till ökade övertonsnivåer.

Det rekommenderas att Kraftringen expanderar antalet permanenta mätstationer för elkvalitet för att skapa en bättre bild över nuläget. De bäst lämpade platserna att börja med är sådana som tidigare mottagit klagomål och då helst med mätning på lågspänningssidan av nätstationens transformator för att då också registrera andelen övertoner av nollföljdskaraktär. Nästa steg i expansionen av antalet mätstationer är på nätstationer vilka är kända för att belastas mer än övriga och där PEN-ledaren har en mindre area än fasledarna vilken matar typiska kontorslaster där en hög andel tredjetoner och obalans kan väntas. Utifrån detta är det sedan lämpligt att sprida ut antalet mätställen geografiskt för att bättre förstå elnätets beteende.

Preface

This thesis on 15 credits was conducted during the spring 2015 as the last part of the master´s program (one year) in renewable energy systems at Halmstad University. This work has been done in cooperation with Kraftringen who also has been the initiator.

I would like to thank my supervisor on Kraftringen, Andreas Åkerman for his help and support during the work and Edvin Frankson on Kraftringen for his help with technical questions regarding the grid and Camilla Rydén on Kraftringen for her help with the language in the report. I would also like to thank my supervisor on Halmstad University, Prof. Jonny Hylander for his help and encouragement.

Halmstad, May 2015
Robin Andersson

Nomenclature

- AC – Alternating current
- CSI – Current source inverter
- DC – Direct current
- DPF – Displacement power factor
- Dyn – Transformer connected in delta on high voltage side and wye on the low voltage side with a neutral-conductor
- EI – Energy markets inspectorate
- EIFS – Energy markets inspectorate code of statutes
- EMC – Electromagnetic compatibility
- GTO – Gate turn-off thyristor
- IGBT – Insulated-gate bipolar transistor
- LC circuit – Circuit containing both an inductor (L) and a capacitor (C)
- PEN – Protective earth and neutral combined in a single conductor
- Plt – Long-term flicker sensation
- Pst – Short-term flicker sensation
- pu – Per-unit
- PWM – Pulse-width modulation
- RCD – Residual-current device
- RMS – Root mean square
- SS – Swedish standard
- THD – Total harmonic distortion
- TN-C – A total of four conductors, three phases and a PEN-conductor.
- TN-S – A total of five conductors, three phases and separate neutral and protective earth conductors
- TPF – True power factor
- VSI – Voltage source inverter
- UPS – Uninterruptible power supply

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1. Introduction

1.1. Background

Increased use of non-linear power electronic components since the 1970´s have resulted in a major expansion of harmonics on the electrical grid. The increased use of computers, low energy light bulbs, inverters, frequency converters and battery chargers have made this problem more known for us. Harmonics are however not the only factor which has had a negative impact on the voltage quality. Flicker, voltage levels, transients of voltage and reactive power have also had a major impact on voltage quality [1].

Problems with the electric power quality are often referred to voltage quality since our electrical energy supply is a voltage source which is a system with a preferable stable and constant ac voltage at a constant frequency [1]. The equipment used today are often more sensitive to the electric power quality compared to how they were before, especially energy efficient equipment [2]. Sometimes that energy efficient equipment could be the cause of bad electrical quality [1].

The quality of electric power is not only affecting connected electrical equipment but also us humans. The most common issue is flicker which can be perceived as annoying when reading. Another not so known issue is stray current that could arise from harmonics due to increased impedance in the neutral conductor. The increased impedance could make the return current to take other paths than through the neutral conductor. It can flow through rebars, water pipes, district heating pipes and conductive building structures to the earth. When parts of the return current flow through other parts than the neutral conductor, it causes an increased magnetic field. The aspect of our health being affected by magnetic fields has not been confirmed, however research tells us it could cause cancer and thereby precautions should be taken to reduce the risk. A connected residual-current device (RCD) will detect stray currents and disconnect the circuit [2], [3].

Previous investigations have been done in Umeå where they focused on harmonics and an existing problem with harmonics and their distribution on the grid [4]. Another study has been performed in Växjö with focus on the most common parameters regarding electric power quality. Measurement from these performances on selected locations in Växjö shows us what actions could be taken for future protection [5]. Numerous studies have been conducted in Estonia regarding voltage quality on low voltage grids with plenty of measurements for being able to estimate the present situation. Besides this evaluation of the present voltage quality they tried to find the optimum voltage quality parameters with respect to power consumption and power losses [6]. This thesis have some similarities with the work from Växjö and Estonia but will focus on Kraftringens southern grids, their kind of load and measurements on typical office buildings and one rural substation. A deeper study on the present laws and regulations will be performed and not only Energy markets inspectorate code of statutes 2013:1 (EIFS 2013:1).

Kraftringen is an energy company situated in Lund, Sweden and are responsible for the electrical grid in Lund and a number of other power grids. Today the electric power quality is not measured continuously but two electric power quality meters are to be set up during 2015. Most disturbances to the grid arise in the low voltage grids normally after substation transformers. Kraftringen is therefore interested in the power quality since a majority of their grid operates at low voltage.

1.2.Purpose

There are several purposes with this project including field studies on different objects. These objects were chosen due to their suspected higher impact on the electric quality compared to other. These results will provide a basis of the electric power quality on Kraftringens grid today and what to expect in the future. Which improvements can be done to the electrical power quality from different aspects in present and in the future?

The purpose is to summarize and make the laws and regulations concerning electric quality clearer. For example EIFS 2013:1 (Swedish), SS-EN 50160 (European) and others. Previous work have been done in this field on Kraftringen with a master thesis investigating what impact a sudden expansion of solar cells could have on the electrical grid in Lund [7]. In this thesis there will be an investigation of the electrical power quality in office buildings and one rural substation. The questions that Kraftringen seeks an answer to are:

- What is the present standard of the electric power quality in Kraftringens low voltage grid?
- What could Kraftringens future problems be on the low voltage grid?
- Where will the power quality probably be low in the future?
- To what extent should they measure in the future and where?

1.3.Problem

A common problem with field studies are related to measurement data reliability. Measurement errors such as lost values or loss of great amount of data that results in new measurement in order to get reliable results. New measurements require more time and the evaluation of the great amount of data can be time consuming that might limit available time on other parts of the project.

Another possible problem concerning measurement is that a measuring station is not able to be set up in time or that the measured data shows no or very small impact on the electrical power quality.

1.4.Limitations

This work is limited to cover Kraftringens southern grids and only the low voltage (0.4 kV) grids since most disturbances arise there. Frequency will not be evaluated even though it is measured by electric quality meters since the control of frequency lies outside of Kraftringens control.

The factors regarding power failure will not be a part of this work, since that is oriented more towards the possibility to deliver electricity rather than the delivered electricity power quality.

2. Electric power quality

Electric power quality is a general expression regarding the electricity quality. Electrical power quality can be divided in the two main groups: delivery reliability and voltage quality where this report will focus on voltage quality. Utility companies can only control the voltage since the customer will be "controlling" the loads and thereby the currents. This results in that the laws and regulations which will be focused on voltage. Electric power quality can be seen as an umbrella concept that covers different aspects of current but voltage in particular. All aspects are not new but a few are getting more interesting day by day in today's demanding electrical society [1].

Electrical equipment connected to the grid should be able to withstand a certain amount of deviation in voltage quality. This is called that the products should have a certain immunity to voltage quality deviations. Another aspect is that connected products should not draw a current that could have a large negative impact on the grid. This is called that the products should have a certain emission demand [8].

To determine the electrical quality in the grid, analyses are performed to show waveform magnitude, frequency and voltage symmetry compared to the ideal sinusoidal current and voltage at one given frequency. Deviations from the ideal case can be divided in two parts: periodic and non-periodic lapse. Periodic lapse comprises harmonics in current and voltage and the non-periodic lapse comprises voltage variations, under- and over-voltage, transients and flicker [2].

In the work to determine whether the electrical power quality is acceptable or not there are two ways for an electrical utility company to go about it. Either retroactive where measurements are made from customer complaints or proactive to prevent the appearance of non-acceptable power quality. Proactive work can be done by continuously measure the electrical power quality in different locations on the grid and to make improvements on areas that are affected before the customer notice it [1].

2.1. Long-term voltage deviations

Long-term voltage deviations occur mostly because power load varies during day to night but also from weekdays to holidays and are measured in the voltages root-mean-square (rms) value. Fluctuations depend on the grids impedance where high impedance gives larger deviations from the nominal voltage compared to grids with low impedance at a certain load. High impedance grids are often known as weak grids. The deviations could be in both directions i.e. over-voltage and under-voltage [2], [1]. Usually these long time limits are set to ±10 % but the optimal voltage level is somewhat lower. Some report estimate the voltage variation to be between ± 2.5 up to ± 3.0 % as an optimum level [6].

2.1.1. Over-voltage

The rms-value of the voltage can be over the nominal voltage and still be considered as accepted electric quality. It is when the rms-value exceeds the nominal voltage with 10 % that it is considered over-voltage. In the Swedish low voltage grid this occurs at 253 V (line-neutral) [9]. Over-voltage could be the result of connecting a capacitor bank or disconnecting a large inductive load. Another reason can be that the system needs to adapt to a lower seasonal demand by moving the substation transformers tap-changers manually. The last is mostly of concern in high impedance grids outside urban environment [1].

2.1.2. Under-voltage

The rms-value of the voltage is considered under-voltage in Sweden when it is 90% or less than the nominal voltage [9]. Reasons for under-voltage are the opposite of events that cause over-voltage. These events could be an overloaded circuit, malfunction of a transformers tap-changer, breakers connecting a large inductive load to the grid or a disconnected capacitor bank and thereby lowering the inductive power factor [2], [1]. For example three-phase induction motors consume a higher current when the voltage drops to be able to deliver the same amount of power resulting in increased losses and thereby decreased efficiency [2], according to:

$$P = 3 * V_{L-N} * I_L * cos\varphi \qquad \text{(eq. 1)}$$

2.2. Short-term voltage deviations

Short-term voltage deviations can be divided in three main parts called interruptions, dips (sags) and swell. The main reasons for short-term voltage deviations are faults on the grid or energization of large loads as starting currents for a large induction machine. In short-term voltage deviations time is limited due to the grids protective equipment, when the fault is cleared the voltage usually return to the level before the failure. Often a failure on the power grid results in a short-term voltage dip then followed by an interruption when the breaker clears the fault and then hopefully back to normal as the breaker recloses [1].

2.2.1. Interruptions

When the rms-value of the voltage is less than 0.1 pu (10 %) of the nominal voltage it is considered an interruption. Interruptions are defined between 10 milliseconds (0.5 cycle) up to 60 seconds, shorter duration is considered as a transient. Reasons behind interruptions could be power system faults (short-circuits), equipment failures and/or failures of the control equipment. Interruption time is limited by how time-effective the protective equipments are in their performance to clear or disconnect the fault [1].

2.2.2. Dips (Sags)

Dips are defined by a voltage level between 0.1 to 0.9 pu of nominal rms-voltage under a time span of 10 milliseconds (0.5 cycle) to 60 seconds at power frequency. Voltage dips are often related to system faults (short-circuits) but could also arise because energization of heavy loads or start of a large induction motor. If the starting current drawn from the induction motor is large compared to available fault current (short-circuit current) the voltage dip will be considerably larger. The increased current due to a voltage dip for recovery is the main cause for equipment failure. Dips with a duration less than 10 milliseconds (0.5 cycle) are considered a transient and a durations longer than 60 seconds are long-term voltage deviations and can usually be controlled by voltage regulation equipment [1], [10].

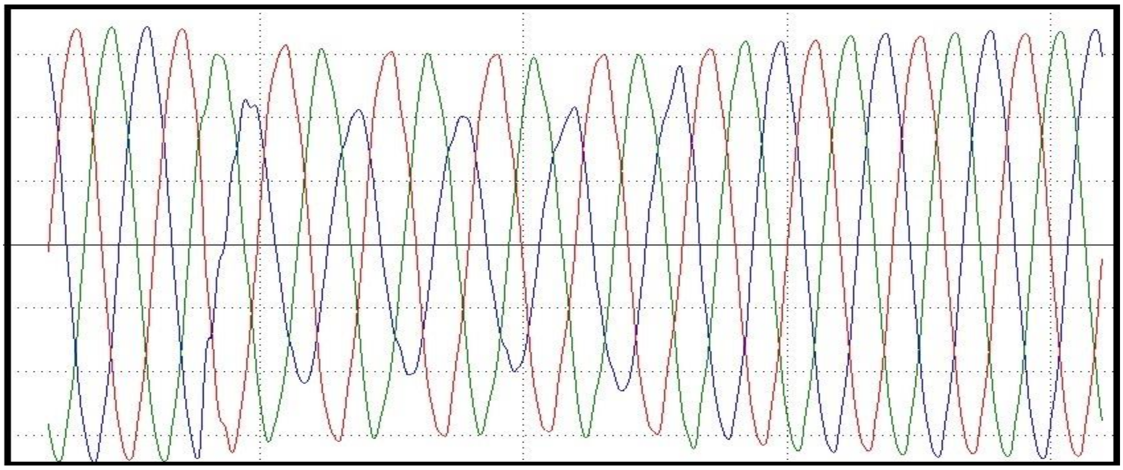

Figure 1 - Voltage dip on mainly the blue phase. This is a registered wave-shape during one of the measurements.

2.2.3. Swell

Swells are defined by a voltage level between 1.1 to 1.8 pu of nominal rms-voltage under a time span of 10 milliseconds (0.5 cycle) to 60 seconds at power frequency. Voltage swell often arise because of power grid failures but do not occur as often as dips. Swells could also be created when switching off a large inductive load or when energizing a capacitor bank [1].

2.3. Voltage unbalance

Voltage unbalance occurs when the three-phase voltages does not have the same amplitude or respective angular displacement. Since some electrical equipment only is connected between phase and neutral a small amount of voltage unbalance will occur. Voltage unbalance could occur because of different impedance in the conductors or by a non-symmetric loaded grid were the currents in the phases will differ resulting in a current in the neutral conductor. These differences will result in voltage unbalance in the three phases and the neutral point gets a value of nonzero [11], [12].

Voltage unbalance is often defined as the maximum deviation from the average three-phase voltage divided by average voltage, presented in percent. In different standards it is defined as the minus-sequence voltage divided by the positive-sequence voltage. Normal reasons for voltage unbalance less than two percent usually depends on single-phase loads [1].

Voltage unbalance can cause an over-load on induction machines and frequency converters can malfunction. If negative-sequence currents are present in the stator of an electrical machine they reduce the normal (positive) magnetic flux in the motor that leads to a reduced torque [8], [13].

2.4. Transients

Transients can be divided in two groups: impulsive and oscillatory. Impulsive transient is what most people referred to as a transient. It is a sudden and fast change from the steady state operation of voltage or current in either direction (i.e. positive or negative direction). The most common cause of impulsive transient is lightning [1], [2].

Oscillatory transients are like the impulsive transients but with variations in both positive and negative direction and their duration can be slightly longer than impulsive transients. Frequencies higher than 500 kHz is considered high-frequency transients, medium-frequency is between 5-500 kHz. Back-to back capacitors energization usually responds with an oscillatory transient in the medium-frequency interval because of their switching technology. Oscillating frequencies smaller than 5 kHz are considered low-frequency and mainly consists of capacitor bank energization [1].

2.5.Harmonics

Harmonics are sinusoidal currents or voltages with a frequency that is an integer multiple of the fundamental frequency. Harmonics develops from the use of non-linear electrical components on the grid. Linear components are commonly referred to as resistors, inductors or capacitors were the proportion of the effective values of voltage and current are linear. Examples of non-linear components are diodes, thyristors and IGBT´s (Insulated-Gate Bipolar Transistor). Non-linear components mainly consist of loads and create current harmonics, therefore the amount of harmonics are larger on the low-voltage grid compared to medium-voltage grid. Harmonics in the voltage arise because of the current harmonics and are dependent on the grids impedance, strong grid generates a smaller amount of voltage harmonics compared to a weak grid when both are affected by the same amount of current harmonics. If the power grid is properly dimensioned the impact of harmonics would most likely not cause any problem [1], [2].

One common problem with harmonics is resonance with a capacitive part of the system which increases the harmonic itself, for example a capacitor bank failure due to resonance phenomena. A common way to describe the amount of harmonics on a system is by Total Harmonic Distortion (THD) which is an effective value of the total harmonics. THD can describe either voltage (THD_v) or current (THD_i) harmonic distortion [1], [14].

$$THD_x = \frac{\sqrt{\sum_{k=2}^{\infty} x_{k,RMS}^2}}{x_{1,RMS}} \qquad \text{(eq. 2)}$$

Total harmonic distortion is calculated according to the mathematical relationship described above. X value in denominator is the effective value of either voltage or current of base frequency. X value in numerator is the sum of all effective values of either voltage or current with start on the second harmonics (100 Hz in Sweden) and goes up to desired level [2].

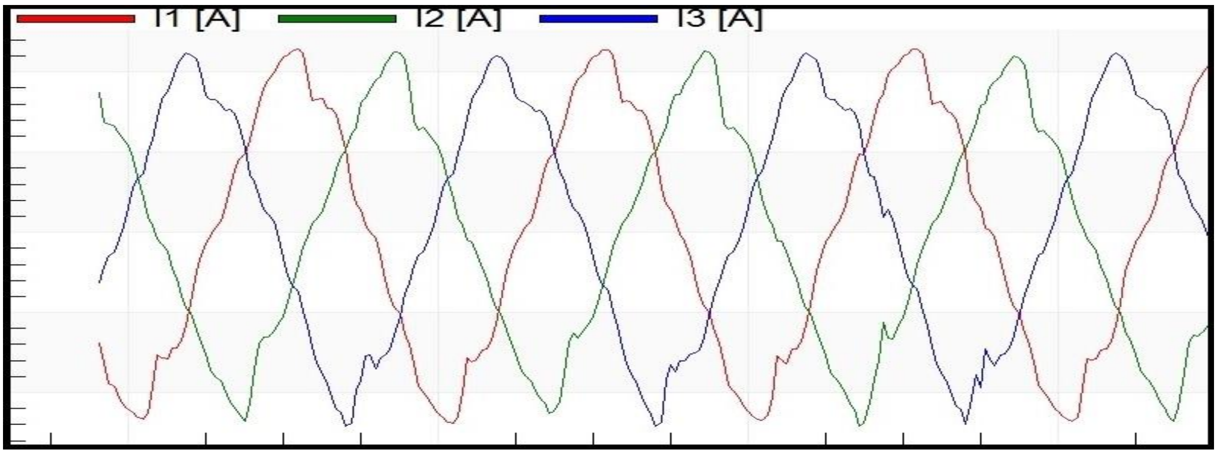

Figure 2 - Harmonics present in current. This is a registered wave-shape during one of the measurements.

When the curve has an identical positive and negative half period it only consists of odd numbers of harmonics which is the most common kind. Even numbers of harmonics often indicate that something are wrong, either with the load/system or measurement equipment but could be to an uneven arc at an arc furnace or produced by half-wave rectifiers. Often harmonics above the 50th is negligible in power systems because they do not cause any damage to power equipment and to collect data at these frequencies are rather demanding [1].

As voltage and current no longer consists of a pure sinusoidal waveform some of the common mathematical relationships are changed. Voltage and current true rms-value will now be the absolute value of the sum of fundamental effective value added with every present harmonics effective value [2], [14]:

$$x_{true\ rms} = \sqrt{\sum_{k=1}^{\infty} x_{k,RMS}^2} \qquad \text{(eq. 3)}$$

THD-value is related to the rms-value and given that the true rms-value can be calculated as well according to equation 4 [1], [14].

$$x_{true\ rms} = x_{1,RMS} * \sqrt{1 + THD_x^2} \qquad \text{(eq. 4)}$$

Another mathematical relationship that changes with the presence of harmonics is power factor. Power factor can be seen as the amount of total delivered power (apparent power) that can be used for real work (active power). In a sinusoidal case the power factor is described by the angle between the voltage and current, cosφ (P/S) called displacement power factor (DPF). In the non-sinusoidal case were harmonics is present it becomes more complex. It is still calculated by the active power divided by the apparent power but with the effective values of all components [2], [14]:

$$PF = \frac{P}{S} = \frac{P}{V_{1,RMS} * I_{1,RMS} * \sqrt{1+THD_V^2} * \sqrt{1+THD_I^2}} \qquad \text{(eq. 5)}$$

This power factor that takes harmonics in account is called true power factor (TPF). As an example a pulse width modulated (PWM) frequency converter could have a displacement power factor (DPF) of almost 1 but the true power factor (TPF) around 0.5 [1], [2].

Harmonics behave differently based on their phase sequence. The fundamental voltage or current phase sequence is called positive-sequence, L1 (0°), L2 (-120°), L3 (120°) with a counter clockwise rotation. Second harmonics is called negative-sequence, L1 (0°), L2 (120°), L3 (-120°) also with a counter clockwise rotation. Third harmonics is of zero sequence were L1 (0°), L2 (0°), L3 (0°) and this is the way the triple harmonics add up in the neutral conductor and does not cancel each other out like the positive- or negative-sequence. The harmonics phase sequence for the first harmonics can be seen in table 1 below [1], [13], [12]:

Table 1 - Harmonics phase sequence

1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
+	-	0	+	-	0	+	-	0	+	-	0

Triple harmonics are odd multiples of the third harmonics and are one of the harmonics with greatest concern on the power system like a low voltage grid. Low voltage grids consist of four (TN-C) or five (TN-S) conductors with either separate protective earth and neutral conductor (five) or protective earth and neutral used in the same conductor, PEN-conductor. Presence of balanced triple harmonics put a larger demand on the neutral conductor since their currents add up in the neutral conductor that results in the triple harmonic current three times as large as in the phase conductors. This might lead to an over-loaded neutral conductor that could burn off. Symmetric loads with only fundamental currents cancel each other out instead of flowing in the neutral [1], [2].

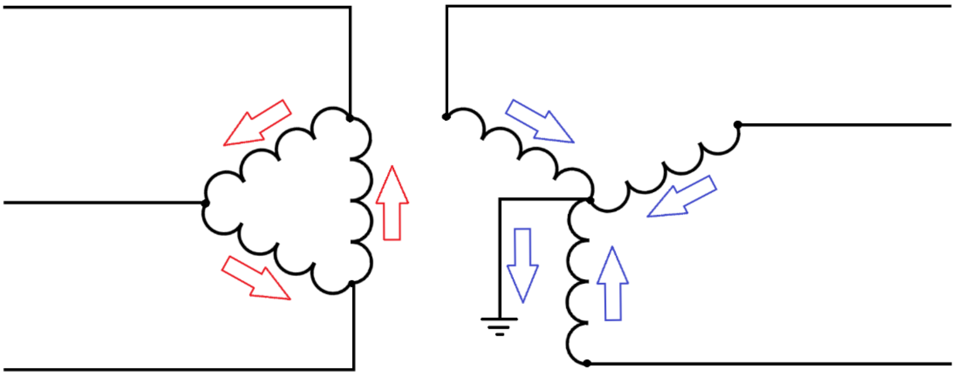

Figure 3 – Zero sequence current harmonics in a Dyn connected transformer

Most transformers between medium voltage to low voltage grids are connected in Dyn. When triple current harmonics are present in balance between phases they flow back to the transformer in the neutral conductor and are eliminated in the delta winding as a circulating current which produce heat, see figure 3. Because of this triple harmonics are not as prominent on the upside of the transformer when it is Dyn connected since it cannot flow upstream from the delta winding and has to be measured on the down-side. If triple harmonics are present in the system in an unbalanced condition they can behave differently from a balanced case [1], [2], [13].

