How do solar cells affect the power quality?

A study focusing on the voltage fluctuations and power quality parameters of photovoltaic systems.

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Abstract

Sweden has recently been growing quickly when it comes to solar power. One of the developments is to increase the share of renewable microgeneration that is locally or regionally connected to the power grid. There are many advantages, such as reduction of the fossil energy and an increased energy supply. However, it can also be challenging for the electric companies to provide their customers electricity with good quality when the numbers of installations increases.

A good power quality implicates electrical systems to function in their intended manner without loss of performance or life. This is a study about how PV -(photovoltaic) systems affects the fitness of electric power by focusing on voltage variations and unbalances that can arise for various reasons. Loads and production with uneven distribution between the three-phases is the reason for unbalance in the low voltage network. Consequences of lacking power quality can affect the connected equipment in the following ways:

- Not at all
- Shortened life
- Damage
- Stop/interruption

This study carries out simulations at some of Öresundskraft low voltage network with different customer configurations in microgeneration. How customers are affected by the changes depending on their distance from the transformer, and how sunlight affects the power, voltage and current. Most of the measurements in these thesis are from three-phase systems, but some are from single-phase systems.

All the measurements and simulations yielded the conclusion that there are no serious threats to the quality of electricity if there would be a large share of PV-systems, as long as the installations are done with great awareness and reliable dimensioning of three-phase connections. However, the simulation shows that there can be a great impact if many customers with uneven output on the grid start having a large production in the same area. One should avoid such scenarios, where all customers in the same network area have PV-systems.

Keywords: Power quality, PV-systems, microgeneration, solar cells, solar panels

Sammanfattning

Sverige har nyligen växt snabbt när det gäller solenergi. En av utvecklingen är att öka andelen förnybar mikrogeneration som lokalt eller regionalt som är ansluten till elnätet. Det finns fördelar, såsom minskning av fossil energi och en ökat energiförsörjning. Det kan vara en utmaning för de företag som producera och sälja el att leverera elen med god kvalité till sina kunder när antalet installationer ökar.

En god elkvalitet handlar om att minska händelser och fenomen i elnätet som påverkar maskiner och elektriska utrustningar negativt. Detta är en studie om hur solceller påverkar elkvaliteten genom att fokusera på spänningsvariationer och obalans som kan uppstå av olika anledningar. Laster och produktion med ojämn fördelning mellan de tre faserna är orsaken till obalans i lågspänningsnätet. Konsekvenser av dåligt (bristande) elkvalitet kan påverka den anslutna utrusningen på följande sätt:

- Inte alls
- Förkorta livslängden
- Skada
- Stopp/avbrott

Denna studie utför simuleringar på några av Öresundskraft lågspänningsnät med olika kunder som har solceller (microproduktion). Hur kunderna påverkas av de förändringar som beror på deras avstånd från nätstationen (transformatorn) och hur solinstrålningen påverkar effekten, spänningen och strömmen. De flesta mätningar är i tre fas men det finns mätningar som är i en fas.

Alla mätningar och simuleringar gav slutsatsen att det inte finns några allvarliga hot mot elkvaliteten om det skulle vara en stor del av solcellsanläggningar, så länge installationen görs med stor medvetenhet och tillförlighet i tre fas anslutning.

Simuleringen visar att det kan finnas en stor inverkan om många kunder med ojämn utgång på nätet börjar med en stor(15-20KW) produktion i samma område. Man bör undvika sådana scenarier, där alla kunder i samma nätområde har solcellsanläggningar.

Nyckelord: Elkvalitet, solceller, microproduktion, solceller, solpaneler

Foreword

This thesis of 22.5 credits represents the final step in our path before getting a bachelor degree in Electrical Engineering with Automation at Lund University, Campus Helsingborg. The work has been carried out on behalf of, and in cooperation with Öresundskraft and has been performed during the period 2016.02.16 – 2016.05.22.

We would like to start by thanking our fantastic supervisors at Öresundskraft, Anders Höglund, Adam Matulaniec, and Magnus Sjunnesson. You have all always stood up at all times and helped us along with all of the stages of the project. Thank you all for your great support and knowledge. We also want to thank our supervisor Johan Björnstedt and Mats Lilja at LTH for giving us advices and wise words that can help us later in life.

A special thanks to Lars Hansson at Öresundskraft for giving us the opportunity to learn a lot from you. You have helped us gradually, and without you, this work would not even be possible. Thank you for having patience by having us and for all the kindness and knowledge you gave us. We are really going to miss working with you.

Anza Ahmed

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Helsingborg, May 2016

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1. Introduction

1.1 Background

Today's grid is facing a huge change when most people and companies produce their own electricity in small installations through so-called microgeneration. Along with smaller wind turbines, solar cells are the most common electrical systems that are being installed in various areas and this development is still growing. One of the explanations for the growing interests in solar cells may be an increased awareness of the environmental and climate impact of today's fossil energy. Usage of renewable energy sources is more important than ever, especially in industrialized countries where the level of energy consumption is very high.