Eddy currents are induced in the transformer mainly in the core by the changing magnetic flux and producing heat. When the frequency increases due to the presence of harmonics eddy current losses also increase and thereby the produced heat. Eddy current losses are proportional with current and frequency in square. A general rule when it comes to transformer load is that a THD_I of more than 5 % makes the transformer suitable for a de-rating because the increased eddy current loss. The K-factor is often used to determine the amount of de-rating according to mathematical expression below were I_h denotes specific values of that currents harmonics and h denotes the specific harmonic number [1], [4]:

$$K = \frac{\sum_{h=1}^{\infty}(I_h^2 * h^2)}{\sum_{h=1}^{\infty} I_h^2} \qquad \text{(eq. 6)}$$

The transformer de-rating can then be estimated if the per unit eddy current loss factor is known. This factor can be found by the transformer designer or by values based on a certain type and size of transformer in tables [1].

Harmonics of frequencies below 2 kHz mostly flows up towards the delivery source. Harmonics of higher frequencies flows between devices in the low voltage grid instead of upstream towards the delivery source [15].

2.5.1. Resonance

How much the currents harmonics are affecting the voltages is depending on the systems impedance. Impedance consists of a resistance and a reactance. The reactance could either be inductive or capacitive. Reactance varies with frequency according to [1]:

$$X_C = \frac{1}{-j*\omega*C} \quad \text{(eq. 7)}$$

$$X_L = j*\omega*L \quad \text{(eq. 8)}$$

Resistance is also depending on the frequency due to the skin effect. When the frequency increases the current is moving more on the edges (skin) of the conductor. This results in a higher current density on the edges compared to the centre. The result from the skin effect is that the useful conductor area gets smaller with increased frequency and therefore the resistance increases. But the inductance is decreased due to skin effect, which means that the increase in reactance is lower. Skin depth (δ) is calculated according to equation 9 were μ_r is relative magnetic permeability of the conductor and μ_0 is the permeability of empty space and σ is the electric conductivity of the conductor [1], [16].

$$\delta = \frac{1}{\sqrt{\pi\mu_r\mu_0\sigma f}} \quad \text{(eq. 9)}$$

With presence of harmonics both the resistance and reactance of the cable increases. The flowing current might take alternative ways due to the increased impedance through building structures, water pipes, district heating pipes etc. named stray currents. Stray current leads to an increased magnetic field in the surroundings and the health aspects regarding increased magnetic fields are not certain but some research shows that it could cause cancer and thereby precautions should be taken to reduce the risk. If a residual-current device (RCD) is connected it will detect stray currents and disconnect the circuit [2], [3].

When a system consists of both inductive and capacitive components the system has one or more natural frequencies. If harmonics are present in the system at the same frequency as the natural frequency resonance could occur. Resonance phenomena in power systems are divided in parallel resonance and series resonance. Resonances occur when the reactive part on the grid cancel each other out and leave only resistance. The frequency when the reactive parts cancel each outer out is known as resonance frequency. At parallel resonance the circuit total admittance (Y) is the smallest possible and therefore the total impedance is the largest possible according to equation 10 [1], [17].

$$|Y| = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\omega C - \frac{1}{\omega L}\right)^2} \quad \text{(eq. 10)}$$

Since the circuits total impedance is the largest possible resulting in the current being the smallest possible. However the current between the capacitive and inductive parts could be much larger than the systems total current. The mathematical expression for calculation of the parallel resonance frequency is given in equation 11 [1], [17].

$$f_P = \frac{1}{2\pi}\sqrt{\frac{1}{L*C}} \quad \text{(eq. 11)}$$

Series resonance have similarities with parallel resonance, when the impedances imaginary part is zero. Resistance, inductance and capacitance connected in series could give resonance at a certain frequency or frequencies. When series resonance frequencies occur the LC-circuit will attract a large part of the harmonic current. The impedance gets smallest possible at series resonance frequency according to equation 12. Harmonic current at resonance frequency is only restricted by the resistance in the circuit [1], [17].

$$|Z| = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\omega C - \frac{1}{\omega L}\right)^2} \qquad \text{(eq. 12)}$$

This principle is used in filters for absorbing harmonic current at certain frequencies. However, voltages over the inductor and capacitor are equal and in opposite phase at series resonance that could make these voltages much larger than the supplied voltage [1], [17].

2.5.2. Sources of harmonics

Switch-mode power supplies

Most single-phase electronic equipment today is fed by a switch-mode power supply. These are known to produce a high amount of third harmonic that as mentioned is a zero sequence component that adds up in the neutral conductor. They consist of a full-wave rectifier on the ac-side with a shunt capacitor on the dc-side to smoothen out the voltage. The dc-voltage is then switched to ac-voltage again at a high frequency and then rectified again from a switch mode dc-to-dc converter [1].

Fluorescent light

Large amount of all lights in public buildings consists of fluorescent light that is an energy effective way to produce light. The downside of fluorescent light is the produce of harmonics. For being able to start the fluorescent light high voltage is needed to produce an arc between the two electrodes. After ignition voltage is lowered and the current is reduced from short-circuit current to produce the proper amount of light. Modern techniques use an electronic ballast of switch-mode to produce the high frequency voltage for lightning, that high frequency also make the needed inductance to reduce the current rather small according to equation 8 [1].

Low-energy light bulbs and diode light

Since the out-phasing of the traditional incandescent bulb it has commonly been replaced by low-energy light bulbs of different types. Low-energy light bulbs have a capacitive power factor (current before voltage) and creates mostly the third harmonics followed by the fifth harmonics due to a full-wave rectifier and a shunt capacitor. This capacitive power factor is not considered a problem for the moment due to the lower demand for capacitor bank in the medium voltage grid according to a recent study [15]. Low-energy light bulbs produce a larger amount of harmonics around 10-15 kHz and around 40 kHz due to the switching transistor. Harmonics at these frequencies can disturb signals used by the electrical system for remote reading of the electricity meters [18].

Three-phase power converters

A large advantage with three-phase power converters compared to single-phase is the lack of the third harmonic. The most common type of three-phase power converter is frequency converter using Pulse Width Modulation (PWM) for induction motors. Input voltage is first rectified by either diodes or thyristors then the dc-link often use a capacitor in shunt for voltage stability (VSI) or an inductor in series for current stability (CSI). The dc-power is inverted to ac-power by Gate Turn-Off thyristors (GTO) or transistors and fed to the motor. The amount of harmonics in the current depends on the speed (frequency) where a higher speed leads to higher amounts of harmonics. The most prominent harmonics from a three-phase power converter are mainly the fifth and seventh harmonics but also the converters switching frequency.

2.5. Interharmonics

Voltages and currents with a frequency that is not an integer multiple of the nominal frequency is called interharmonics. Interharmonics arise with the use of static frequency converters, cycloconverters and induction furnaces. The total amounts of interharmonics are not constant but changes with the load. Interharmonics can create resonance with the mechanical parts of the system. Signals transmitted through the power grid can be affected by interharmonics making remote reading of electrical meters difficult [1].

2.6. Voltage fluctuations (Flicker)

Voltage fluctuations are a repeating deviation of the voltage rms-value between 1-30 Hz, usually within the long term voltage deviations of 0.9 and 1.1 pu of nominal voltage. Voltage fluctuations are commonly named flicker, but flicker is the result of voltage fluctuations on light bulbs which can be perceived as annoying for humans. As little as 0.5 % variations of the nominal voltage with a frequency of 6-8 Hz can result in annoying flicker [2], [1].

Voltage fluctuations could also lead to increased starting currents and temperature in electrical equipment but still the humans are the most effected of these fluctuations [2]. Voltage fluctuations are linked to long-term voltage deviations because the system is too weak to deliver power to the load. However for voltage fluctuations to arise the load needs to be constantly changing like elevators, compressors, pumps and arc furnaces leading to voltage fluctuations in pace with connections and disconnections or load variations. With arc furnaces the load mainly relates to voltage fluctuations due to their high power demand even if they are connected to a rather strong grid. This is because the arc is not consistent between the electrodes before the metal is melted resulting in a fluctuating current [1], [2].

Voltage fluctuation measurements are performed related to what humans experiences in form of flicker based on the voltage fluctuations. Short-term flicker sensation (Pst) is one of two parts in the standard measurement system. A value of 1.0 indicates that 50 % of a sample will consider the flicker as notable. Long-term flicker sensation (Plt) is the other part of the standard measurement system. Plt is the long term average of Pst samples. Whether a load will result in flicker depends on the loads size, system impedance (short-circuit effect) and the frequency of the resulting voltage fluctuations [1].

These limits regarding flicker is developed based of the light a 230 V, 60 W incandescent lamp emits during small voltage changes. Today other types of light sources are used like fluorescent light and low-energy light bulbs and they are affected in another way and the limits cannot directly be used as a reference for unacceptable levels. Incandescent lamps are often but not always more sensitive to voltage variations than fluorescent light and low-energy light bulbs [15], [8].

3. Laws, regulations and standards

3.1. Electric law

In the Swedish law third chapter 9 § electric law (1997:857) there are demands on the grid owner that the delivered electricity should be of accepted quality. The law does not mention any specific values that need to be obtained for the electricity to be classified as accepted. Earlier the demands written in Swedish Standards (SS) were used as the only factor to classify the electricity as accepted quality. A main rule in the electric law says that the grid owner is obliged to repair flaws in the transmission of electricity if costs are reasonable compared to the inconvenience it causes customers. Since 2011 Energy markets Inspectorate (EI) have published a code of statutes regarding electric quality (EIFS 2011:1 later 2013:1) and are therefore superior to the Swedish Standards. Energy markets inspectorate code of statutes 2013:1 can be seen as summary of already given standards on electric power quality and it is not intended to change the given standards, although there are some differences between them. All electric quality groups except flicker and interharmonics are regulated under EIFS 2013:1 which is the latest code of statutes from energy markets inspectorate [9], [19].

3.2. EIFS 2013:1

Energy markets inspectorate is the responsible authority for the electric quality on the Swedish grid. They have developed a code of statutes that were introduced in 2011 (EIFS 2011:2) and then replaced by a new version 2013 called EIFS 2013:1 that was inset 1st of October 2013. Voltage quality is considered accepted when it is measured and approved according to the standard SS-EN 61000-4-30 called measuring class A. No values on transients and interharmonics are given in the code of statutes. All values should be obtained in the point of the consumers connection, the delivery point [9].

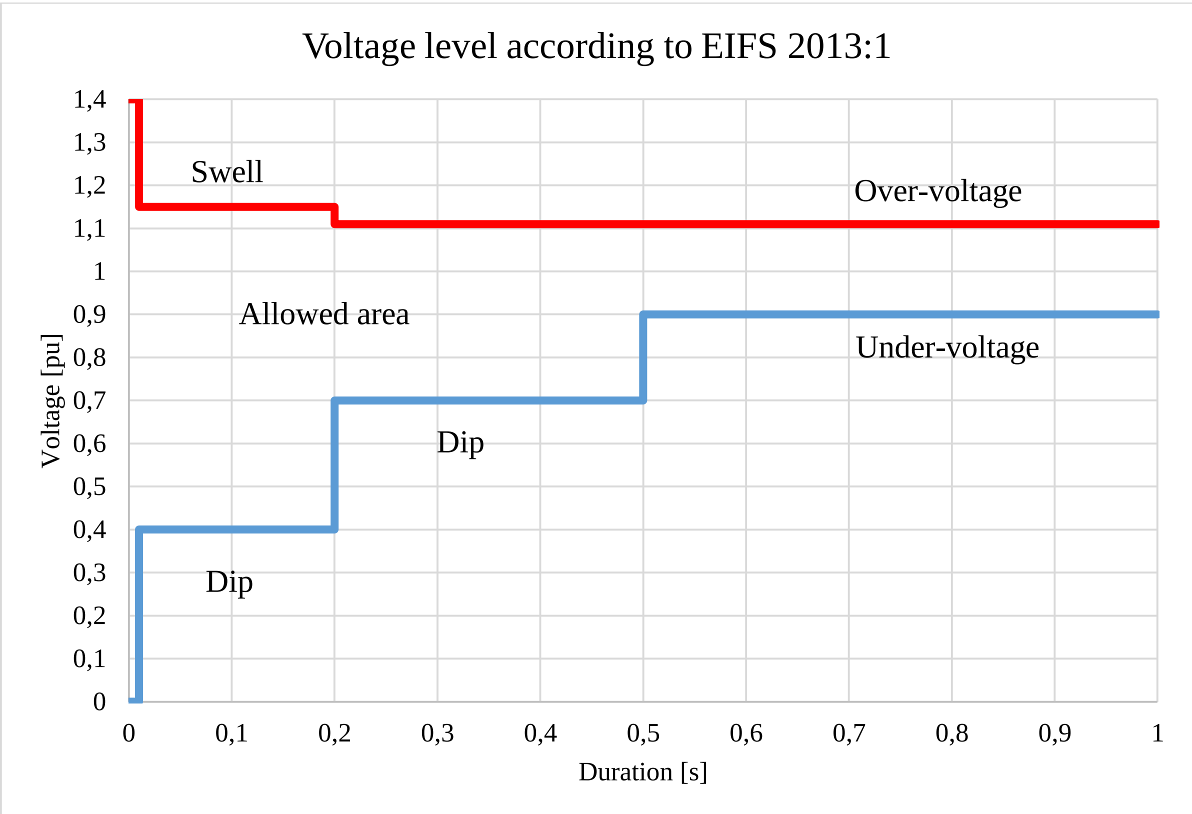

Figure 4 - Voltage levels according to EIFS 2013:1 [9].

Long-term voltage deviations

During a period of one week every average 10 minute value of the voltage should be between 0.9 pu to 1.1 pu of reference voltage i.e. between 207-253 V. Reference voltages up to 1000 V uses phase-voltage as reference [9].

Short-term voltage dips

Voltages up to 45 kV uses table 2 to determine suitable procedures. Voltages in area C should never occur. Voltages in area B the grid owner is obliged to correct if the costs are reasonable compared to the inconvenience it causes customers. Voltages in area A should be considered as normal and if the customer needs higher quality they have to install equipment for preventing this to occur, like an UPS (Uninterruptable Power Supply) [9].

Table 2 - Short-term voltage dips according to EIFS 2013:1 for reference voltage up to 45 kV.

V [pu]	Duration [ms]				
	$10 \leq t \leq 200$	$200 \leq t \leq 500$	$500 \leq t \leq 1000$	$1000 \leq t \leq 5000$	$5000 \leq t \leq 60000$
$0.9 > V \geq 0.8$	A				
$0.8 > V \geq 0.7$					
$0.7 > V \geq 0.4$			B		
$0.4 > V \geq 0.05$					C
$0.05 > V$					

Short-term voltage swell

Voltages up to 1000 V uses table 3 to determine what procedures that needs to take place. Voltages in area C should never occur. Voltages in area B the grid owner is obliged to correct if the costs are reasonable compared to the inconvenience it causes customers. Voltages in area A should be considered normal and if the customer needs higher quality they have to install equipment for preventing this to occur like an UPS (Uninterruptable Power Supply) [9].

Table 3 - Short-term voltage swell according to EIFS 2013:1 for reference voltage up to 1000 V.

V [pu]	Duration [ms]		
	$10 \leq t \leq 200$	$200 \leq t \leq 5000$	$5000 \leq t \leq 60000$
$V \geq 1.35$			C
$1.35 > V \geq 1.15$			
$1.15 > V \geq 1.11$		B	
$1.11 > V \geq 1.10$	A		

Fast voltage-changes

A change in the voltage faster than 0.005 pu per second when the voltage is kept between 0.9-1.1 pu of the reference voltage is considered fast. Voltage changes below 0.005 pu per second of reference voltage is considered stable i.e. approximately below 1.15 V/second for Swedish low voltage grid. There are two categories for fast voltage-changes, stationary and max. Stationary is the difference between before and after the change and max is the maximum voltage difference.

$$V_{stationary} = \frac{\Delta V_{Stationary}}{V_n} * 100\% \quad \text{(eq. 13)}$$

$$V_{max} = \frac{\Delta V_{max}}{V_n} * 100\% \quad \text{(eq. 14)}$$

The number of fast voltage-changes added with the number of short-term voltage dips in the area A of table 2 should not exceed values in table 4 [9].

Table 4 - Maximum number fast voltage-changes per day according to EIFS 2013:1 up to a reference voltage of 45 kV.

Fast voltage-changes	Maximum number per day
	$V_n \leq 45$ kV
$\Delta V_{stationary} \geq 3$ %	24
$\Delta V_{max} \geq 3$ %	24

Voltage unbalance

During a measuring period of one week every average 10 minute value of voltage unbalance should be equal or less than two percent of minus sequence divided by positive sequence voltage [9].

Harmonics

During a measuring period of one week every average 10 minute value for every single harmonic should be less or equal to the values in table 5 for reference voltage up to 36 kV. The total harmonic distortion (THD_v) for the voltage should be less or equal to 8 percent for every average 10 minute value up to the 25^{th} harmonic [9].

Table 5 - Single harmonic limits for voltages up to 36 kV according to EIFS 2013:1.

Odd harmonic. Not multiples of three		Odd harmonic. Multiples of three		Even harmonic	
Harmonic (n)	$\frac{v_n}{v_1}$ [%]	**Harmonic (n)**	$\frac{v_n}{v_1}$ [%]	**Harmonic (n)**	$\frac{v_n}{v_1}$ [%]
5	6.0 %	3	5.0 %	2	2.0 %
7	5.0 %	9	1.5 %	4	1.0 %
11	3.5 %	15	0.5 %	6…24	0.5 %
13	3.0 %	21	0.5 %		
17	2.0 %				
19	1.5 %				
23	1.5 %				
25	1.5 %				

Interruptions

An interruption occurs when one or more of the phases are electrically disconnected from other parts of the grid. This condition results in a voltage close to zero. An interruption that have not previously been announced by the utility company is classified as long if it consists longer than three minutes and short if it consists between 100 milliseconds and up to three minutes. When the amount of non-mentioned long interruptions are below three per year the electric quality is considered good. When the amount of non-mentioned long interruptions excess 11 per year it is considered bad electric quality [9].

3.3. Swedish Standard (SS)

Most standards contain information that directive and laws do not cover e.g. measurement, measurement technologies, testing and installation rules. Standards can be seen as the lower level needed to be obtained. Standards are optional to follow but are used as a compulsory reference for example authorities in their work in developing regulations. Today the EU-commission makes agreements with the European standardization agencies to develop standards that follow EU directives. Standards that follow those directives are named harmonised standards e.g. SS-EN 61000-3-2 and SS-EN 61000-3-3 are harmonised with EMC-directive. So if harmonised standards are followed it implies that concerned EU-directives are followed. Those standards that are mentioned below can be divided in either grid standard or device standard [20], [21], [8].

Voltage characteristic

<u>SS-EN 50160</u>
"Voltage characteristics of electricity supplied by public electricity networks".
This standard covers voltage characteristics in normal condition on low voltage ($V_n < 1$ kV), medium voltage (1 kV < V_n < 36 kV) and high voltage (36 kV < V_n < 150 kV) grids and is therefore considered a grid standard. Voltage characteristics means frequency, amplitude, curve shape and symmetry values compared to a given limit in the consumers connection, the delivery point. It does not cover EMC levels and current emissions that are regulated under SS-EN 61000. Measurement for deciding voltage characteristics should be conducted according to SS-EN 61000-4-30 [22].

SS-EN 50160 states that every average 10 minute value of voltage should be between 0.85 pu to 1.1 pu of nominal voltage (i.e. 196-253 V on low voltage) and 95 % of the average 10 minute value should be between 0.9-1.1 pu during a week. Fast voltage variations should be lower than 5% normally and lower than 10 % if they occur rarely during 95 % of a week. Resulting Plt should be lower than 1.0 during 95% of a week compared to EIFS 2013:1 were it is not regulated. SS-EN 50160 covers harmonics up to 40^{th} were THD_v should be below 8 %. Interruptions occur when voltage in the delivery point is below 0.05 pu of reference voltage on all three phases otherwise it is considered voltage dip. Voltage unbalance should be below 2 % during 95 % per week on every average 10 minute value, defined as minus-sequence divided by positive-sequence. One main difference with SS-EN 50160 compared to EIFS 2013:1 are that demands should only be fulfilled 95 % of the time according to SS-EN 50160 in most cases [22].

Table 6 - Single harmonic limits for low voltage grid according to SS-EN 50160 [22]

Odd harmonic. Not multiples of three		Odd harmonic. Multiples of three		Even harmonic	
Harmonic (n)	$\frac{v_n}{v_1}$ [%]	**Harmonic (n)**	$\frac{v_n}{v_1}$ [%]	**Harmonic (n)**	$\frac{v_n}{v_1}$ [%]
5	6.0 %	3	5.0 %	2	2.0 %
7	5.0 %	9	1.5 %	4	1.0 %
11	3.5 %	15	0.5 %	6…24	0.5 %
13	3.0 %	21	0.5 %		
17	2.0 %				
19	1.5 %				
23	1.5 %				
25	1.5 %				

EMC environment

SS-EN 61000-2-2
"Electromagnetic compatibility (EMC) - Part 2-2: Environment - Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems."
There are a lot of similarities with SS-EN 50160 and SS-EN 61000-2-2 were the last one only covers low voltage and also comprises EMC levels and can be considered a grid standard. SS-EN 61000-2-2 do not have the same demands as SS-EN 50160 when it comes to measurement. That means it is not necessary to measure according to SS-EN 61000-4-30. The main differences between these two are mentioned below [22].

Voltage unbalance should be a maximum of two percent 100% of the time. It is defined as the minus-sequence voltage divided by the positive-sequence voltage. Flicker levels are for Pst = 0.8 and for Plt = 1.0. THD_v should always be below 6 % and interharmonics upper limit at 0.3 % which is different compared to SS-EN 50160 were THD_V is 8% and interharmonics lacks any limit [8], [22].

Table 7 - Single harmonic limits for low voltage grid according to SS-EN 61000-2-2 [8].

Odd harmonic. Not multiples of three		Odd harmonic. Multiples of three		Even harmonic	
Harmonic (n)	$\frac{v_n}{v_1}$ [%]	**Harmonic (n)**	$\frac{v_n}{v_1}$ [%]	**Harmonic (n)**	$\frac{v_n}{v_1}$ [%]
5	6.0 %	3	5.0 %	2	2.0 %
7	5.0 %	9	1.5 %	4	1.0 %
11	3.5 %	15	0.4 %	6	0.5 %
13	3.0 %	21	0.3 %	8	0.5 %
$17 \leq n \leq 49$	2.27*(17/n)-0.27	$21 \leq n \leq 45$	0.2 %	$10 \leq n \leq 50$	0.25*(10/n)+0.25

EMC limits

SS-EN 61000-3-2

"Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current = 16 A per phase)"

This standard is harmonised with the EMC-directive and puts demands on devices (not professional devices) connected to the low voltage grid and their amount of harmonic current emission for being able to fulfil SS-EN 61000-2-2 and are therefore considered a device standard. Devices are categorised in four groups named Class A-D mainly related to equipment of homes and offices [23], [8].

During testing of the device the supply voltage should be within these intervals:
Supply voltage level 0.98-1.02 pu.
Phase angels between fundamental voltages (three-phase) are 120°±1.5°.
Harmonic levels [23]:

Table 8 - Maximum harmonics level on supply voltage on testing

Harmonic (n)	$\frac{v_n}{v_1}$ [%]
3	0.9 %
5	0.4 %
7	0.3 %
9	0.2 %
2,4,6,8,10	0.2 %
11-40	0.1 %

Some exceptions from this standard are [24], [23]:

- Equipment under 75 W (not lightning).
- Professional equipment over 1000 W.
- Symmetrical heating control under 200 W.
- Independent dimmers for incandescent lamps under 1000 W.

These loads are considered to be increasing which causes a harmonic none regulated current emission. Optimum performance is not guaranteed from the device when the supply voltage is not sinusoidal. Laboratory experiments have shown us that a supply voltage with high amounts of harmonics can produce considerable larger amount of current harmonics [24], [25].

SS-EN 61000-3-3

"Electromagnetic compatibility (EMC) - Part 3-3: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current = 16 A per phase and not subject to conditional connection."

This standard is harmonised with the EMC-directive and is considered a device standard. Flicker evaluation from equipment is the voltage differences measured on the connection terminals. Pst can be evaluated not only by measurements but also from simulations and analytical methods. When measuring is applied it should be conducted according to SS-EN 61000-4-15 regarding flickermeter and is considered the reference method [26].

Maximum values under testing are Pst not greater than 1.0 and Plt not greater than 0.65 but are not applied if the product is manually switched. Three levels of voltage changes are allowed under the test at 4, 6 and 7 % ($\Delta U/U_n$) depending on the tested equipment. The supply voltage (open-circuit voltage) should be kept between ±2 % of nominal voltage during the test. THD_v should be lower than 3 %. Fluctuations of the supply voltage could be neglected if it is less than Pst 0.4. Observation periods to determine the levels of flicker are for Pst 10 minutes and for Plt 2 hours [26].

<u>SS-EN 61000-3-11</u>
"Electromagnetic compatibility (EMC) - Part 3-11: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems - Equipment with rated current ≤ 75 A and subject to conditional connection."
This standard is harmonised with the EMC-directive and is considered a device standard. This standard primarily put demands on devices connected to the low voltage grid with a rated input current from 16 A up to and including 75 A, which is subject to conditional connection. Equipment tested according to SS-EN 61000-3-3 without passing the set limits is a subject for conditional connection and therefore tested under SS-EN 61000-3-11. Demands regarding flicker is the same as in SS-EN 61000-3-3 [27].

<u>SS-EN 61000-3-12</u>
"Electromagnetic compatibility (EMC) - Part 3-12: Limits - Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16 A and =75 A per phase."
This standard is harmonised with the EMC-directive and is considered a device standard. This standard put demands on devices with a rated input current larger than 16 A and up to and including 75 A per phase intended to be connected to public low voltage grids. SS-EN 61000-3-12 defines emission limits for devices and methods for testing a devices emission [28].

During testing of the device the supply voltage should be within these intervals:
Supply voltage level 0.98-1.02 pu [28].

Table 9 - Maximum harmonics level on supply voltage on testing [28]

Harmonic (n)	$\frac{v_n}{v_1}$ [%]
3,7	1.25 %
5	1.5 %
11	0.7 %
9,13	0.6 %
2,4,6,8,10	0.4 %
12,14-40	0.3 %

EMC testing and measurement techniques

SS-EN 61000-4-30
"Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques - Power quality measurement methods."
This is a standard about details of measuring electric power quality with help of SS-EN 61000-4-15 for flicker measurements and SS-EN 61000-4-7 for harmonic measurements. Measurements can be divided in the categories, A and B. Category A is the most accurate instrument and two different meters in category A should perform the same within the given accuracy and is therefore classed as a reference instrument. Category B is still a valid measurement but the exact accuracy may not be met as well as category A [1].

3.4. EMC-directive

EMC stands for Electromagnetic Compatibility and describes devices capability to work together without interference. Devices should not produce emission in such amount that it could disturb other devices main purpose e.g. radio networks, mobile networks and electrical power distribution systems. Devices should not only cope with demands regarding emissions but also their capability to withstand electromagnetic emissions from other devices to a certain limit; their immunity. EMC divide the equipment in two groups; single devices and fixed installations [8].

Single devices should be CE marked according to the EMC-directive. With a CE marked device the manufacturer are responsible for that the device have gone through and passed certain standardized tests and are therefore approved according to the EMC-directive. Manufacturers give instructions for installation of the device and if they are followed the device should not conflict with the EMC-directive. If the device should emit emissions that are not within the limit even though the device is installed according to the instruction by the manufacturer, the manufacturer or the supplier should be contacted for actions [8].

With fixed installations there are demands that the documentation is present after installation to approve that installation is done according to relevant praxis and manufacturer instructions. To support this given EMC-regulations standards under SS-EN 50065 and SS-EN 61000 are used [8].

4. Method

The best way to get a perception on the electric power quality on the grid is by measurements. An ideal case would be one electric quality meter at every customer electricity meter and also at the transformer stations on different voltage levels. This is not an economically viable solution because most meters would not indicate any problems and also creates a massive amount of data which needs to be analysed. Most electrical quality meters used today sends an alarm if limits according to EIFS 2013:1 are exceeded [29]. With strategically placed meters on the grid indicating power quality problems additional measurements can be made to locate the interfering source. With this procedure it is possible to locate and take actions to reduce the interfering source rather than installing equipment to reduce the problem on a higher voltage level at a higher cost.

Low voltage consumers can be divided in different categories based on their typical load. Following categories can be assumed for low voltage connected consumers and their typical electrical power quality issues can thereby be expected:

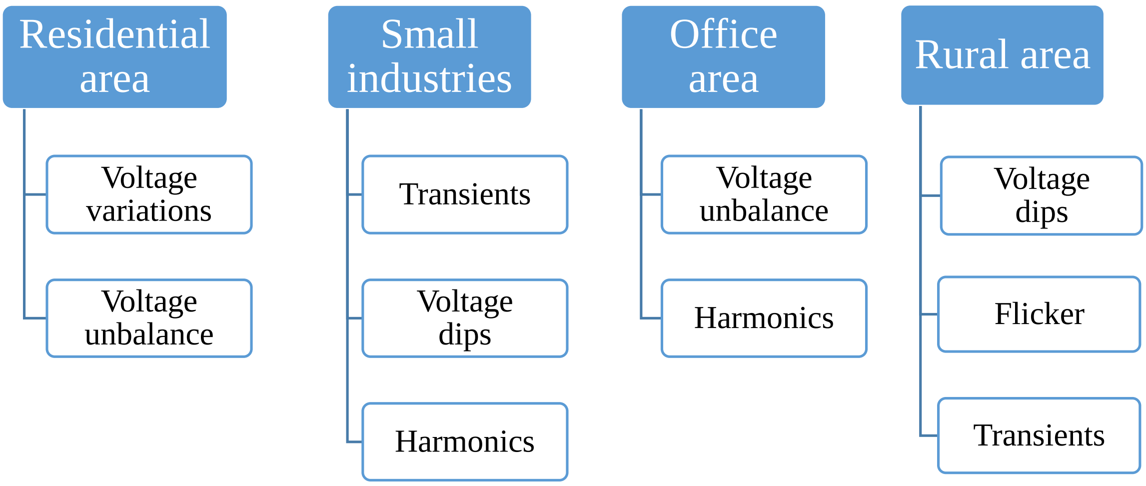

Figure 5 - Voltage quality aspects that might get exceed based on different load types.

Buildings within these categories usually are gathered together in small areas and therefore creating their typical load.

Residential areas that use heat pumps or electricity for heating are more interesting due to the higher electrical load. Residential areas with electric heating are usually dimensioned for that typical load and mainly consist of a balanced resistive load. Modern heat pumps are on the other hand more interesting since they regulate with frequency converters or by switching the compressor on and off more often with a high inrush current compared to the regular electric heating. Heat pumps are expected to represent the future heating system better than the ordinary electrical heating and gives us therefore a better understanding in what to expect in the future from that typical load.

Small industries could be different kinds of workshops, gas filling stations and process industries. Loads could consist of welding equipment, induction motors for different applications controlled by frequency converters or by a direct start. A majority of the larger loads are connected to all three phases and an unbalanced load would most certainly not be as prominent as the other three categories. Induction machines could also be direct connected with an eventual voltage dip as a result.

An office area consists mostly of computers, computer screens, UPS, printers and fluorescent lights. Most of these units have a switched power source and are connected to a single phase that result in a more or less unbalance and third harmonic.

Rural areas are mostly connected to weak parts of the grid that might result in large voltage deviations and voltage harmonics induced due to their high impedance related to a city area. Large parts of the consumers on rural areas are farms and other large buildings. They often have equipment with high power demands that could have a negative influence on the weak grids and therefore the voltage quality.

4.1.Measurement equipment

For a measurement to be acceptable according to EIFS 2013:1 it should be measured according to SS-EN 61000-4-30. Therefore all equipment used in this thesis is classified according to category A in SS-EN 61000-4-30. Category A is classified as a reference instrument and should all perform within a certain limit. Both measurement equipments also measured flicker which lies outside of SS-EN 61000-4-30 and active power, reactive power, DPF and TPF.

The equipment is connected with current clamps on the three phases. Three voltage probes are connected to the phases and one voltage probe to the PEN-conductor. Certain parameters can be chosen in how the measurement device should trigger on incidents and for how long they should be recorded. Both devices save every average 10 minute value on power quality parameters in normal conditions. In case of a change outside the given regulations the system triggers and momentarily logs values and waveforms. Both units creates reports according to EIFS 2013:1 and SS-EN 50160 of the measurement for a faster analysis and to directly show deviations.

The first measurement on Kraftringens office the internal memory was used and downloaded from the measurement device Unilyzer 900 from Unipower for analysis. The other two measurements were recorded live and synced from the measurement device Metrum SC to a measurement server via mobile phone network for analysis. Both devices comes with a software that helps to analyse and interpret the raw measurement data in to useful information. Technical details of devices can be seen in appendix 8.1 and 8.2.

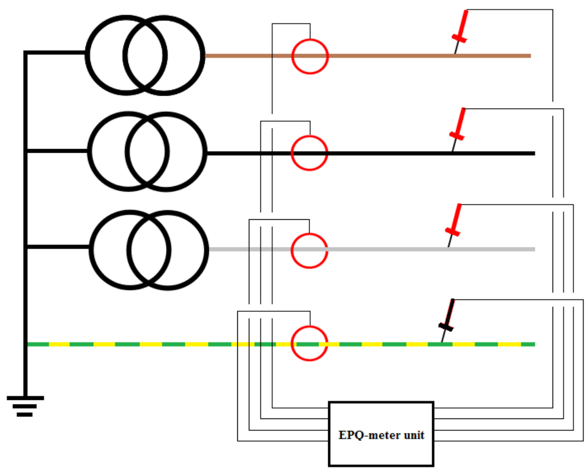

Figure 6 - Electric power quality meter connection scheme. Measurements on current in PEN-conductor was not performed.

Figure 7 - Measurement equipment on a substation supplying a larger building. Metrum SC device to the left. Current clamps on transformer supply to the right.

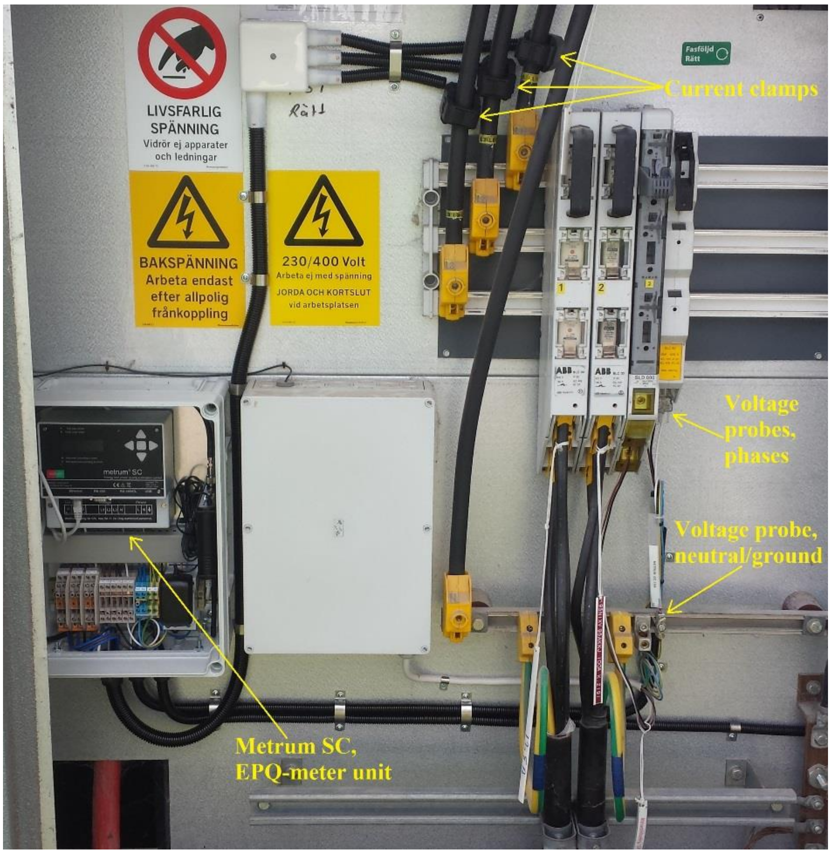

Figure 8 - Measurement equipment on a rural substation.

4.2.Measurement on an office building

Kraftringens office in Lund is a fairly new build building and represents the typical office environment. A large part of the typical load in Lund consists of offices and it is therefore appropriate to get a perception on the typical office behaviour on the electrical grid. Kraftringens building layout is considered to represent the typical office building but with a greater opportunity to analyse the causes of different aspects than other buildings due to better access. The building is relatively new from 2008 with modern technical equipment as dimmable fluorescent light, motion sensors and solar cells on total 5 kW. The building is heated by district heating and cooled by local placed cooling units. Measurements were conducted during two weeks from 2015-01-30 to 2015-02-13 with one major event in form of a backup generator test. Measurement equipment consists of Unilyzer 900 from Unipower connected to the three-phase input to the building measuring according to category A of SS-EN 61000-4-30. All measures were accepted according to EIFS 2013:1 with one exception from the backup generator start that resulted in a voltage dip.

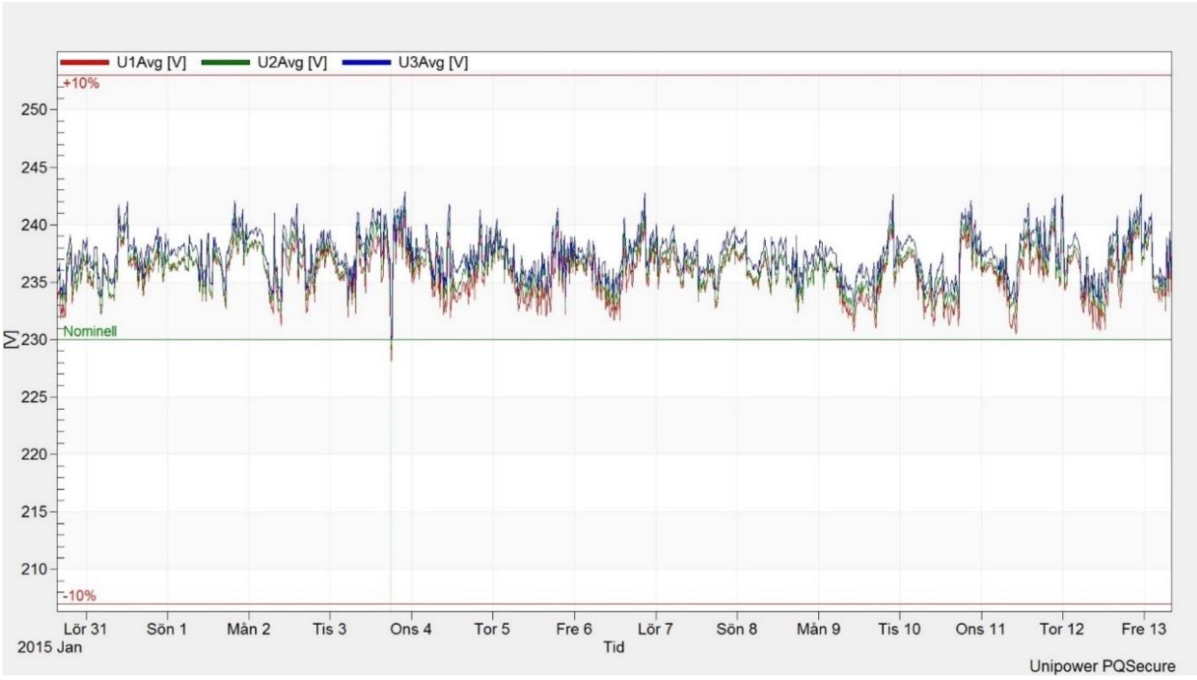

Figure 9 - Voltage level during measurement on Kraftringens office

The voltage level is somewhat higher than nominal voltage level, approximately 2-5 % over nominal voltage. Maximum voltage was 242.9 V in one phase and lowest voltage was down to 131.9 V in one phase but it occurred during the test of a backup generator the 3th of February. Besides this test the voltage was at its lowest around nominal voltage 230 V. Voltage is lowest during work hours and highest during nights and weekends with lower load but within the limits of 207-253 V. The solar cells does not seem to have any influence on the voltage level at those rather low radiation levels during the measuring period. Highest radiation levels occurred during noon on 8th and 9th. Worth mentioning is that the office is close to the substation transformer at approximately 80 meters which in turn is close to the distribution substation.

The voltage unbalance is well within given limits with a minimum at 0.15 % and a maximum at 0.43 %. At office hours the unbalance rise from 0.2 % up to around 0.4 % due to the increased use of single-phase equipment like computers, printers, screens and lights.

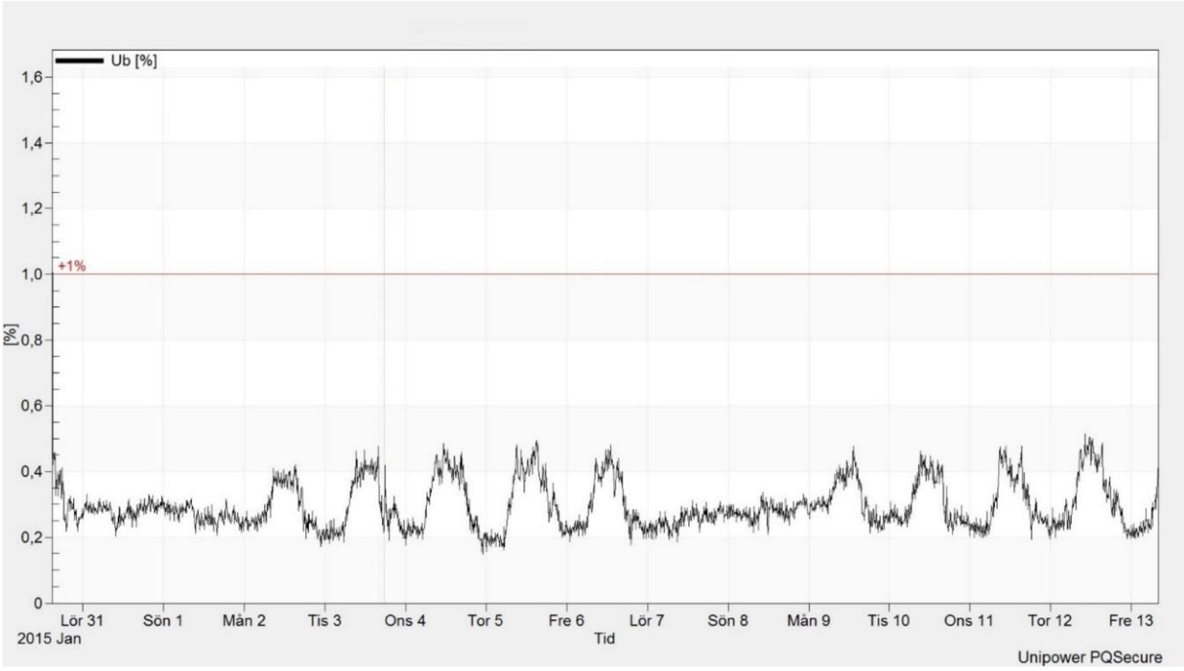

Figure 10 - Voltage unbalance during measurement on Kraftringens office

As can be seen below in figure 11 the current in phase 3 is always lower than phase 1 and 2 during nights and weekends that is one reason to the lower value on voltage unbalance at 0.2 %. During office hours phase 1 rises above phase 2 that could be one reason behind the larger unbalance up to 0.4 %. A majority of the voltage unbalance will most likely be due to interleaved non-symmetric currents with other loads. Lowest current are drawn during weekends on phase 3 of 18 A compared to phase 1 using 27 A. Maximum value occur during work hours with a peak of 127 A on phase 1 compared to phase 3 of 100 A.

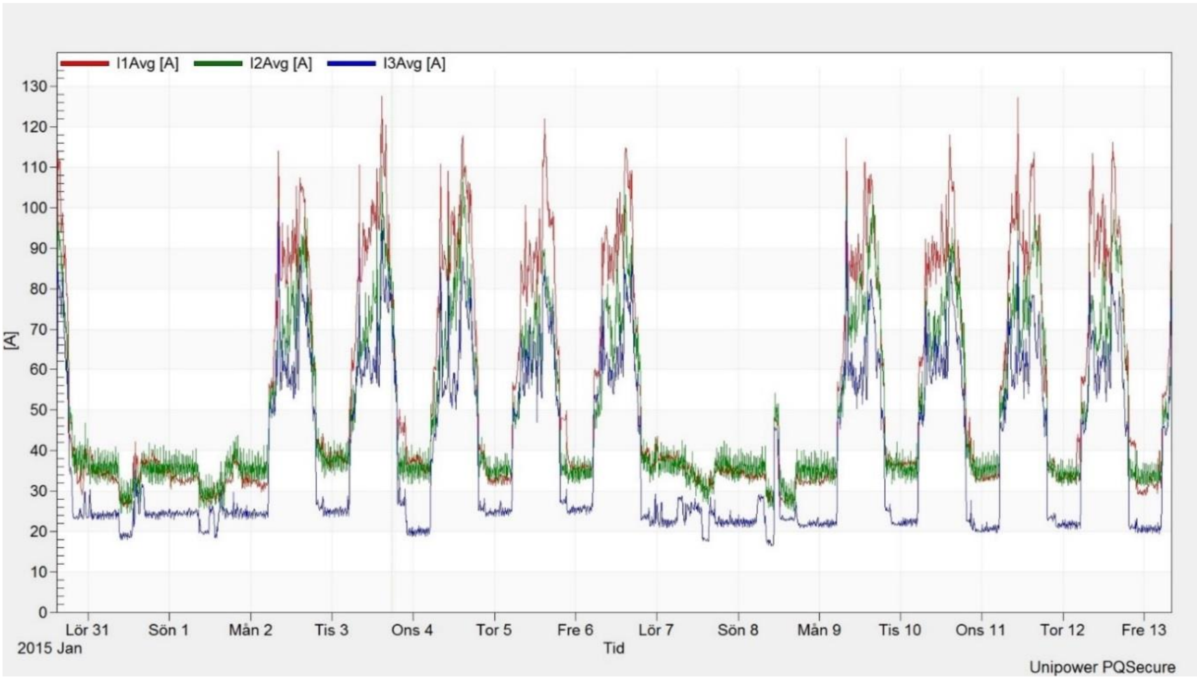

Figure 11 - Currents during measurement on Kraftringens office.

Active and apparent power follow the same pattern as current as expected since they are proportional. Power measurements indicate a capacitive power factor (negative QTot) during most part of the time when the opposite was expected and can therefore be seen as a slightly capacitive load. During the weekend the reactive power amplitude increases at the same hours that the active power reduces. This capacitive power factor could occur due to the use of low energy light bulbs that use a shunt capacitor. This could not be the only reason since the reactive power amplitude is not significantly lower during nights with no current flowing through the bulbs. The TPF is still close to unity in average 0.97 capacitive while the DPF is slightly higher at 0.99 capacitive. This difference is as mentioned due to harmonics.