Microgenerators have also the possibility to reduce their energy cost significantly by producing their own energy and selling it to the companies, something that both producers and consumers can benefit from, thus have microgeneration gained attention due to its many opportunities.

1.2 The purpose

The aim of this bachelor thesis is to investigate how the power quality is affected by the photovoltaic systems, with a focus on variations in voltage and current for both single- and three-phase. This report will also focus on how customers contribute to disturbances on electrical grids when the microgeneration of solar cells is increased. Lastly, this report will also show how the sunlight affects the different power quality parameters.

1.3 The Objective

In summary, this work should answer the following questions:

- How do solar cells connected with single- and three-phase affect the power quality?
- What would happen if too many customers used solar cells connected to same network?
- What are the reasons for a bad power quality?
- What can be done to create a better power quality?
- How does the solar radiance affect the power quality?

The long-term goal is to increase understanding of solar cells impact on the power quality under different conditions. The results can be used as a basis for Öresundskraft to evaluate how photovoltaic systems affect the power quality in a negative or positive way.

1.4 Limitations

Any disturbances that spread to medium and high voltage network has been left out from this report since the measurements have only been done on low voltage network, which is the network that is most affected by interference since the solar cells are connected here. However, the probability of that interference can walk up to mid and high voltage is still high.

Wind power or any other microgeneration technology has not been taken into account because Öresundskraft have already done their evaluation on that, and their area of interest is the solar panel installments.
Some of the measurements for single-phase were not possible to do due to lack of time and equipment, but that should not be a big problem since the conclusions were still obtainable. Some power quality parameters of the simulations have been left out, parameters such as flickers, harmonics and unbalance, because there has not been any support for these parameters in the simulation program (xPower). It is possible that some of these parameters can cause problems if the number of photovoltaic systems installments increases. The simulations are done in worst case scenarios where the electrical power produced from the solar cells go out on the grid.

1.5 Öresundskraft

Öresundskraft is one of the Sweden’s major energy companies. Their vision is “Energy for a better world”, a vision that is indicative for all work in Öresundskraft. Their core business is the sale and distribution of energy (electricity, heating, natural gas, and district cooling), and sales of broadband and vehicle fuel. Sales and distribution of electricity are operated in two separate companies. They own the city network in Helsingborg [12].

2. Method

This section describes the methods and analysis used to achieve this projects aims and objectives. It also presents the grids and customers geographical placements, strategy behind the simulations as well as the equipment used for measurements.

2.1 Literature

A number of reports, web pages, books, and compendium have been used as a basis for this thesis. Most material was made available from Öresundskraft, which can be considered a reliable source. The sources of all information are presented in the reference list.

2.2 Data collection

All data that have been used for the simulation are from Öresundskraft program called Xpower. The measuring instrument Metrum, has given all data collected from customers and networks. Solar radiance measured in w/m^2 for Helsingborg are from Öresundskraft and some from SMHI.

2.3 Equipment

There were mainly two pieces of equipment used for measurements and data collection, Metrum and Pqube 3. All parameters for power quality have been measured both by metrum and with Pqube.

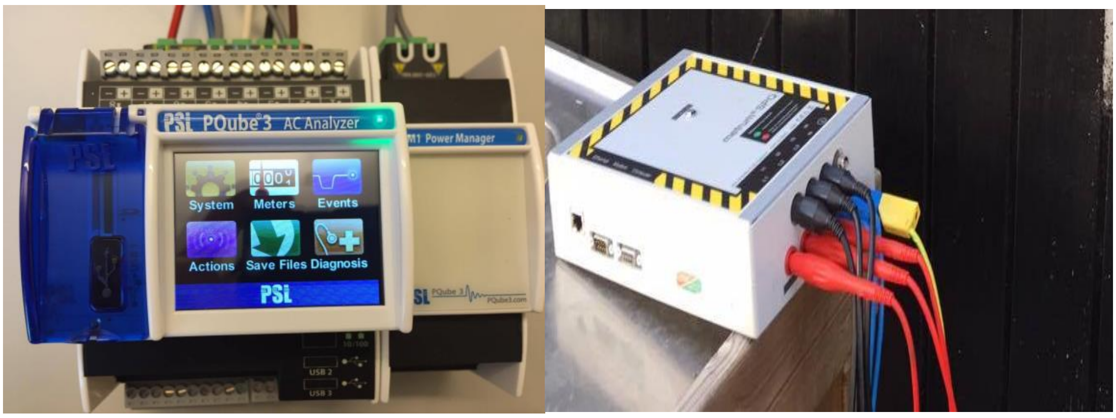


Figure 2: Measuring instruments PQube and Metrum (on right).