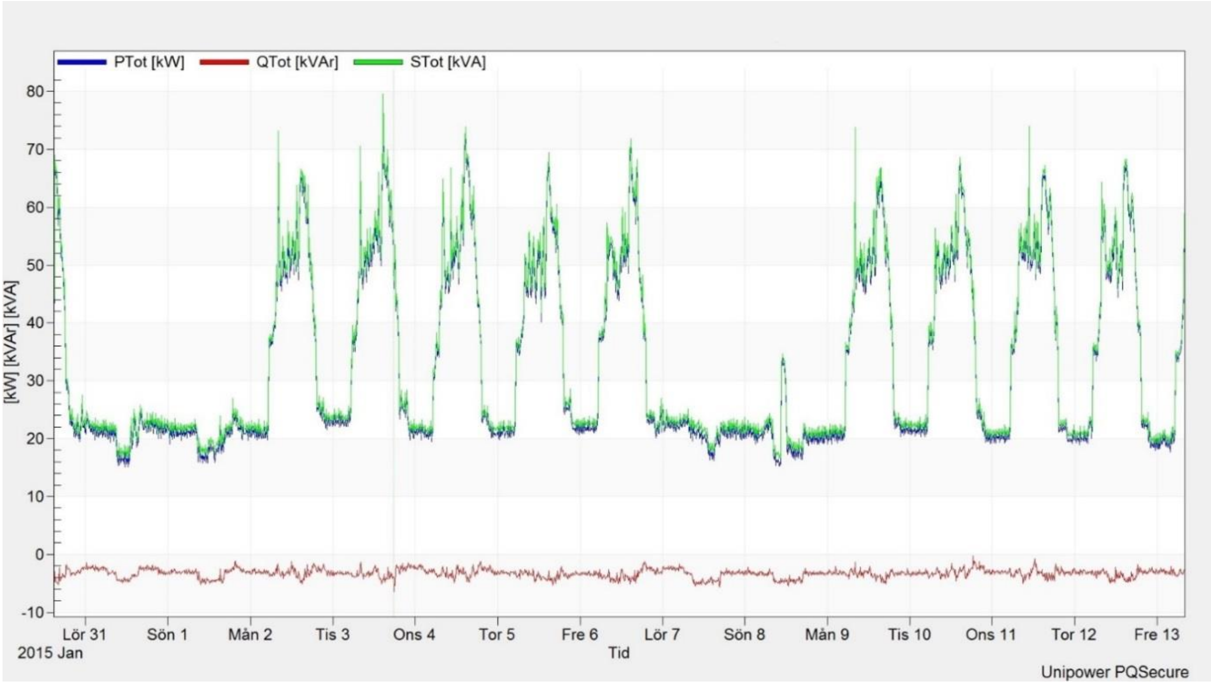

Figure 12 - Active, reactive and apparent power during measurement on Kraftringens office

Total harmonic distortion on voltage is as expected at its highest values during working hours and lowest during nights and weekends. Maximum values are obtained on the highest loaded phase 1 with about 2.3 % compared to 2.1 % on phase 3 and 2.05 % on phase 2; the peak at Tuesday 3th is not taken in account because of the backup generator start. These values are way within the given limit of THD_v (8 %) according to EIFS 2013:1. Since THD_v do not follow the same pattern as THD_I this can be linked to the low impedance grid and the THD_v will consist of interleaved currents from other nearby loads.

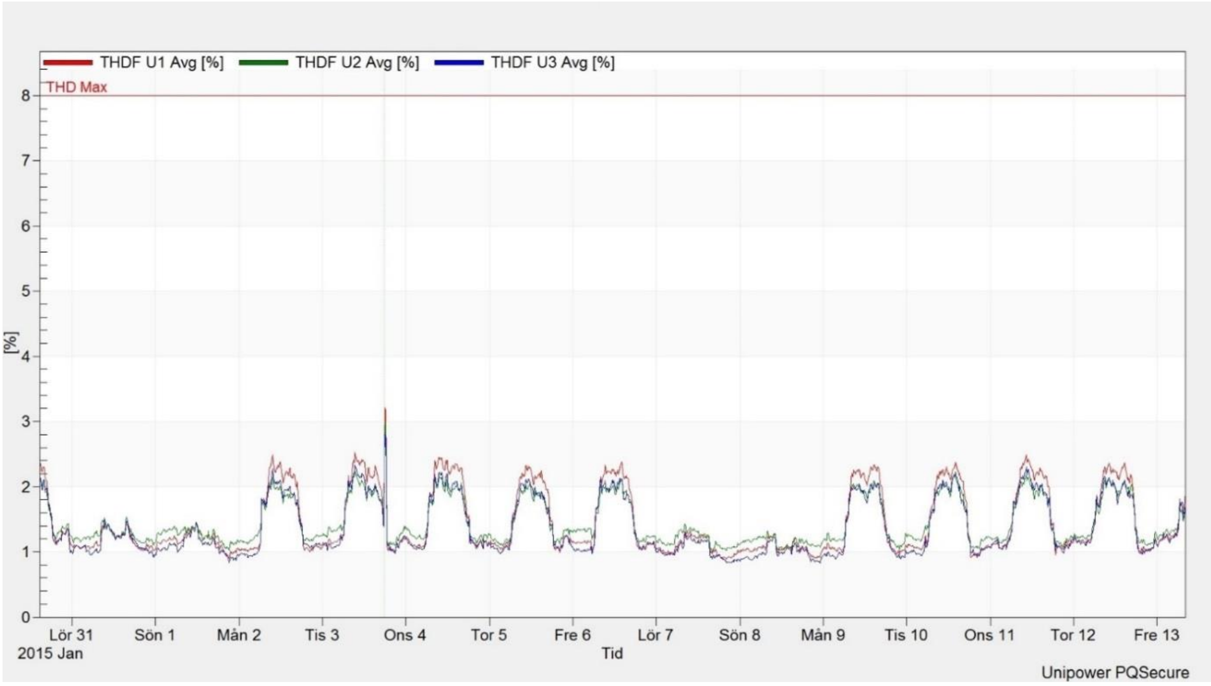

Figure 13 - THD on voltage during measurement on Kraftringens office

Total harmonic distortion on current is at its highest values during weekends and nights compared to voltage were it is at its highest during working hours. This is quite misleading because the total current is low but with high THD_I outside office hours and will most likely not affect the voltage quality. On office hours with high load, phase one has significantly lower THD_I than the other phases indicating more linear loads connected to phase 1 since that phase also is the most loaded.

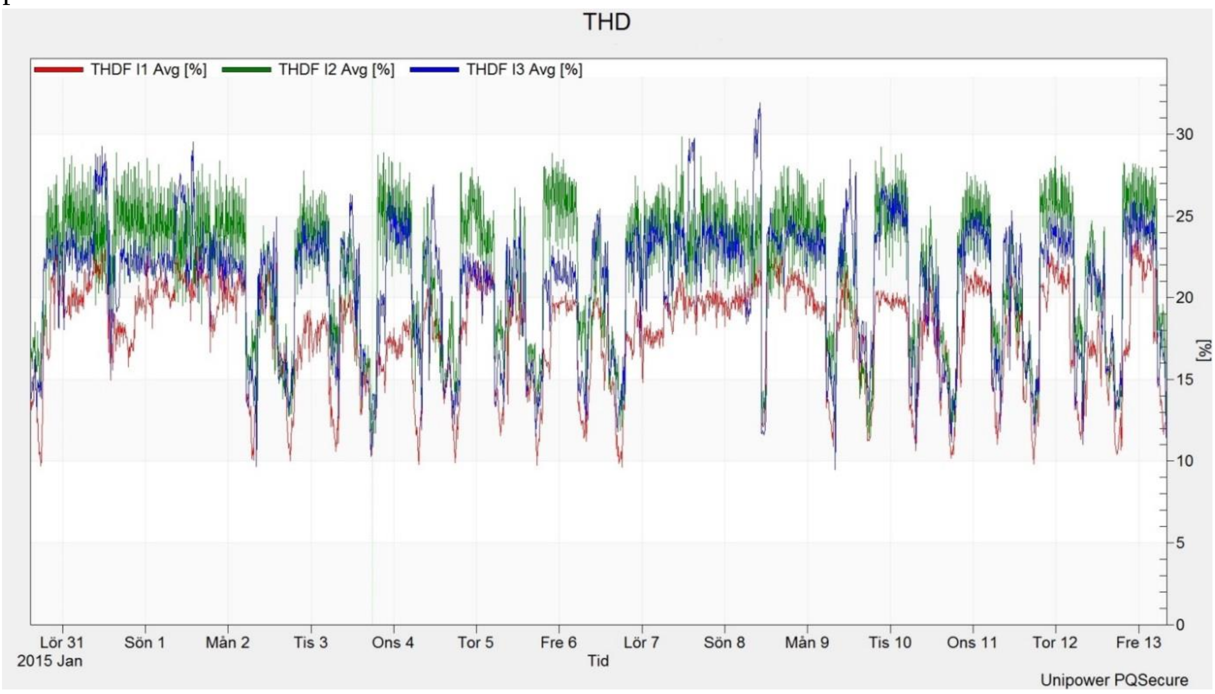

Figure 14 - THD on current during measurement on Kraftringens office

The third, fifth and seventh harmonic on phase 2 with the highest THD_I can be seen in figure 15 below. It shows that the three most prominent harmonics is lower during nights compared to days compared to THD_I were the opposite was registered, this gives therefore a better representation of the current harmonics. As expected the third harmonic represents a large part of the THD_I. A large increase can be seen during working hours when there are an increased amount of single-phase loads. The solar cells does not seem to have any larger impact on the current harmonics at those low radiation levels.

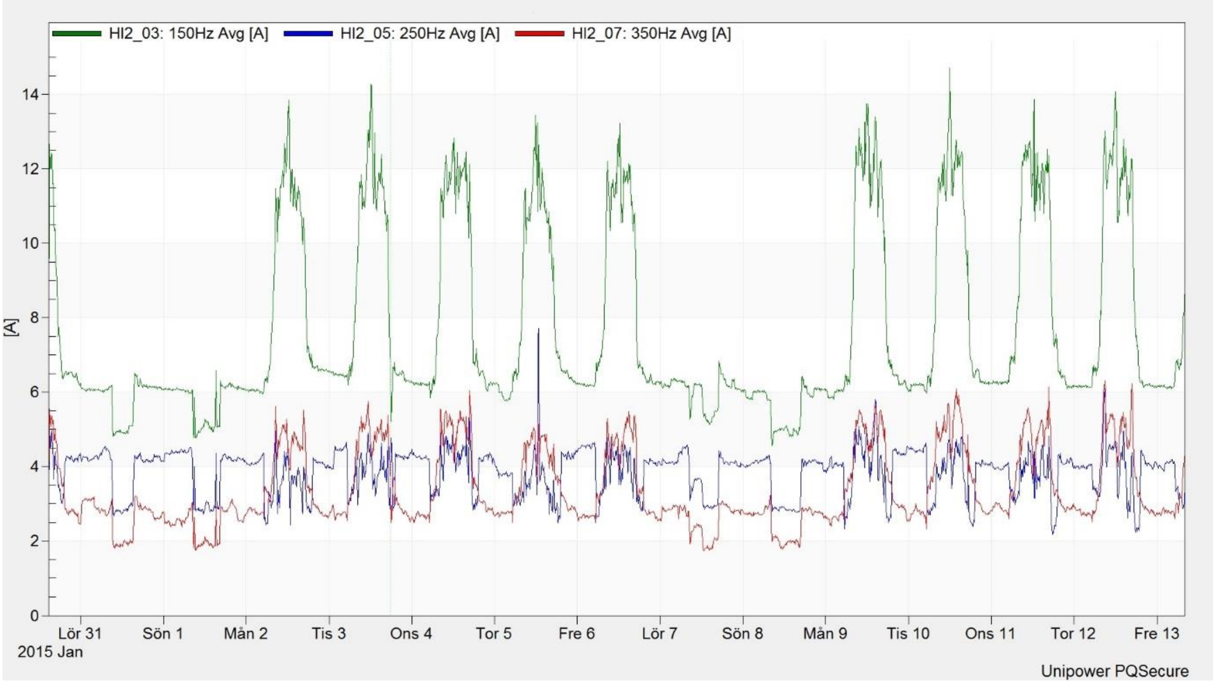

Figure 15 - 3, 5, 7 harmonic on current during measurement on Kraftringens office

When studying the individual harmonics the average value during the measuring period of all the logged average 10 minute values are used both on voltage and current.

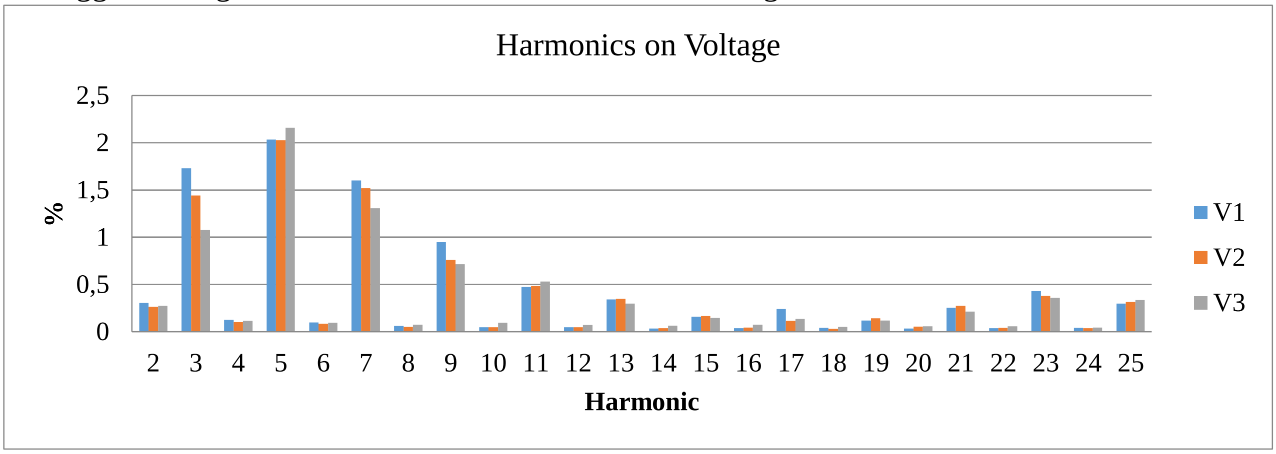

Figure 16 - Average harmonic on voltage during measurement on Kraftringens office

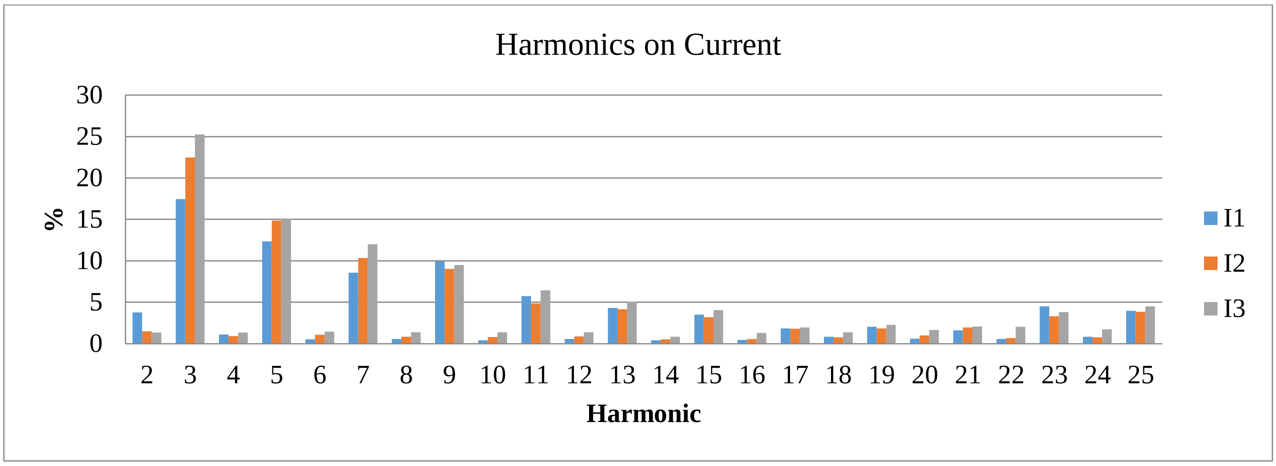

Figure 17 - Average harmonic on current during measurement on Kraftringens office

On voltage harmonics the fifth followed by the seventh and third are the largest most likely due to interleaved current harmonics from other loads that affect harmonic levels on voltage since the same pattern cannot be seen on the current. But with the current harmonics the highest values are obtained from the third followed by the fifth as expected due to the high amount of single-phase loads.

4.3. Measurement on substation feeding a larger building

A second measurement was conducted on a two year old building consisting of 19 floors housing a hotel, offices among other businesses in Lund. Measurement equipment was set up in the substation that only feeds that particular building with heating and cooling excluded from that substation. This building is supposed to give a good comparison with the other measurement on Kraftringens office due to their typical load, working hours, location and that both have solar cells installed. Total amount of installed solar cell power is larger here at 105 kW.

On this measurement another electric quality meter was used from the company Metrum with the model SC. This model is also in category A according to SS-EN 61000-4-30 like that meter used in Kraftringens office and should therefore be comparable. Measurement data were collected during the period of 2015-04-08 to 2015-04-15 to give the weekly values according to EIFS 2013:1.

The voltage level in this measurement was slightly over nominal like that on Kraftringens office. About 2-5% over-voltage but well within the given limits of 207-253 V. The voltage decreased during the weekend on 11th and 12th of April most likely due to tap-changer movement because a lower loaded grid during weekends. The same pattern as on Kraftringens office with higher voltages during nights and weekends cannot be seen as prominent here. Instead the voltage drops during the weekend when the load is lower compared to office hours. However, this load is at least twice as large as the first measurement on Kraftringens office. The solar cells does not seem to have any visual impact on the voltage level here either during this type of weather were maximum radiation levels occurred during 10th.

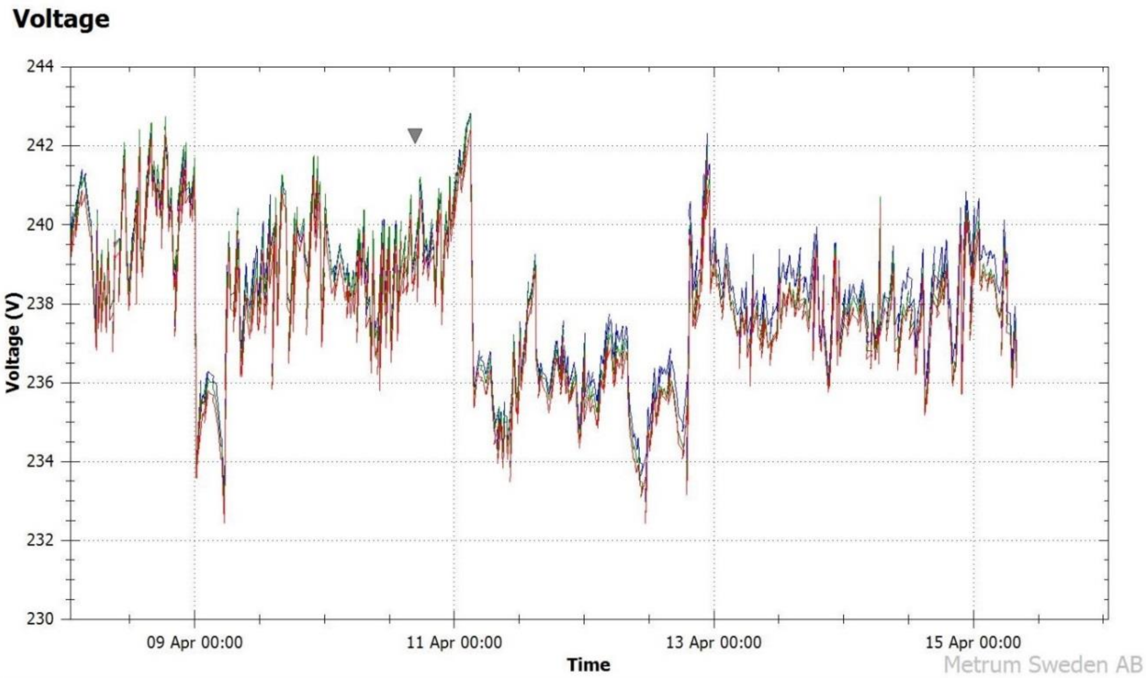

Figure 18 - Voltage level during measurement on large building substation V1=Red,V2=Green,V3=Blue

During the measurement one voltage dip was noticed on phase 3 that could be derived to the grid above because the current on the same phase did not increase rapidly during the dip. If it would have been located to the building it would most likely have logged a current rush in the same phase that would have created the voltage dip. Further analysis is not considered since it most likely could be derived to the grid above and therefore falls outside this thesis.

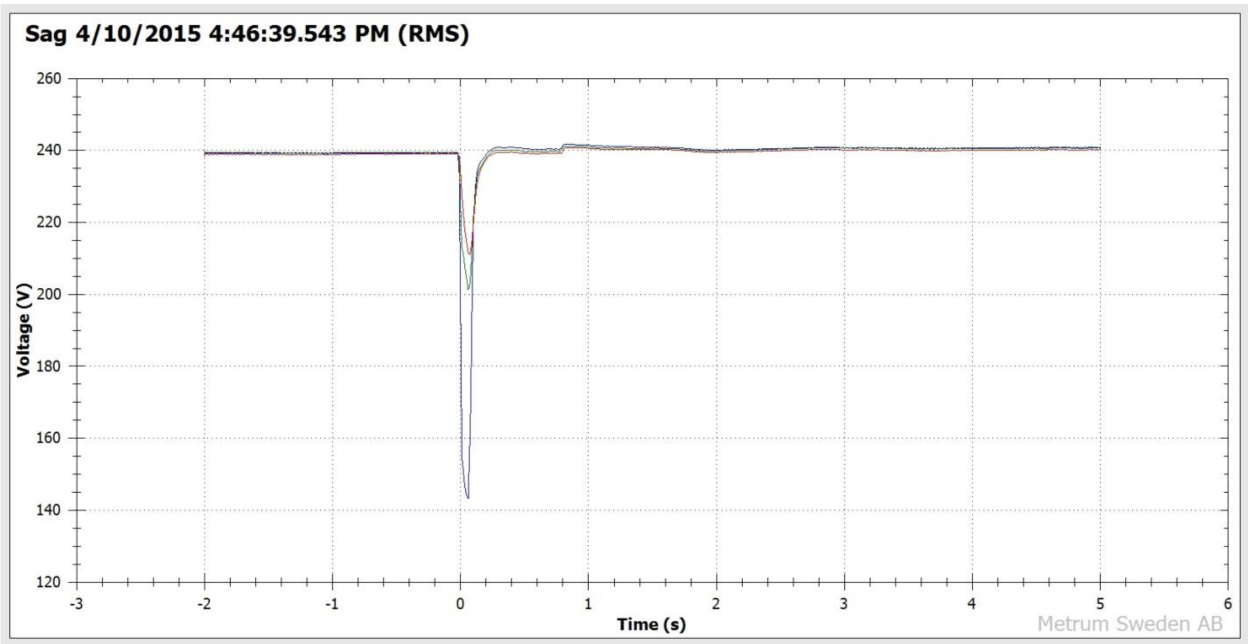

Figure 19 - Voltage dip during measurement on large building substation. V1=Red,V2=Green,V3=Blue

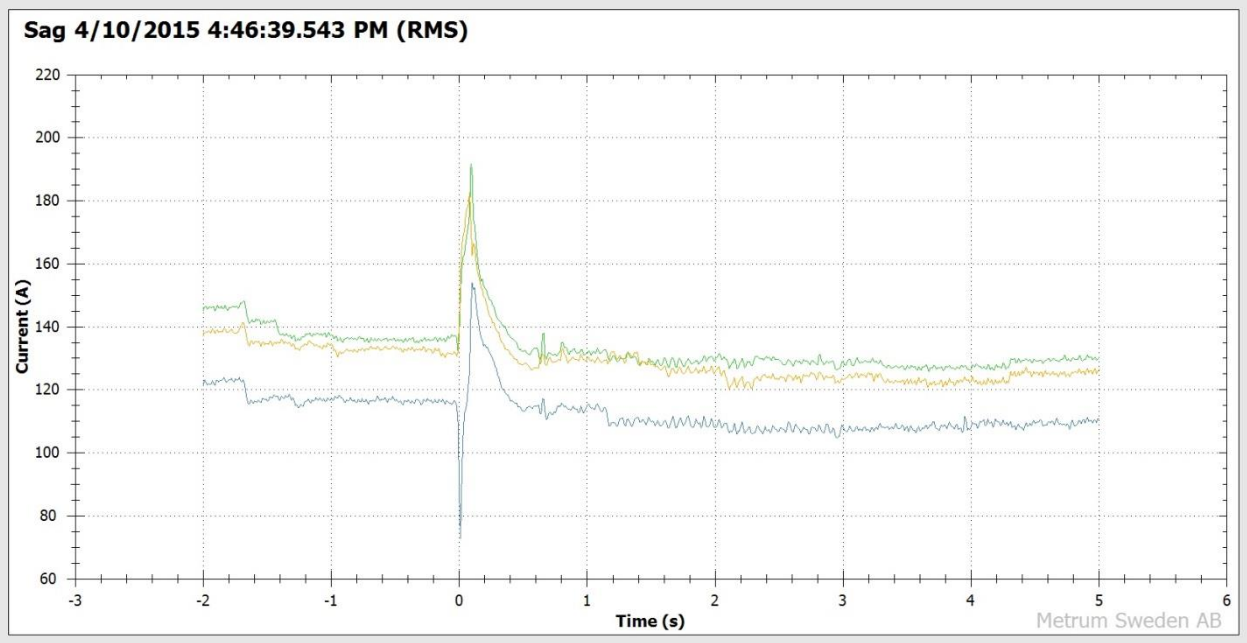

Figure 20 - Current during voltage dip on large building substation. I1=Yellow,I2=Green,I3=Blue

Unbalance is slightly better on this measurement but it does not follow the same pattern as former measurement with better average during nights and weekends. This pattern could arise because of the hotel with activity outside of office hours but the value is still well within given limits of 2%.

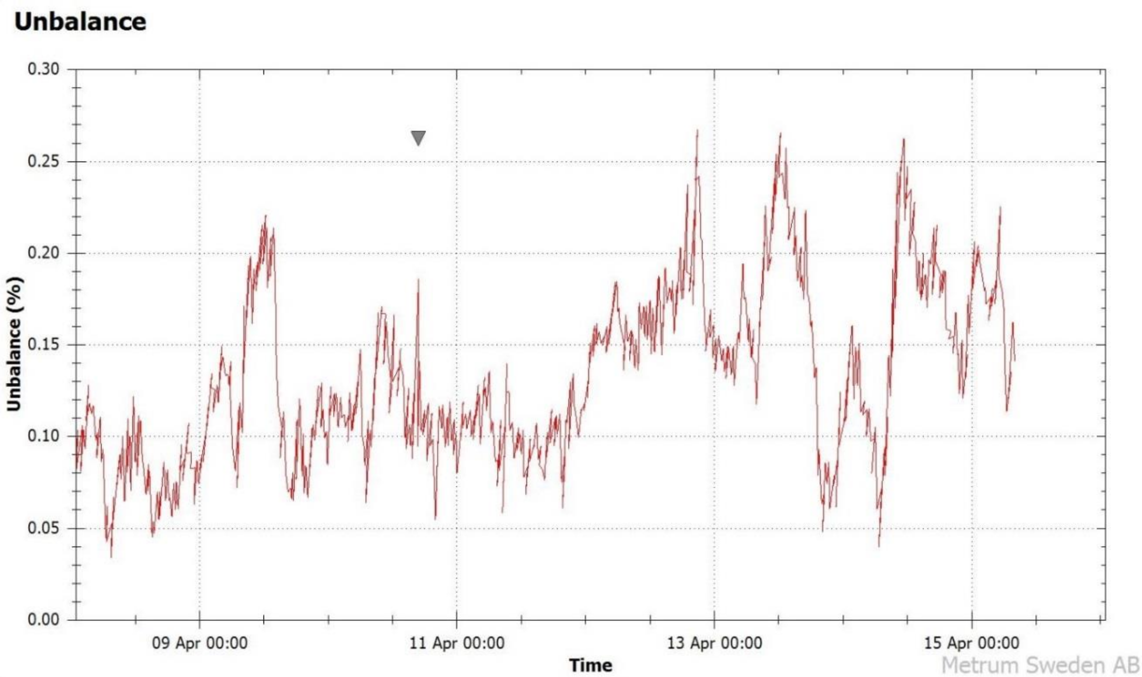

Figure 21 - Voltage unbalance during measurement on large building substation

Current follows the expected shape with higher values during working hours and lower during nights and weekends. One increased value on the night 11th April was detected perhaps due to some event on the hotel. This measurement shows that the third phase is the least loaded like the measurement on Kraftringens office.

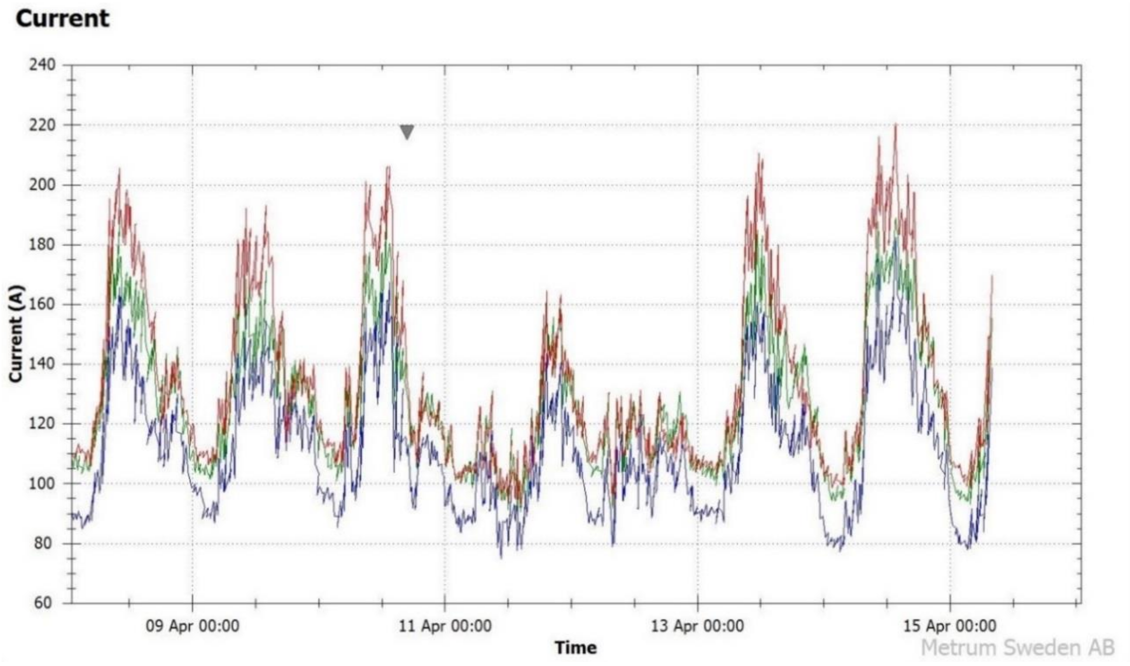

Figure 22 - Currents during measurement on large building substation. I1=Red,I2=Green,I3=Blue

A capacitive power factor can be seen due to the negative amount of reactive power just like the measurement on Kraftringens office. The average value on TPF was 0.98 and the average value on DPF was 0.99. Lowest average 10 minute value on TPF was down to 0.94 capacitive. It strengthens the theory that the typical office buildings are a capacitive load although close to a unity power factor. The reactive power does not follow the same pattern as previous measurement. There is an increase during working hours and minimum level during nights. This pattern shows the expected behaviour from the capacitive power factor from fluorescent light and low-energy light bulbs creating higher reactive amplitudes during working hours compared to nights.

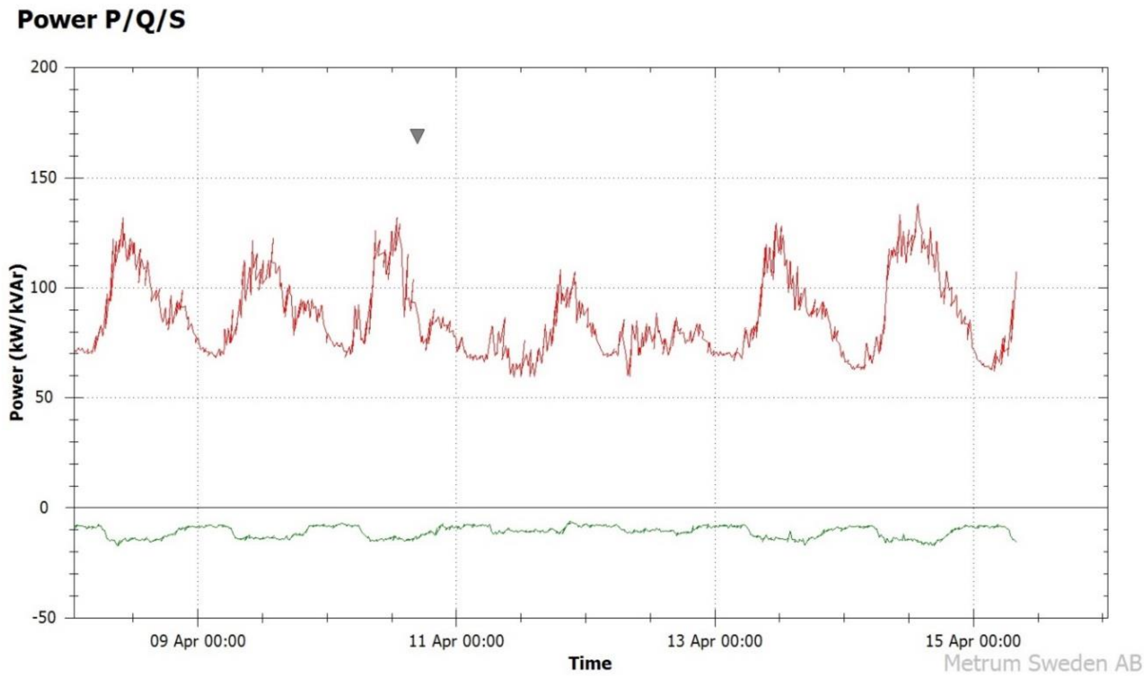

Figure 23 - Active and reactive power during measurement on large building substation. Active=Red, Reactive=Green

Total harmonic distortion on voltage is well within given limits (8%) with highest values on phase 3. THD_v follows the typical nights and weekend behaviour as expected like previous measurement on Kraftringens office. Phase 3 with highest THD_v is the least loaded conductor and that could be the result of three reasons. Either the loads connected to that phase in the building emit high amounts of current harmonics or that the voltage harmonics are from the grid above or a combination of these two. From the other measurement on Kraftringens office the conductor with highest load also contained the most THD_v.

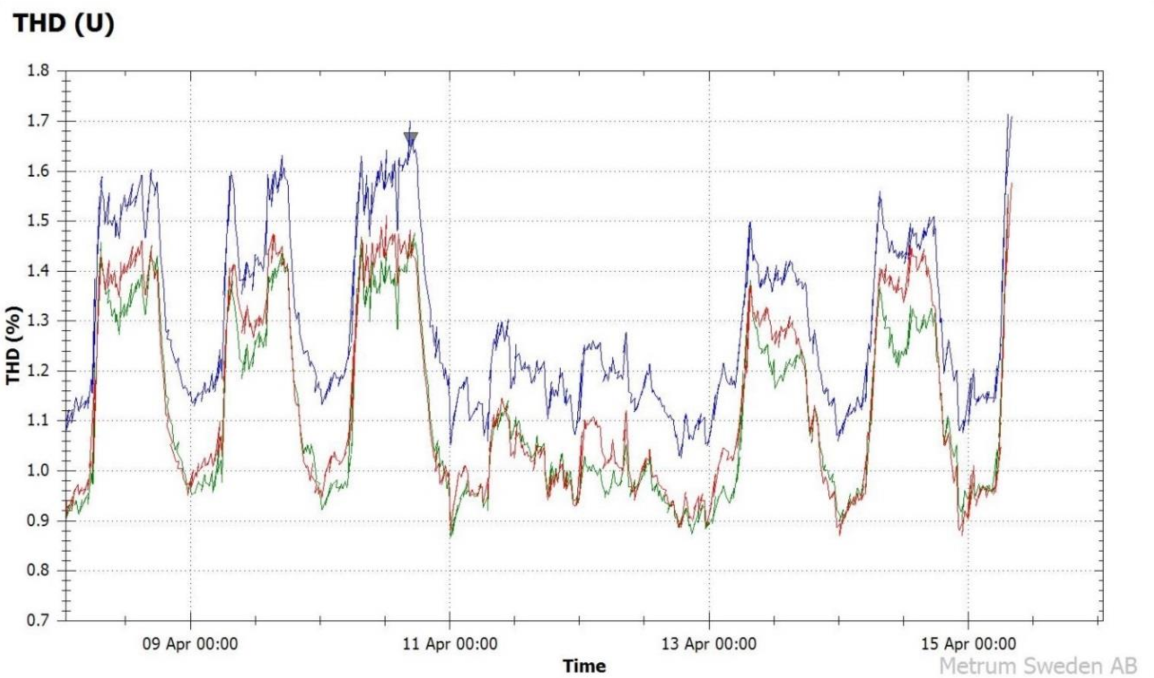

Figure 24 - THD on voltage during measurement on large building substation.V1=Red,V2=Green,V3=Blue

THD_I is in the same range as measurement on Kraftringens office but shows a pattern more affected by the load. This could be the result of that the loads connected during nights and weekends perform like those during working hours when it comes to current harmonic emissions. Since THD on current could be quite misleading the three most prominent harmonics on current from phase three with the highest THD_I is shown in figure 26. The higher value on THD_I on phase 3 could be because that phase also has the highest THDv resulting in that the devices connected to that phase performs worse than the others.

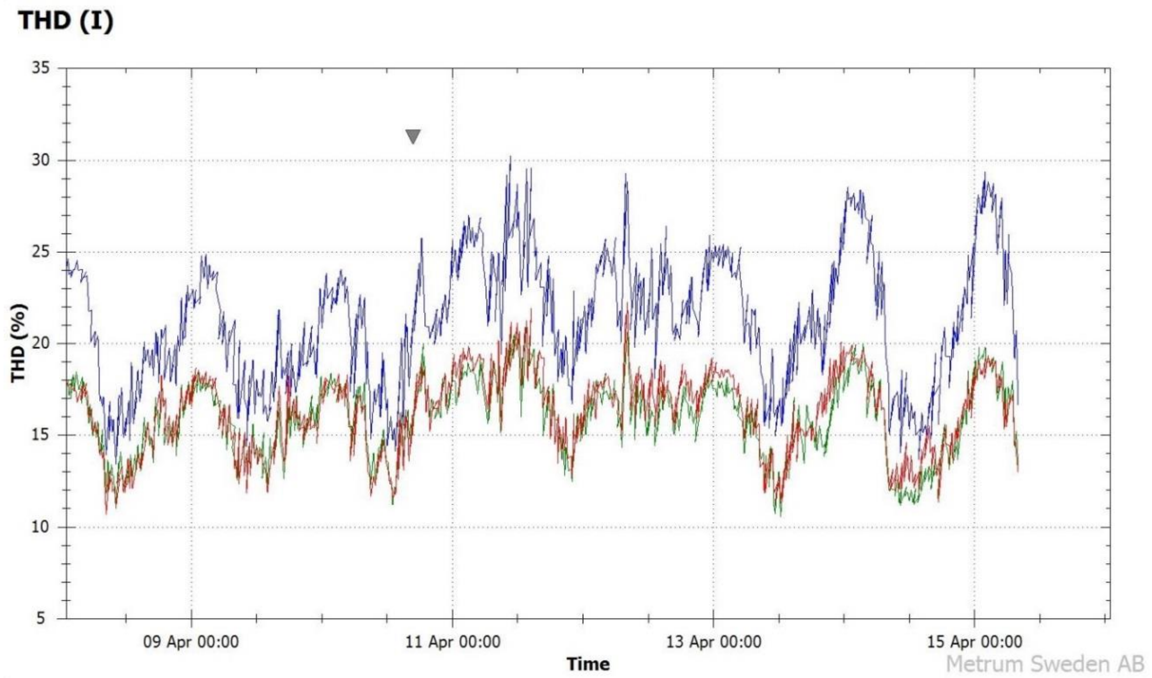

Figure 25 - THD on current during measurement on large building substation I1=Red,I2=Green, I3=Blue

Here the third and fifth harmonic on current are within the same range unlike the measurement on Kraftringens office. The other two phases show the same type of behaviour like the measurement on Kraftringens office were the third current harmonic is the largest. The fifth harmonic is larger on the phase three shown in figure 26 compared to the other two were it is more close to the seventh harmonic. The solar cells does not show any differences on the fifth and seventh current harmonics on the 10th when the highest levels of radiation were obtained.

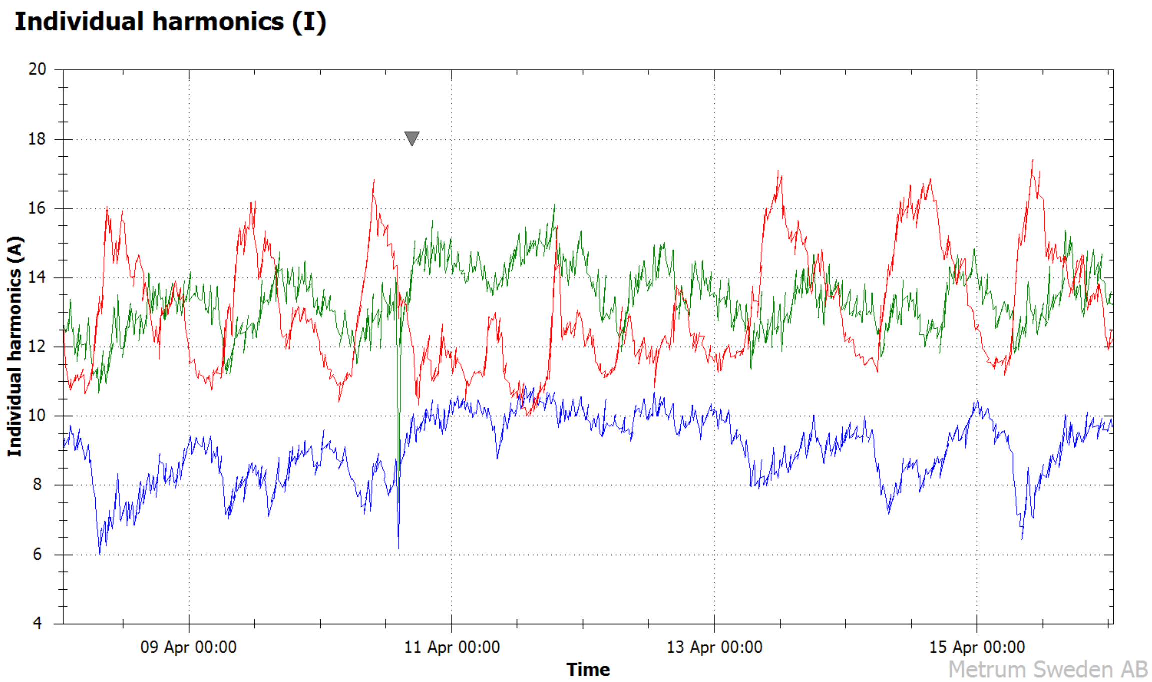

Figure 26 - 3, 5, 7 harmonic on current on phase 3 during measurement on large building substation H3=Red, H5=Green, H7=Blue

When studying the individual harmonics the average value during the measuring period of all the logged average 10 minute values are used. Individual harmonics differs somewhat from the previous measurement mostly by lower values. The third voltage harmonic is not as prominent as expected perhaps due to the slightly lower value on the third current harmonics, almost half the value from previous measurement.

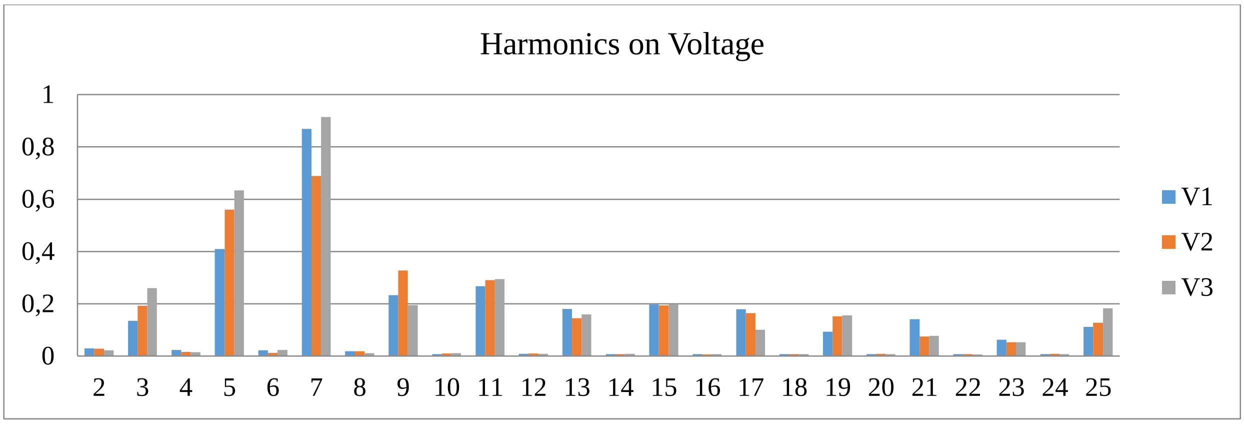

Figure 27 - Average harmonics on voltage during measurement on large building substation

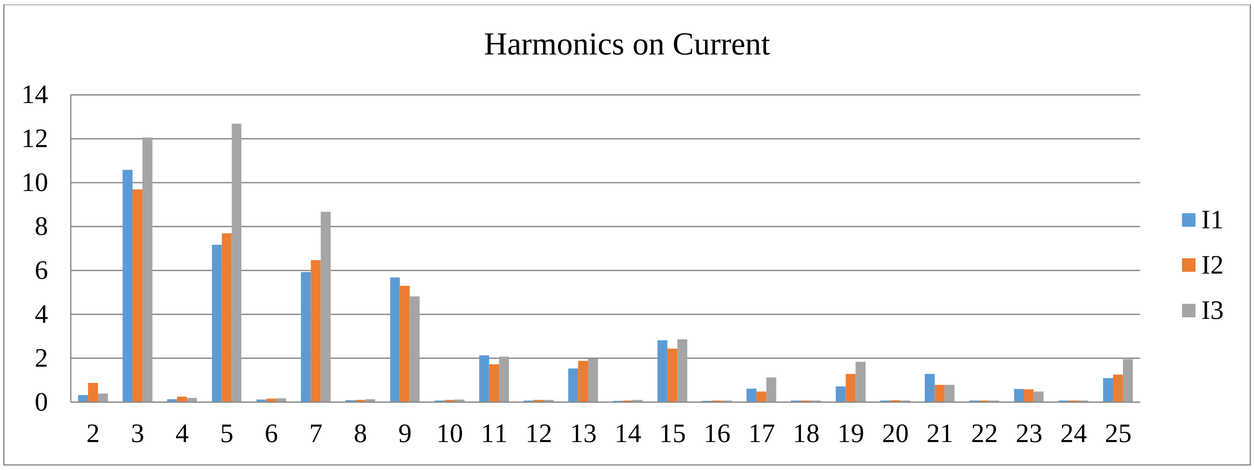

Figure 28 - Average harmonics on current during measurement on large building substation

4.4.Measurement on rural substation

The previous two measurements have been conducted in typical urban environment and a representation of the more rural areas is needed. The chosen substation is located a long distance from the distribution substation and consists of long low voltage cables after the substation transformer. Complaints have been received from residents supplied from this substation with regard to voltage levels.

Measurements were conducted during 2015-04-08 to 2015-04-15 with the electric quality meter from Metrum with the model name SC performing according category A from SS-EN 61000-4-30. Measurements were conducted during one week to enable evaluation according to EIFS 2013:1. Measurement with this type of equipment gives accurate values that can be compared with other equipment from category A.

The voltage level as mentioned have been a problem in this area and as can be seen the voltage level is at average lower compared to that in the urban areas, deviation about 15 V. Here the voltage deviation from night compared to day can be seen more prominent unlike in the substation supplying the larger building. The voltage is within given limits of 207-253 V on the substation but the limits are given at consumers connection point and a slight voltage drop is expected leading to a voltage level under nominal.

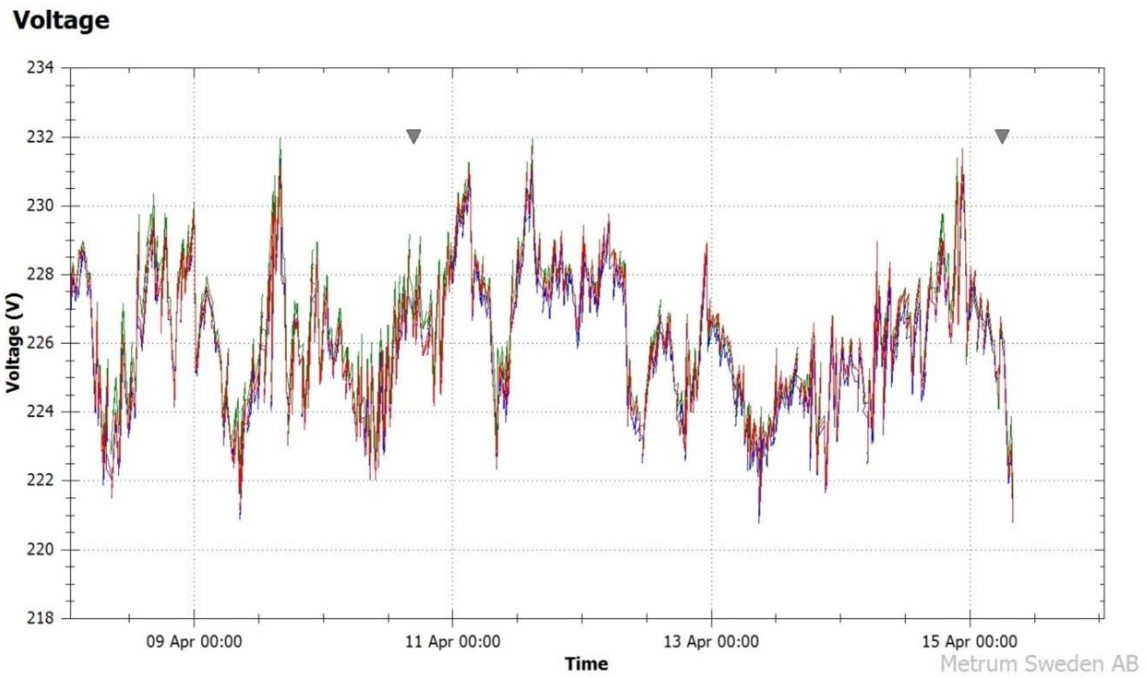

Figure 29 - Voltage level during measurement on rural substation.V1=Red,V2=Green,V3=Blue

One voltage dip was registered during measurement on mainly the phase 2 (green). This could be linked to some sort of incident on higher voltage level since the current also dropped (green). This was most certainly not an incident caused by high sudden current increase and will not be investigated any further.

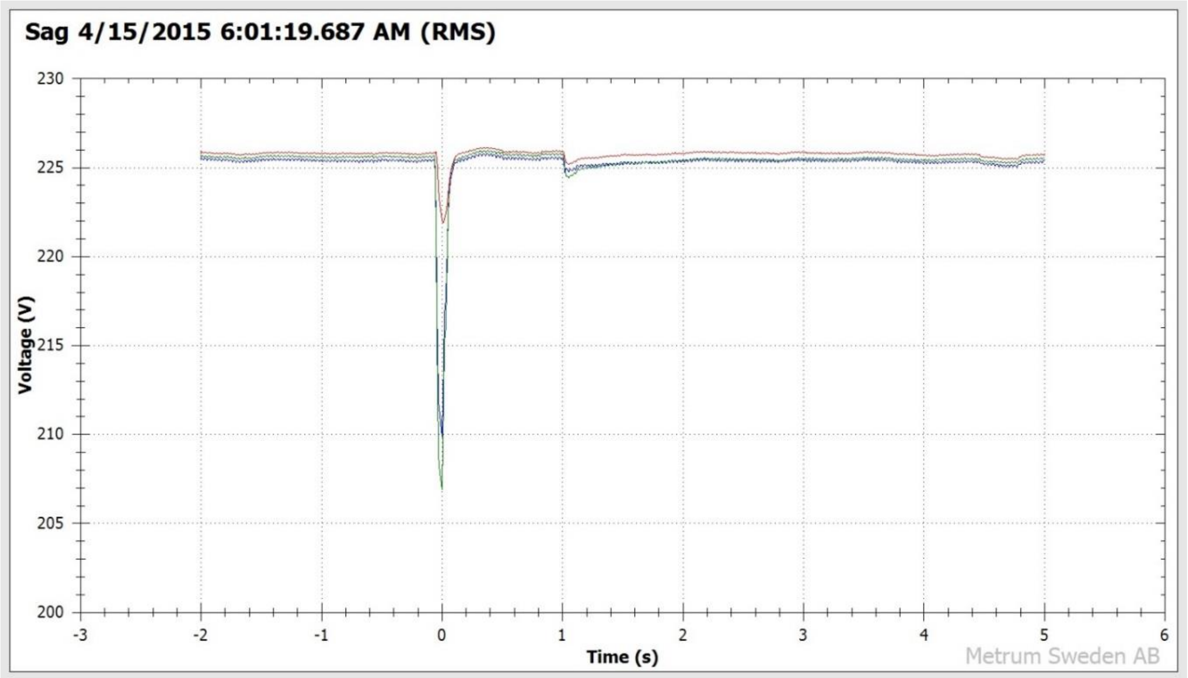

Figure 30 - Voltage dip during measurement on rural substation.V1=Red,V2=Green,V3=Blue

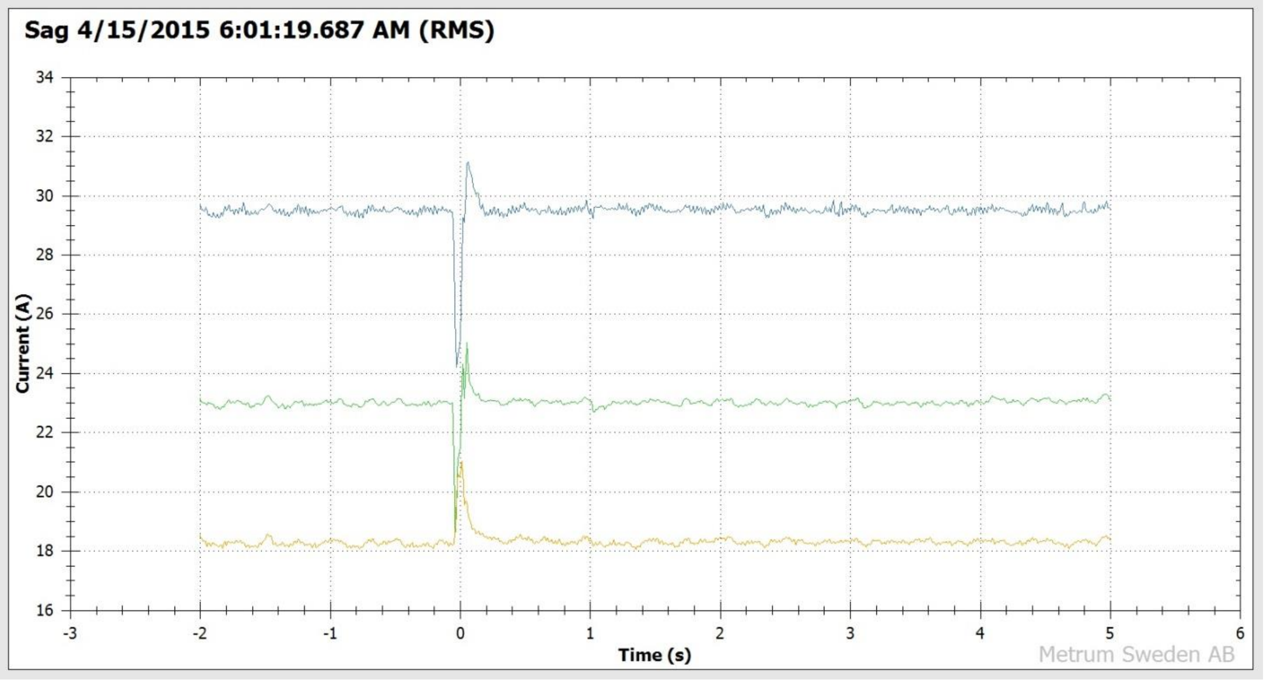

Figure 31 - Current during voltage dip on rural substation. I1=Yellow,I2=Green,I3=Blue

Unbalance is well within given limits (2 %) and slightly lower than the other measurements. Perhaps because the total amounts of loads are smaller and a larger part of those loads are connected to all three phases.

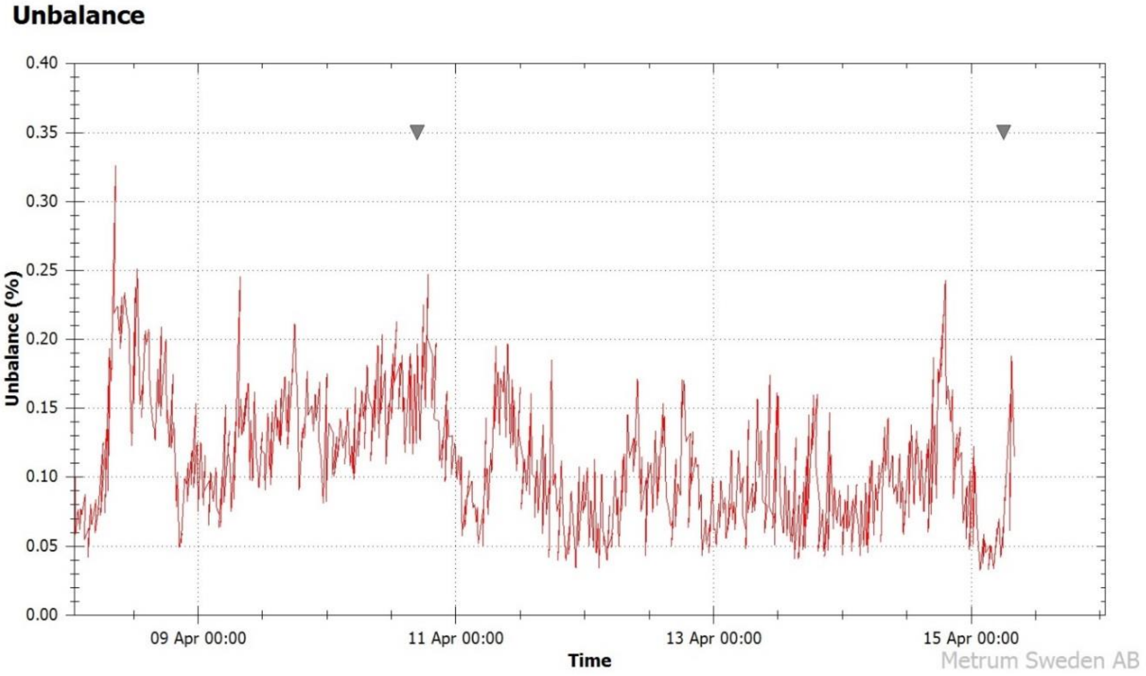

Figure 32 - Voltage unbalance during measurement on rural substation

Current have a more constant behaviour than the previous two measurements but it involves a current peak of twice or more of the normal current level each morning sometime between 08:00 to 10:00 on all three phases. Perhaps this is because the start-up of some sort of processes e.g. a large induction motor. Even though those peaks are large in amplitude it does not influence the voltage enough to deviate from ± 10 % of 230 V.

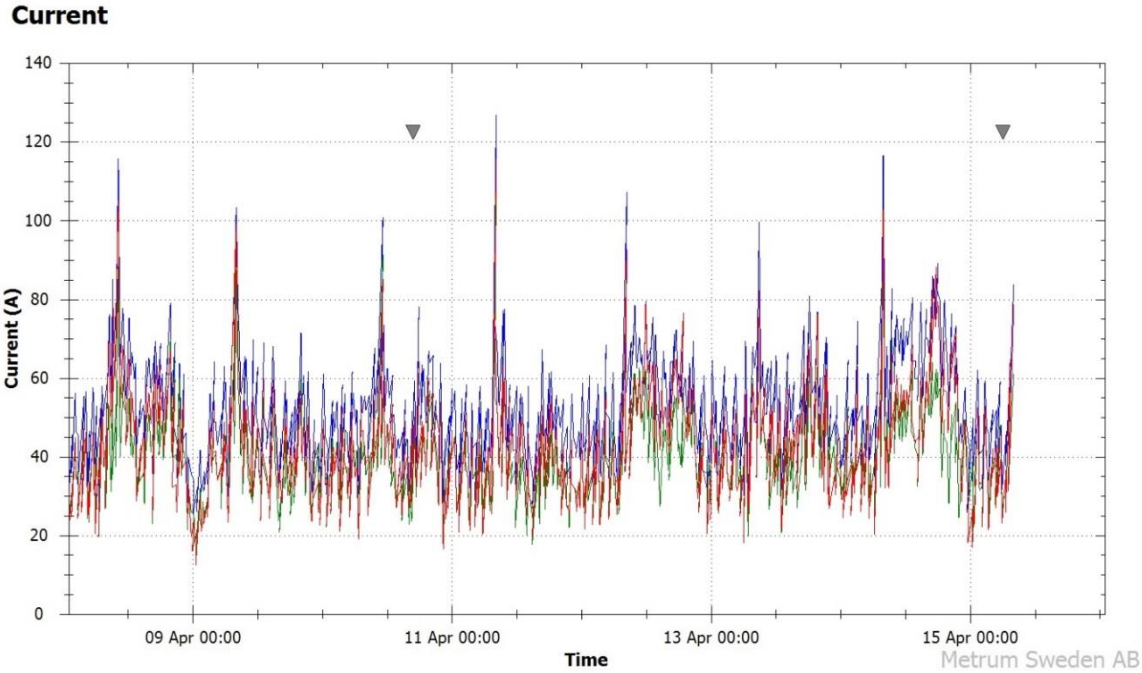

Figure 33 - Currents during measurement on rural substation.I1=Red,I2=Green,I3=Blue

When studying active and reactive power it shows that both peaks at the same time as the current. That strengthens the theory of the start of an induction motor which has a low inductive power factor in the start to magnetizing the motor coils. Unlike the office measurements the load has an inductive power factor with a TPF on average at 0.89 and a DPF on average at 0.90 which represents the old typical load. The load variations are quite large and with higher frequencies compared to the other two measurements perhaps to a smaller amount of loads making the current less interleaved.

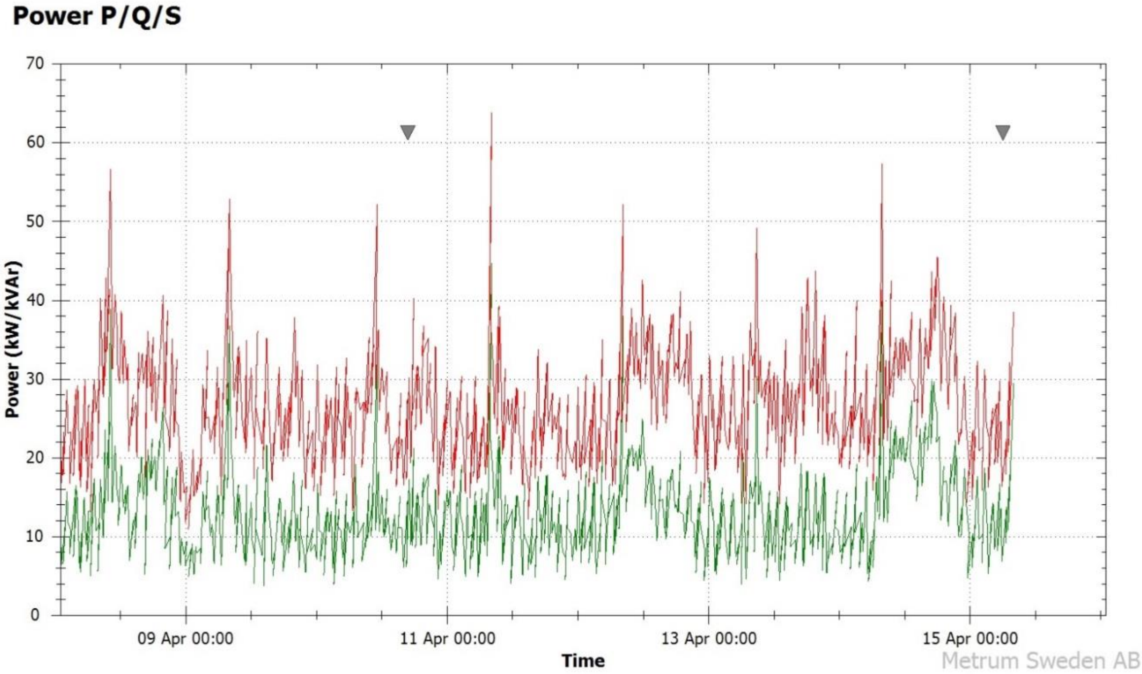

Figure 34 – Active and reactive power during measurement on rural substation. Active=Red, Reactive=Green

Total harmonic distortion on voltage follow the more typical work hours and weekend behaviour that could be derived from the grid above. Even though the grid is weaker the load does not seem to influence the THD_V as much as expected. THD on voltage is well within given limit (8 %) and around the same value as previous two measurements.

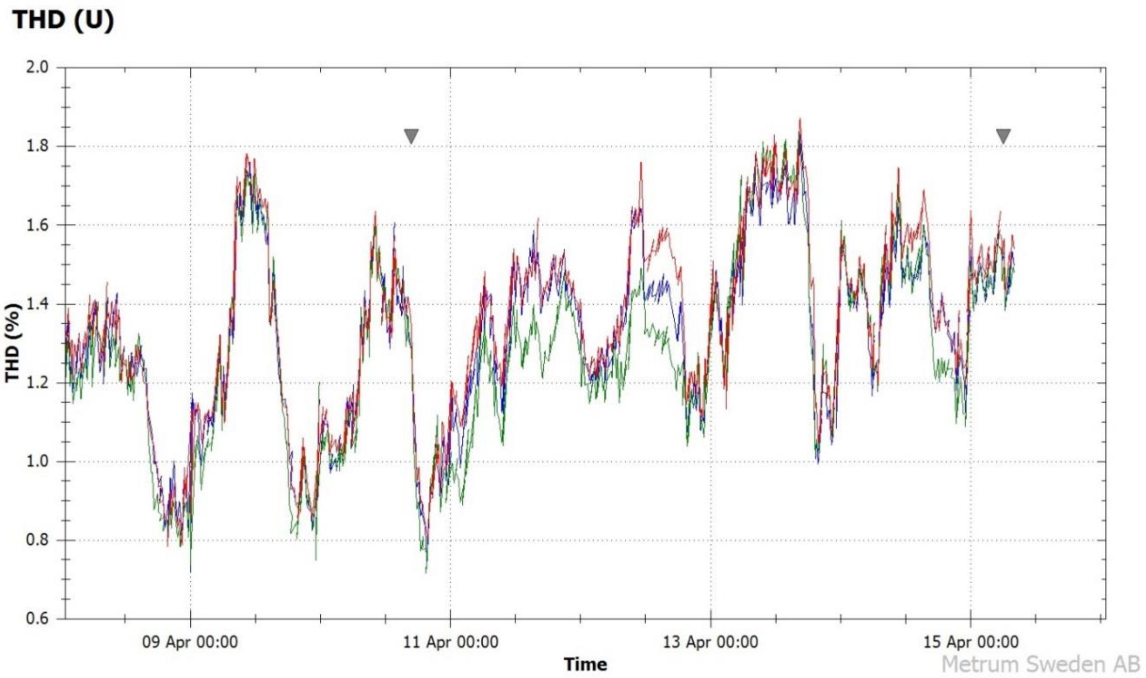

Figure 35 - THD on voltage during measurement on rural substation.V1=Red,V2=Green,V3=Blue

Total harmonic distortion on current is slightly lower than the other two measurements indicating that the amounts of non-linear loads are fewer compared to previous two measurements. THD_I could as mentioned above be misleading and should be analysed with caution. To give another view of harmonics on current the three most prominent ones are shown in figure 37 from phase 2; that phase with the largest amount of THD_I.

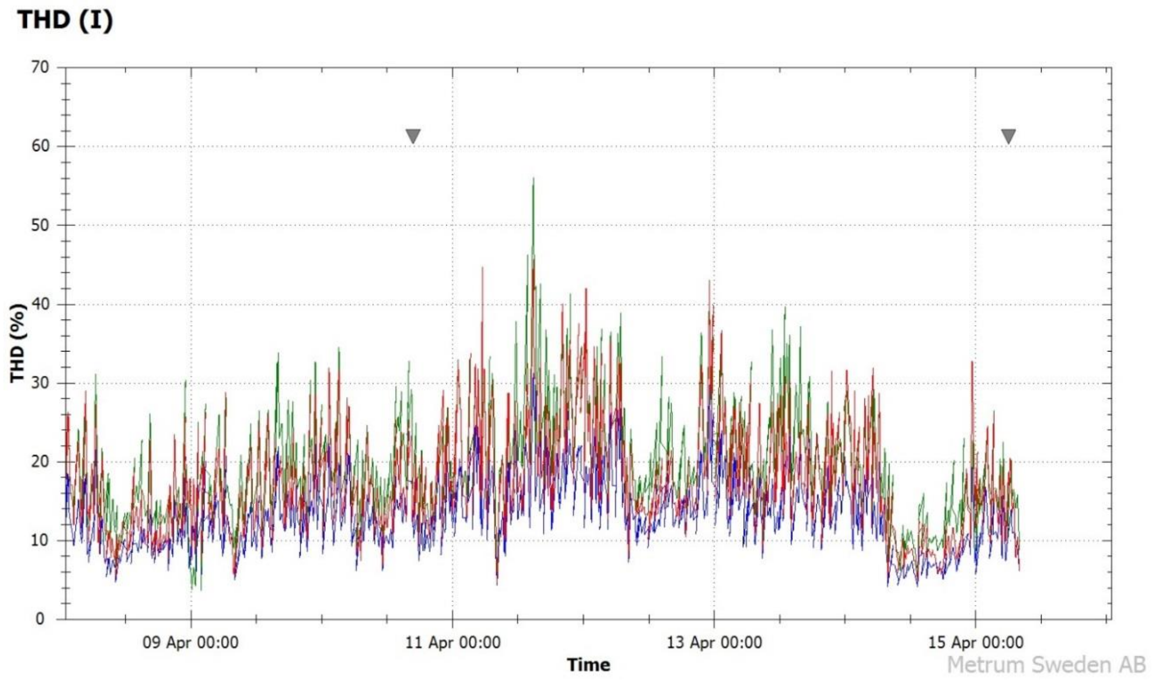

Figure 36 - THD on current during measurement on rural substation.I1=Red,I2=Green,I3=Blue

The three first odd current harmonics shows a completely different behaviour than previous two measurements. The third harmonic shows like previous two measurements a more behaviour like shape. However it is four to five times smaller than the fifth and seventh harmonics. The fifth and seventh harmonics does not show the same behaviour as the third instead they follows THD_I that implies that the fifth and seventh current harmonic stands for a large part of the THD_I.

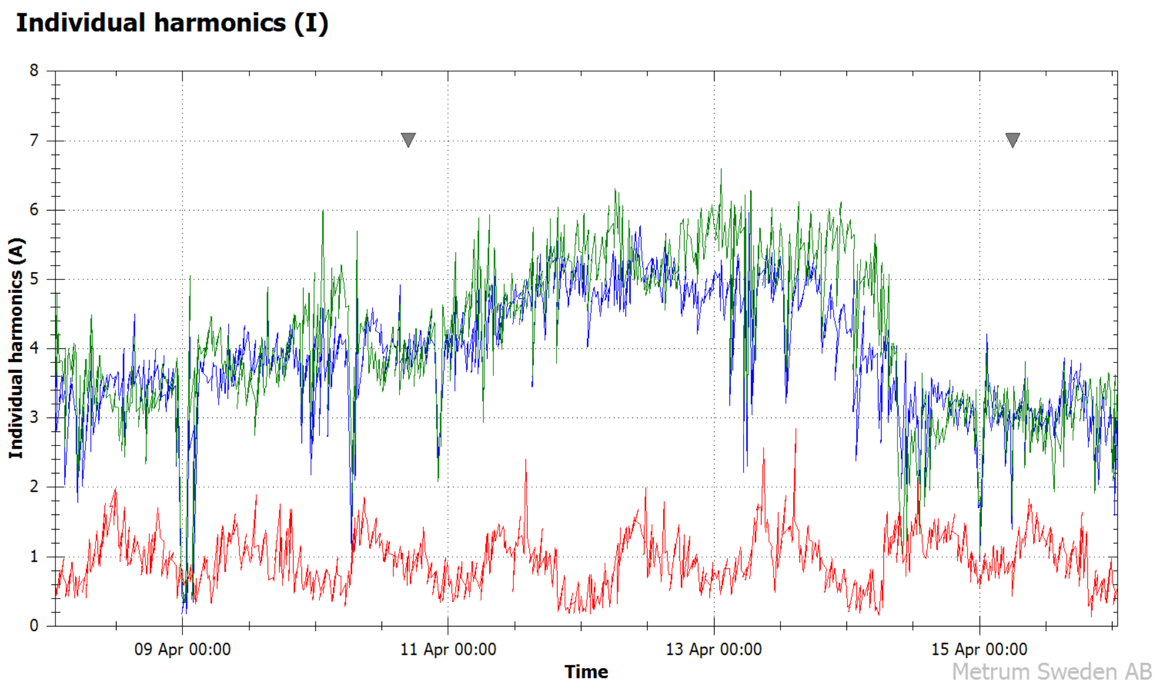

Figure 37 - 3, 5, 7 harmonic on current on phase 2 during measurement on rural substation. H3=Red,H5=Green,H7=Blue

When studying the individual harmonics the average value during the measuring period of all the logged average 10 minute values are used. As can be seen from the individual harmonics they differ from the previous two mostly by lower values of triple harmonics. This indicates that the loads consists of more three phase connected loads.

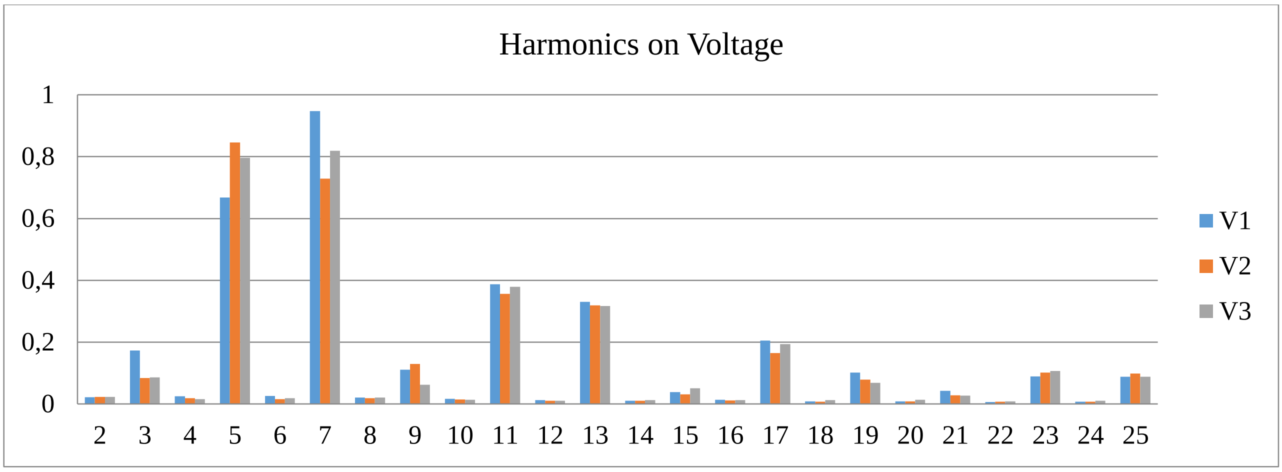

Figure 38 - Average harmonic on voltage during measurement on rural substation

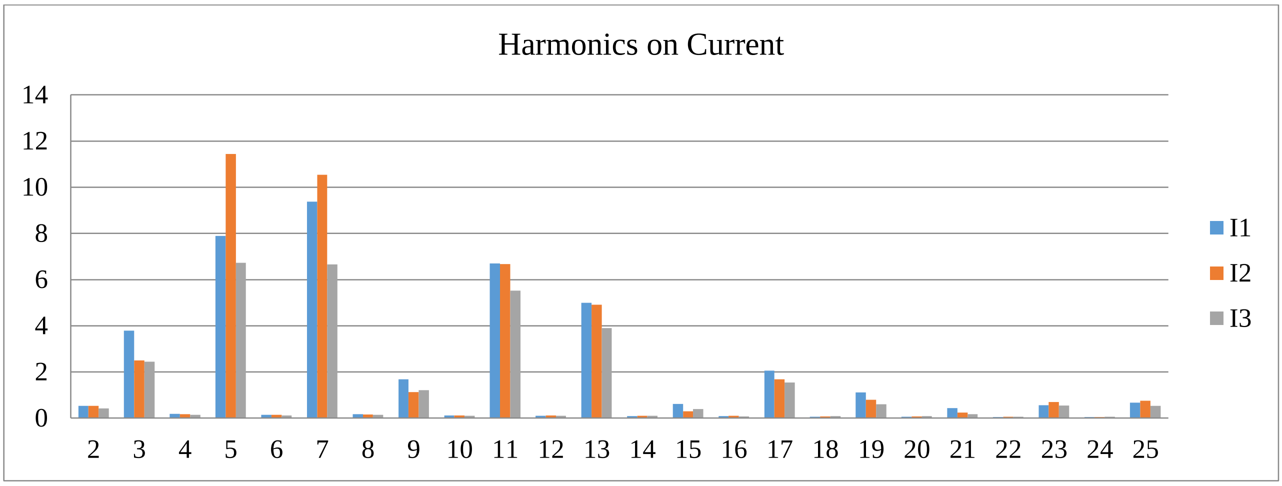

Figure 39 - Average harmonic on current during measurement on rural substation

5. Discussion

5.1. Laws and regulations

Limits on voltage quality in low voltage grids have previous been regulated in different standards. But since 2011 Energy markets inspectorate has developed code of statutes called EIFS 2011:2 and the latest version 2013:1 that used standards as a base in their development. This code of statutes provides an easier access and should make it clearer for everyone from utility company to consumers on what is defined as accepted voltage quality [19].

All electric power quality phenomena are not mentioned in this regulation. Transients with a duration under 10 ms (half cycle) lacks regulations on what is acceptable because protection from such fast events are difficult. Flicker is another electric power quality phenomena that is not mentioned in EIFS 2013:1. Harmonics are given limits in EIFS 2013:1 that are the same as SS-EN 50160 except that the limits in EIFS 2013:1 needs to be accepted 100% of the time. Total harmonic distortion on voltage has the hardest limit in standard SS-EN 61000-2-2 were it is 6 % compared to 8% in EIFS 2013:1 and SS-EN 50160.

Interharmonics are not mentioned in EIFS 2013:1 or SS-EN 50160 but are given the value of 0.3% in SS-EN 61000-2-2. Limits on flicker are stated in the standard SS-EN 50160. A simple overview on routes to achieve strictest accepted voltage quality values are given below. The strictest demands of different voltage quality aspects have been chosen from EIFS 2013:1 and different standards. If any standard represent the same limit as EIFS 2013:1 then EIFS 2013:1 has been chosen [9] [22].

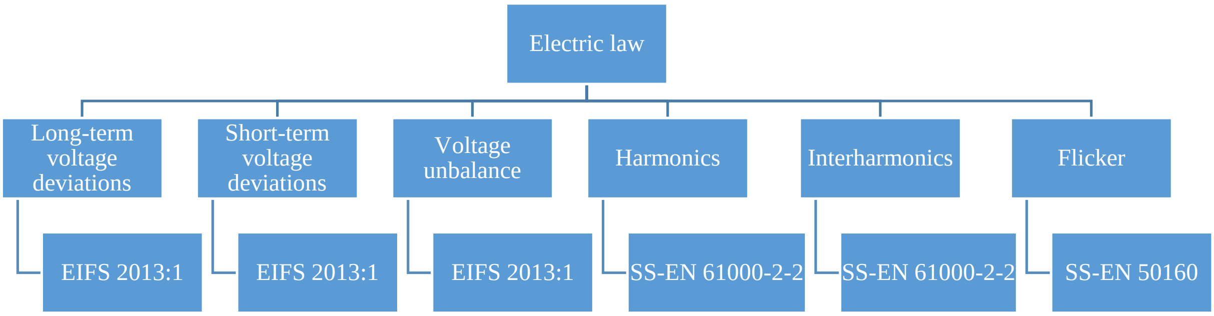

Figure 40 - Routes for achieve the strictest accepted voltage quality of different power quality aspects

The limit on long-term voltage deviations has been a little narrower than it is today. Today EIFS 2013:1 states that the long-term voltage deviation should be within ±10% all the time i.e. 207-253 V. According to the old Swedish standard SS 4211811 the long-term voltage levels should be kept within 207-244 V [2]. Norway have stricter regulations than EIFS 2013:1 and SS-EN 50160 that state that the average voltage value should be logged as one minute average instead of the 10 minute average values that are used in Sweden [30].

In a report [31] from European Copper Institute they mentioned that there are a few utility companies that charge consumers for a high current harmonic pollution like the charge for reactive power. Perhaps the amount of utility companies that charge for high current harmonics will increase in the future as the problem with harmonics eventually grow.

5.2.Measurements

The overall electric power quality from measurements are within the given limits due to a well dimensioned grid. The voltage level is somewhat higher in the urban areas compared to the rural areas as expected. But the voltage in urban areas are over nominal voltage with about 2-5% since the goal is to keep the voltage level on 240 V at substations. This trend with higher voltages in the low voltage networks have been seen in other studies from Estonia [6] and the Netherlands [32] were it have raised over time mostly because of the wider voltage limits. In the work to lower the voltage on the low voltage grid to nominal level there are two ways to go. The simplest and fastest is to change the settings on the automatic tap-changers on distribution transformers between high voltage and medium voltage grid. The other way is to change the setting manually on all the affected substation tap-changer but that need to be done disconnected from the grid.

Voltage levels above nominal in substations supplying a slightly capacitive load would result in a little higher voltage level at consumers connection compared to the substation. This because the voltage level is higher when the reactive power amplitude is large (building) compared to when it is smaller (substation). Since the grid in Lund consists of almost only cables this might lead to an even more increased voltage during summers with a low loaded grid and cables representing a capacitive load instead of an inductive load like when the grid is on higher load.

Another problem that might occur with a capacitive load is resonance with the inductive parts of the grid such as transformers and cables. This will be a parallel resonance that might damage equipment due to the high currents during parallel resonance. This type of problem in cable grids are also mentioned in [10]. Since the opportunity is available to supply Kraftringens office by a mobile backup generator precaution has to be taken on what type of backup generator that is going to be used due to the capacitive power factor.

Historically backup generators have delivered power to a slightly inductive load but when the generator should deliver to a slightly capacitive load problems might arise. If the loads power factor gets to capacitive it could lead to that the backup generator shuts down due to overvoltage as it is not able to reduce the voltage any lower by the voltage controller. The voltage control unit cannot supply a negative current to the rotor windings and therefore the voltage raises until protection system stops the generator due to overvoltage [33].

In the work to confirm that the two buildings in urban areas have a capacitive power factor the accumulated produced and delivered reactive power from the electricity meters were controlled. All electricity meters indicated that there have been a majority of produced reactive power (capacitive power factor) compared to delivered reactive power (inductive power factor). Accumulated values on Kraftringens office indicated that the building has produced over 2.7 times more reactive power compared to what was delivered to the building. On the substation supplying the large building two meters are connected. The electric meter for the building indicates that the building has produced reactive power all the time and none has been delivered to the building. The other electricity meter for the hotel indicates that 1.5 times more reactive power has been produced compared to delivered reactive power.

The reason for this capacitive power factor could perhaps be linked towards todays larger use of energy efficient lights. Research has shown that modern energy efficient light equipment has a capacitive power factor but the conclusion is drawn that it will most likely not cause any problem today and only minimize the need for capacitors on medium voltage grid [18]. A thesis from Växjö shows that a clothing store has a capacitive power factor during working hours and a power factor of almost unity outside working hours. This strengthen the theory of that the energy effective light could stand for a large part of the capacitive load [5].

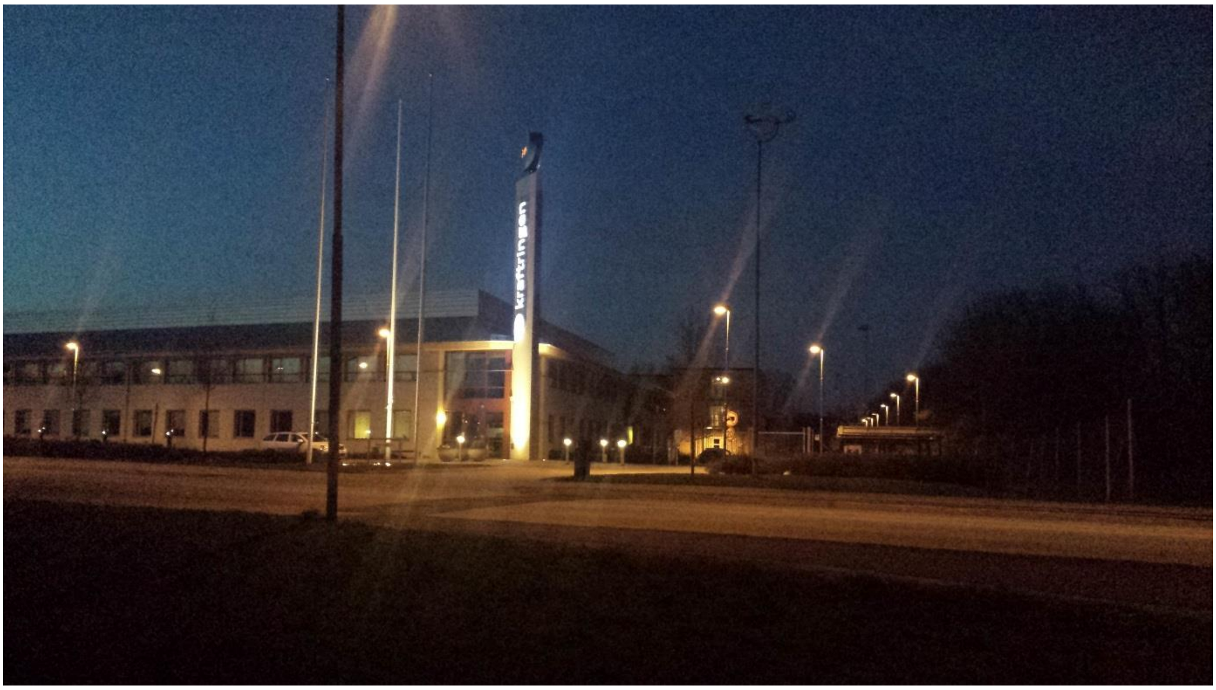

Figure 41 - Kraftringens office during night

The capacitive power factor from energy efficient light could not explain the reason for the capacitive power factor during nights and weekends and would therefore being related to another aspect. As can be seen in figure 41 no lights are on in Kraftringens office during nights and just some lights on the outside and still the building represents a capacitive load. Modern devices are equipped with an EMC-filter for not interfere with high frequency signals. This filter is connected to the grid even though the device is not on and for disconnection the cable need to be unplugged from the grid. Those filters consist of capacitors among other components and many devices could perhaps interleave to a notable capacitive power factor [18].

A study from the Netherlands [24] were they have measured power quality on typical office equipment shows that computer screens in stand-by and laptop charger at no load have a capacitive power factor. This strengthens the theory about that it could be the EMC-filter that is one of the reasons that the building is still a capacitive load even outside office hours.

Harmonics are another electric power quality aspect needed to be commented from the measurements. The overall harmonics on voltage is well within given limits and follows a typical load behaviour pattern, high during work days and low during nights. Both measurements on the typical office building indicate that the third harmonic on current is the most prominent followed by the fifth and seventh on similar values. Since the third harmonic is of zero sequence it will add up in the neutral conductor.

This collection of zero sequence current harmonics will put a larger demand on the neutral conductor compared to the measurement on the more rural substation where the odd multiples of third harmonic were significantly lower. On modern installations the neutral conductor is of the same size as the phase conductors. In the past the neutral conductor was often in a smaller dimension compared to phase conductors leading to that those building are more vulnerable to an over-loaded neutral conductor and possible stray currents. District heating supplies a majority of Lund with heat and therefore largely over-dimensioned cables due to old electric heating will most likely not be found to any building. Buildings that need more focus when it comes to odd multiples of third harmonics and unbalance should be on older office buildings or similar loads with high amounts of single-phase loads.

5.3. Future measurement locations

In Kraftringens work to becoming more proactive regarding electric power quality they need to expand their number of measurement locations. An expanded number of measurements do not only provide information about whether or not the electric power quality are within given limits but can also help to clear faults faster and perhaps show faults on equipment before a complete failure.

The ideal case would be an electric quality meter at every substation on the low voltage side to also cover zero sequence harmonics. This cannot be done during a short period of time. The substation gives a good overview of consumers connected to that substation; a voltage dip at the substation will be noted by all connected consumers. Strategically measurement locations have to be chosen in the beginning and successively expand over the years.

The most obvious locations to start with are areas that have received complaints in the past and locations with sensitive consumers. From there it is more difficult to select substations to measure on. A suggestion is to start with substations that are known to be under higher load than the average substation. If the transformer is relatively high loaded and with a high amount of harmonics it could reduce the transformers lifetime due to higher heat production and eventually lead to a premature failure.

Another suggestion is to measure on an older substation were smaller dimension on the PEN-conductor was used that are loaded with lots of single-phase loads like office buildings. Zero sequence current harmonics combined with unbalanced loads could lead to an overloaded PEN-conductor. An overloaded PEN-conductor result in a voltage drop on the way to the substation that leads to stray currents and that the grounded devices could obtain dangerous voltages. In extreme cases the PEN-conductor might burn off leaving grounded devices ungrounded.

The last advice would be to start measure on substations that supply other types of loads like more urban residential areas, smaller industries, larger workshops, bathing facilities, larger malls and larger supermarkets. From this a wider perspective on different types of loads can be achieved and then it is easier to know where to focus the measurements. Last advice is then to spread out the measurement devices over the whole concession area to establish better understanding in how the grid behaves under certain incidents. This is possible if all electric power quality meters synchronize to the same server.

The substation with the worst electric quality parameters can then be suited for performance improvements so that the grid always performs within a certain range. The exact number of substations to measure on is hard to quantify. To buy the measurement device is a one-time fee but calibration and data transmission are continuously expenses.

6. Conclusions

Today it is less complicated to follow the electric law on that the delivered electricity should be of accepted quality than it have been in the past. Energy markets inspectorate codes of statutes 2013:1 (EIFS 2013:1) give the highest acceptable limits for different voltage aspects needed to be obtained. Theses codes does not involve all electric quality parameters like interharmonics and flicker. Some standard put higher demands on voltage quality like SS-EN 61000-2-2 on total harmonic distortion.

The conducted field studies did not indicate any violation of given limits but shown some other interesting results. In the urban areas the voltage level were above nominal voltage level during all measurements from 2-5 %. Both the urban measurements on an office building and the substation supplying a larger building consists of loads with a capacitive power factor. A slightly over-voltage in the substation supplying a capacitive load implies that the voltage level in consumers connection point are higher. The difference in voltage level between the substation and the consumer depends on the grids impedance and load. It is therefore recommended to lower the voltage level by either change the setting of the tap-changers of the distribution transformers supplying the medium voltage grid or change the tap-changer settings of substations transformer manually but with a bigger effort.

In the future the amount of loads will perhaps move from an inductive power factor towards a more capacitive power factor in urban areas. The voltage level will then increase slightly at consumers and during seasons with low load the voltage level might get to high due to the grid also becomes capacitive during low load. Another eventual problem with capacitive loads are that it could lead to resonance with the inductive parts of the grid due to presence of harmonics. This could result in a higher total harmonic distortion on voltage at resonance frequency and reduced lifetime of components. Other conclusions are hard to draw without a larger amount of measurement locations on Kraftringens grid since most problems often are local in the grid.

It is suggested to expand the number of permanent electric power quality measurement locations to get a better overview of the present situation. Best suited locations to start with are such that have received complaints earlier, measured on the low voltage side of the transformer to register the amount of zero sequence harmonics. Next step in the measurement expansion would be substations known to be under higher load than others or substations with a PEN-conductor in a smaller area than the phase conductors supplying a typical office load with large amounts of third current harmonics and unbalance.

Last the measurement location could be chosen based on the load type like more urban residential areas, smaller industries, larger workshops, bathing facilities, larger malls and larger supermarkets. From there the locations should be spread out geographically over the entire concession area for a better understanding of the grids behaviour during incidents.

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8. Appendix

8.1. Technical specification of Unipower Unilyzer 900 [34]

Voltage inputs	
Voltage channels	4 inputs
Range	0-1000V RMS
Resolution	Dynamic. Typically 0.0008% range
Sampling rate	From 256 points/cycle
Transient detection	From 78 micro sec. Multiple triggers
Transient resolution	Dynamic. Typically 0.0008% range
Event recording	Waveform and RMS for all channels
Input impedance	3,5 Mohm
Bandwidth	5kHz@50Hz
Accuracy	IEC 61000-4-30 class A

Current inputs	
Current channels	4 inputs
Range	Clamp on ammeters up to 5000 A
Resolution	Dynamic. Typically 0.0008% range
Sampling rate	From 256 points/cycle.
Transient detection	From 78 micro sec. Multiple triggers
Transient resolution	Dynamic. Typically 0.0008% range
Bandwidth	5kHz@50Hz
Accuracy	<0.1%

Miscellaneous	
Measurements	According to IEC 61000-4-30 class A
Storage intervals	Individual settings for each parameter group, from 3 sec or more. Standard setting 10 min.
Storage capacity	32 MB flash memory (standard). With standard setting memory can store more than 170 days of measure data.
Communication	USB 2.0 (standard). Modem. WLAN router.
Time synchronisation	Synchronisation with configuring computer.
Power supply	85-264 VAC. Dc optional. Internal UPS 0.5 hour.

8.2. Technical specification of Metrum SC [29]

Voltage inputs	
Voltage channels	3 inputs
Range	0-300 V RMS
Resolution	16 bits
Sampling rate	12.8 kHz
Event recording	Waveform and RMS for all channels
Input impedance	1 Mohm
Bandwidth	3.5 kHz
Accuracy	IEC 61000-4-30 class A, < 0.1 %

Current inputs	
Current channels	3 inputs
Range	0-6 A RMS
Resolution	16 bits
Sampling rate	12.8 kHz
Input impedance	10 mohm
Bandwidth	3.5 kHz
Accuracy	IEC 61000-4-30 class A, < 0.1%

Miscellaneous	
Measurements	According to IEC 61000-4-30 class A. IEC 61000-4-15.
Storage intervals	Frequency 10 sec. Pst 10 min. Plt 10 min. Voltage/current 10 min. Selectable trig-levels.
Storage capacity	64 MB flash memory.
Communication	USB 2.0. Modem. CL port.
Time synchronisation	Synchronisation with configuring computer.
Power supply	230 VAC, 50 Hz. Built-in backup

8.3. Global radiation in Lund during measurements on Kraftringens office [35]

Date	Time	W/m²	Date	Time	W/m²
2015-01-30	08:00:00	6.31	2015-02-06	08:00:00	48.98
2015-01-30	09:00:00	21.97	2015-02-06	09:00:00	124.45
2015-01-30	10:00:00	44.72	2015-02-06	10:00:00	157.54
2015-01-30	11:00:00	53.19	2015-02-06	11:00:00	171.49
2015-01-30	12:00:00	132.19	2015-02-06	12:00:00	105.43
2015-01-30	13:00:00	66.52	2015-02-06	13:00:00	72.26
2015-01-30	14:00:00	27.45	2015-02-06	14:00:00	47.02
2015-01-30	15:00:00	19.77	2015-02-06	15:00:00	28.57
2015-01-30	16:00:00	5.14	2015-02-06	16:00:00	5.37
2015-01-30	17:00:00	0.86	2015-02-06	17:00:00	1.30
2015-01-30	18:00:00	1.35	2015-02-06	18:00:00	1.11
2015-01-30	19:00:00	1.20	2015-02-06	19:00:00	1.51
2015-01-30	20:00:00	1.19	2015-02-06	20:00:00	1.23
2015-01-30	21:00:00	1.43	2015-02-06	21:00:00	1.21
2015-01-30	22:00:00	1.23	2015-02-06	22:00:00	1.07
2015-01-30	23:00:00	1.21	2015-02-06	23:00:00	1.41
2015-01-31	00:00:00	1.24	2015-02-07	00:00:00	1.28
2015-01-31	01:00:00	1.23	2015-02-07	01:00:00	1.33
2015-01-31	02:00:00	1.52	2015-02-07	02:00:00	0.70
2015-01-31	03:00:00	1.24	2015-02-07	03:00:00	0.96
2015-01-31	04:00:00	1.20	2015-02-07	04:00:00	1.20
2015-01-31	05:00:00	1.22	2015-02-07	05:00:00	1.21
2015-01-31	06:00:00	1.00	2015-02-07	06:00:00	0.96
2015-01-31	07:00:00	1.20	2015-02-07	07:00:00	1.74
2015-01-31	08:00:00	7.76	2015-02-07	08:00:00	25.81
2015-01-31	09:00:00	29.70	2015-02-07	09:00:00	121.59
2015-01-31	10:00:00	75.40	2015-02-07	10:00:00	207.80
2015-01-31	11:00:00	47.77	2015-02-07	11:00:00	284.36
2015-01-31	12:00:00	53.58	2015-02-07	12:00:00	115.29
2015-01-31	13:00:00	40.74	2015-02-07	13:00:00	147.30
2015-01-31	14:00:00	19.25	2015-02-07	14:00:00	101.78
2015-01-31	15:00:00	6.30	2015-02-07	15:00:00	61.89
2015-01-31	16:00:00	2.53	2015-02-07	16:00:00	14.27
2015-01-31	17:00:00	1.29	2015-02-07	17:00:00	-0.73
2015-01-31	18:00:00	1.38	2015-02-07	18:00:00	-0.92
2015-01-31	19:00:00	1.25	2015-02-07	19:00:00	-0.85
2015-01-31	20:00:00	0.90	2015-02-07	20:00:00	-1.27
2015-01-31	21:00:00	0.93	2015-02-07	21:00:00	-0.76
2015-01-31	22:00:00	0.52	2015-02-07	22:00:00	-0.92
2015-01-31	23:00:00	1.17	2015-02-07	23:00:00	-0.89
2015-02-01	00:00:00	0.47	2015-02-08	00:00:00	-0.18
2015-02-01	01:00:00	1.20	2015-02-08	01:00:00	-0.41

2015-02-01	02:00:00	0.76	2015-02-08	02:00:00	-0.84
2015-02-01	03:00:00	0.89	2015-02-08	03:00:00	-0.87
2015-02-01	04:00:00	0.90	2015-02-08	04:00:00	-1.11
2015-02-01	05:00:00	0.33	2015-02-08	05:00:00	-1.03
2015-02-01	06:00:00	0.64	2015-02-08	06:00:00	-1.15
2015-02-01	07:00:00	0.70	2015-02-08	07:00:00	2.09
2015-02-01	08:00:00	17.42	2015-02-08	08:00:00	58.25
2015-02-01	09:00:00	53.52	2015-02-08	09:00:00	161.63
2015-02-01	10:00:00	75.43	2015-02-08	10:00:00	256.91
2015-02-01	11:00:00	136.38	2015-02-08	11:00:00	311.63
2015-02-01	12:00:00	138.75	2015-02-08	12:00:00	323.91
2015-02-01	13:00:00	140.57	2015-02-08	13:00:00	296.27
2015-02-01	14:00:00	61.64	2015-02-08	14:00:00	195.70
2015-02-01	15:00:00	32.47	2015-02-08	15:00:00	127.56
2015-02-01	16:00:00	6.60	2015-02-08	16:00:00	18.54
2015-02-01	17:00:00	1.20	2015-02-08	17:00:00	0.77
2015-02-01	18:00:00	1.21	2015-02-08	18:00:00	0.62
2015-02-01	19:00:00	0.72	2015-02-08	19:00:00	0.47
2015-02-01	20:00:00	0.72	2015-02-08	20:00:00	0.62
2015-02-01	21:00:00	0.44	2015-02-08	21:00:00	0.71
2015-02-01	22:00:00	0.77	2015-02-08	22:00:00	0.04
2015-02-01	23:00:00	0.74	2015-02-08	23:00:00	0.48
2015-02-02	00:00:00	0.93	2015-02-09	00:00:00	0.73
2015-02-02	01:00:00	1.31	2015-02-09	01:00:00	1.10
2015-02-02	02:00:00	0.99	2015-02-09	02:00:00	1.04
2015-02-02	03:00:00	1.16	2015-02-09	03:00:00	0.82
2015-02-02	04:00:00	0.92	2015-02-09	04:00:00	0.71
2015-02-02	05:00:00	1.30	2015-02-09	05:00:00	0.69
2015-02-02	06:00:00	1.51	2015-02-09	06:00:00	0.63
2015-02-02	07:00:00	1.42	2015-02-09	07:00:00	2.50
2015-02-02	08:00:00	10.21	2015-02-09	08:00:00	32.36
2015-02-02	09:00:00	54.03	2015-02-09	09:00:00	141.67
2015-02-02	10:00:00	115.67	2015-02-09	10:00:00	247.87
2015-02-02	11:00:00	119.82	2015-02-09	11:00:00	299.44
2015-02-02	12:00:00	128.61	2015-02-09	12:00:00	324.58
2015-02-02	13:00:00	113.58	2015-02-09	13:00:00	251.48
2015-02-02	14:00:00	85.61	2015-02-09	14:00:00	221.42
2015-02-02	15:00:00	42.21	2015-02-09	15:00:00	104.31
2015-02-02	16:00:00	7.67	2015-02-09	16:00:00	29.02
2015-02-02	17:00:00	1.33	2015-02-09	17:00:00	0.86
2015-02-02	18:00:00	1.19	2015-02-09	18:00:00	0.04
2015-02-02	19:00:00	1.08	2015-02-09	19:00:00	0.14
2015-02-02	20:00:00	1.26	2015-02-09	20:00:00	0.14
2015-02-02	21:00:00	0.91	2015-02-09	21:00:00	0.40
2015-02-02	22:00:00	0.67	2015-02-09	22:00:00	0.09
2015-02-02	23:00:00	0.59	2015-02-09	23:00:00	0.30

2015-02-03	00:00:00	0.53	2015-02-10	00:00:00	0.45
2015-02-03	01:00:00	0.66	2015-02-10	01:00:00	0.24
2015-02-03	02:00:00	0.96	2015-02-10	02:00:00	0.17
2015-02-03	03:00:00	0.88	2015-02-10	03:00:00	0.08
2015-02-03	04:00:00	0.27	2015-02-10	04:00:00	0.47
2015-02-03	05:00:00	0.48	2015-02-10	05:00:00	1.07
2015-02-03	06:00:00	0.96	2015-02-10	06:00:00	1.23
2015-02-03	07:00:00	1.49	2015-02-10	07:00:00	3.04
2015-02-03	08:00:00	44.39	2015-02-10	08:00:00	36.94
2015-02-03	09:00:00	142.27	2015-02-10	09:00:00	86.34
2015-02-03	10:00:00	175.27	2015-02-10	10:00:00	118.03
2015-02-03	11:00:00	225.92	2015-02-10	11:00:00	174.26
2015-02-03	12:00:00	169.70	2015-02-10	12:00:00	271.29
2015-02-03	13:00:00	131.81	2015-02-10	13:00:00	271.00
2015-02-03	14:00:00	101.72	2015-02-10	14:00:00	181.33
2015-02-03	15:00:00	36.79	2015-02-10	15:00:00	98.01
2015-02-03	16:00:00	6.95	2015-02-10	16:00:00	28.45
2015-02-03	17:00:00	0.94	2015-02-10	17:00:00	1.26
2015-02-03	18:00:00	1.12	2015-02-10	18:00:00	-0.22
2015-02-03	19:00:00	1.09	2015-02-10	19:00:00	-0.54
2015-02-03	20:00:00	1.10	2015-02-10	20:00:00	-0.51
2015-02-03	21:00:00	1.19	2015-02-10	21:00:00	0.38
2015-02-03	22:00:00	1.14	2015-02-10	22:00:00	0.82
2015-02-03	23:00:00	1.33	2015-02-10	23:00:00	0.96
2015-02-04	00:00:00	1.35	2015-02-11	00:00:00	0.81
2015-02-04	01:00:00	1.10	2015-02-11	01:00:00	-0.04
2015-02-04	02:00:00	1.22	2015-02-11	02:00:00	-0.14
2015-02-04	03:00:00	1.38	2015-02-11	03:00:00	-0.21
2015-02-04	04:00:00	1.24	2015-02-11	04:00:00	0.14
2015-02-04	05:00:00	1.23	2015-02-11	05:00:00	0.10
2015-02-04	06:00:00	1.07	2015-02-11	06:00:00	0.65
2015-02-04	07:00:00	1.98	2015-02-11	07:00:00	3.31
2015-02-04	08:00:00	16.24	2015-02-11	08:00:00	23.63
2015-02-04	09:00:00	49.73	2015-02-11	09:00:00	43.48
2015-02-04	10:00:00	132.97	2015-02-11	10:00:00	60.22
2015-02-04	11:00:00	98.62	2015-02-11	11:00:00	59.12
2015-02-04	12:00:00	58.29	2015-02-11	12:00:00	61.36
2015-02-04	13:00:00	54.30	2015-02-11	13:00:00	50.85
2015-02-04	14:00:00	43.44	2015-02-11	14:00:00	43.06
2015-02-04	15:00:00	23.23	2015-02-11	15:00:00	26.37
2015-02-04	16:00:00	6.62	2015-02-11	16:00:00	8.45
2015-02-04	17:00:00	1.57	2015-02-11	17:00:00	1.63
2015-02-04	18:00:00	1.45	2015-02-11	18:00:00	1.36
2015-02-04	19:00:00	1.57	2015-02-11	19:00:00	1.51
2015-02-04	20:00:00	1.56	2015-02-11	20:00:00	1.49
2015-02-04	21:00:00	1.42	2015-02-11	21:00:00	1.39

2015-02-04	22:00:00	1.43	2015-02-11	22:00:00	1.39
2015-02-04	23:00:00	1.37	2015-02-11	23:00:00	1.38
2015-02-05	00:00:00	1.38	2015-02-12	00:00:00	1.21
2015-02-05	01:00:00	1.41	2015-02-12	01:00:00	1.23
2015-02-05	02:00:00	1.15	2015-02-12	02:00:00	1.28
2015-02-05	03:00:00	1.07	2015-02-12	03:00:00	1.46
2015-02-05	04:00:00	1.11	2015-02-12	04:00:00	1.36
2015-02-05	05:00:00	0.82	2015-02-12	05:00:00	1.31
2015-02-05	06:00:00	0.28	2015-02-12	06:00:00	1.34
2015-02-05	07:00:00	1.71	2015-02-12	07:00:00	2.03
2015-02-05	08:00:00	29.72	2015-02-12	08:00:00	8.23
2015-02-05	09:00:00	139.07	2015-02-12	09:00:00	20.73
2015-02-05	10:00:00	157.12	2015-02-12	10:00:00	31.46
2015-02-05	11:00:00	133.85	2015-02-12	11:00:00	42.44
2015-02-05	12:00:00	289.80	2015-02-12	12:00:00	48.52
2015-02-05	13:00:00	196.99	2015-02-12	13:00:00	45.38
2015-02-05	14:00:00	144.37	2015-02-12	14:00:00	40.23
2015-02-05	15:00:00	104.08	2015-02-12	15:00:00	21.56
2015-02-05	16:00:00	17.61	2015-02-12	16:00:00	6.73
2015-02-05	17:00:00	0.33	2015-02-12	17:00:00	1.64
2015-02-05	18:00:00	0.33	2015-02-12	18:00:00	1.33
2015-02-05	19:00:00	0.21	2015-02-12	19:00:00	1.42
2015-02-05	20:00:00	0.20	2015-02-12	20:00:00	1.48
2015-02-05	21:00:00	0.41	2015-02-12	21:00:00	1.42
2015-02-05	22:00:00	0.16	2015-02-12	22:00:00	1.56
2015-02-05	23:00:00	0.03	2015-02-12	23:00:00	1.33
2015-02-06	00:00:00	-0.12	2015-02-13	00:00:00	1.48
2015-02-06	01:00:00	0.09	2015-02-13	01:00:00	1.42
2015-02-06	02:00:00	0.02	2015-02-13	02:00:00	1.86
2015-02-06	03:00:00	1.38	2015-02-13	03:00:00	1.62
2015-02-06	04:00:00	0.65	2015-02-13	04:00:00	1.31
2015-02-06	05:00:00	0.29	2015-02-13	05:00:00	1.38
2015-02-06	06:00:00	0.54	2015-02-13	06:00:00	1.31
2015-02-06	07:00:00	2.67	2015-02-13	07:00:00	1.83

8.4. Global radiation in Lund during measurements on substation supplying larger building [35]

Date	Time	W/m^2	Date	Time	W/m^2
2015-04-08	01:00:00	0.29	2015-04-11	13:00:00	628.46
2015-04-08	02:00:00	0.11	2015-04-11	14:00:00	457.09
2015-04-08	03:00:00	1.39	2015-04-11	15:00:00	340.3
2015-04-08	04:00:00	1.6	2015-04-11	16:00:00	288.71
2015-04-08	05:00:00	5.35	2015-04-11	17:00:00	145.96
2015-04-08	06:00:00	20.24	2015-04-11	18:00:00	26.12
2015-04-08	07:00:00	75.57	2015-04-11	19:00:00	-0.52
2015-04-08	08:00:00	138.16	2015-04-11	20:00:00	-0.5
2015-04-08	09:00:00	282.96	2015-04-11	21:00:00	-0.58
2015-04-08	10:00:00	364.3	2015-04-11	22:00:00	0.02
2015-04-08	11:00:00	427.24	2015-04-11	23:00:00	0.05
2015-04-08	12:00:00	548.33	2015-04-12	00:00:00	0.23
2015-04-08	13:00:00	453.02	2015-04-12	01:00:00	-0.81
2015-04-08	14:00:00	538.68	2015-04-12	02:00:00	0.47
2015-04-08	15:00:00	446.75	2015-04-12	03:00:00	-0.24
2015-04-08	16:00:00	297.82	2015-04-12	04:00:00	-0.32
2015-04-08	17:00:00	158.83	2015-04-12	05:00:00	15.04
2015-04-08	18:00:00	38.82	2015-04-12	06:00:00	111.43
2015-04-08	19:00:00	0.33	2015-04-12	07:00:00	259.44
2015-04-08	20:00:00	0.06	2015-04-12	08:00:00	388.68
2015-04-08	21:00:00	0.36	2015-04-12	09:00:00	488.79
2015-04-08	22:00:00	0.34	2015-04-12	10:00:00	523.16
2015-04-08	23:00:00	0.18	2015-04-12	11:00:00	516.46
2015-04-09	00:00:00	0.51	2015-04-12	12:00:00	229.52
2015-04-09	01:00:00	0.26	2015-04-12	13:00:00	228.79
2015-04-09	02:00:00	-0.02	2015-04-12	14:00:00	192.74
2015-04-09	03:00:00	0.14	2015-04-12	15:00:00	107.11
2015-04-09	04:00:00	0.53	2015-04-12	16:00:00	44.27
2015-04-09	05:00:00	14.43	2015-04-12	17:00:00	42.06
2015-04-09	06:00:00	86.75	2015-04-12	18:00:00	12.62
2015-04-09	07:00:00	235.68	2015-04-12	19:00:00	-0.62
2015-04-09	08:00:00	409.49	2015-04-12	20:00:00	0.26
2015-04-09	09:00:00	525.14	2015-04-12	21:00:00	0
2015-04-09	10:00:00	641.09	2015-04-12	22:00:00	-0.83
2015-04-09	11:00:00	662.1	2015-04-12	23:00:00	0.08
2015-04-09	12:00:00	571.77	2015-04-13	00:00:00	0.33
2015-04-09	13:00:00	496.2	2015-04-13	01:00:00	0.6
2015-04-09	14:00:00	531.86	2015-04-13	02:00:00	0.75
2015-04-09	15:00:00	431.97	2015-04-13	03:00:00	0.38
2015-04-09	16:00:00	256.12	2015-04-13	04:00:00	1.11
2015-04-09	17:00:00	157.41	2015-04-13	05:00:00	15.44
2015-04-09	18:00:00	39.07	2015-04-13	06:00:00	104.13

2015-04-09	19:00:00	0.72	2015-04-13	07:00:00	212.5
2015-04-09	20:00:00	0.11	2015-04-13	08:00:00	253.81
2015-04-09	21:00:00	0.02	2015-04-13	09:00:00	399.21
2015-04-09	22:00:00	0.08	2015-04-13	10:00:00	322.93
2015-04-09	23:00:00	-0.03	2015-04-13	11:00:00	319.93
2015-04-10	00:00:00	0.1	2015-04-13	12:00:00	473.27
2015-04-10	01:00:00	0.18	2015-04-13	13:00:00	463.08
2015-04-10	02:00:00	0.38	2015-04-13	14:00:00	213.9
2015-04-10	03:00:00	0.3	2015-04-13	15:00:00	185.2
2015-04-10	04:00:00	0.61	2015-04-13	16:00:00	201.43
2015-04-10	05:00:00	20.08	2015-04-13	17:00:00	100.99
2015-04-10	06:00:00	124.79	2015-04-13	18:00:00	31.56
2015-04-10	07:00:00	273.28	2015-04-13	19:00:00	1.02
2015-04-10	08:00:00	417.38	2015-04-13	20:00:00	-0.09
2015-04-10	09:00:00	542.89	2015-04-13	21:00:00	-0.36
2015-04-10	10:00:00	643.62	2015-04-13	22:00:00	-0.6
2015-04-10	11:00:00	688.55	2015-04-13	23:00:00	-0.18
2015-04-10	12:00:00	695.8	2015-04-14	00:00:00	-0.02
2015-04-10	13:00:00	658.16	2015-04-14	01:00:00	-0.04
2015-04-10	14:00:00	574.65	2015-04-14	02:00:00	0.05
2015-04-10	15:00:00	460.47	2015-04-14	03:00:00	0
2015-04-10	16:00:00	318.25	2015-04-14	04:00:00	0.73
2015-04-10	17:00:00	165.61	2015-04-14	05:00:00	38.89
2015-04-10	18:00:00	39.62	2015-04-14	06:00:00	73.66
2015-04-10	19:00:00	0.74	2015-04-14	07:00:00	123.51
2015-04-10	20:00:00	-0.33	2015-04-14	08:00:00	171.1
2015-04-10	21:00:00	-0.28	2015-04-14	09:00:00	173.49
2015-04-10	22:00:00	0.06	2015-04-14	10:00:00	160.17
2015-04-10	23:00:00	-0.02	2015-04-14	11:00:00	153.56
2015-04-11	00:00:00	-0.07	2015-04-14	12:00:00	70.9
2015-04-11	01:00:00	0.07	2015-04-14	13:00:00	47.2
2015-04-11	02:00:00	0.16	2015-04-14	14:00:00	38.13
2015-04-11	03:00:00	0.03	2015-04-14	15:00:00	27.48
2015-04-11	04:00:00	-0.21	2015-04-14	16:00:00	23.34
2015-04-11	05:00:00	17.43	2015-04-14	17:00:00	16.93
2015-04-11	06:00:00	100.7	2015-04-14	18:00:00	8.12
2015-04-11	07:00:00	215.47	2015-04-14	19:00:00	1.24
2015-04-11	08:00:00	375.82	2015-04-14	20:00:00	1.24
2015-04-11	09:00:00	497.98	2015-04-14	21:00:00	1.24
2015-04-11	10:00:00	596.56	2015-04-14	22:00:00	0.68
2015-04-11	11:00:00	623.37	2015-04-14	23:00:00	0.65
2015-04-11	12:00:00	650.89	2015-04-15	00:00:00	0.56

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