2.4 Workplace

All measurements were done on different places in Skåne, near Helsingborg. Each customer with solar cells has been measured in areas shown in the picture (check figure 3). The measurements took place from March 2016 to May 2016. Station networks from two of these areas (2 and 4) have also been studied. Metrum was placed on each area for several days so it could save all the necessary parameters needed for this study.

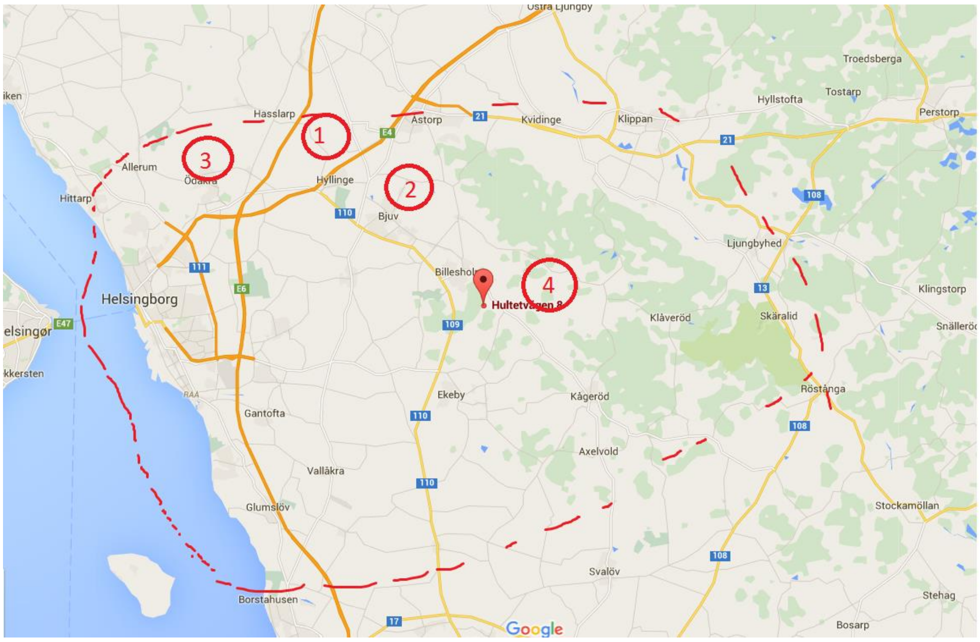


Figure 3: Map of areas where the measurements took place.

2.5 Work description

This work began from 16th February 2016, where Öresundskraft made some study material available that described all the different parameters that are necessary for understanding what power quality is. Two weeks were spent to read and understand all the material. There were some important facts to get a better understanding of, such as how variations in power quality happen, such as voltage variations, short-term interruption, harmonics, flicker, unbalance, and a lot of useful information on how to avoid such problems. The material also had important laws and standards that everyone must follow when it comes to power quality.

Measuring program began from 3rd March 2016. The first measurement was delayed because the instrument Pqube arrived later than expected since it was ordered from abroad. The first assignment from Öresundskraft was to test Pqube in the laboratories at the university. Pqube is a power quality analyzer from USA. With the help of supervisor Johan Björnstedt, Pqube installment went fine.

The first measurement started from 29th March, at a customer who lived 17 km away from Helsingborg. Metrum was placed there for 4 days. Three more measurements were done afterwards. A simulation was done on the second measurement where the main objective was to analyse what would have happen if all residents in that area used solar cells. Two more measurements were done in the end, and the last period (May), was the analysing phase where all results and measurements were compiled. Everything was done by May 15th.

The communication with the supervisors were great and they helped a lot on each step. The schedule was made really well because it is necessary to study all information and know the basics before going out on the field. It makes the study and measurements a lot easier. Therefore, it was important to have two weeks of self-study before going into the main study.

All collected values from Metrum were registered into an excel document. The measurements were done every 10 minutes, which made it easier to compare those with the solar radiance since they also were registered every 10 minutes.

2.6 Source criticism

Sources used in this report are reliable. Most of the material, as mentioned above are from Öresundskraft. No sources such as Wikipedia or any other that can be written by anyone have been used for this thesis. One of the main sources “Emc och Elkvalitet” have been written by experienced engineers and project leaders (more info in the reference list).

3. Definitions and terms

Subject-specific definitions and terms used in this report are described below. The idea is that these explanations will help the reader to understand the content, even if someone lacks advanced knowledge about power electronics and energy.

Real power/Active power (P)

The portion of power from a power source that is useful, of a system that is doing work. Active power is measured in watts (W). It is calculated from these equations:

(1) Single-phase: $\boldsymbol{P = UIcos\,\varphi}$
(2) Three-phase: $\boldsymbol{P = \sqrt{3}UIcos\,\varphi}$

Where U is the voltage, I the current, and cosα the power factor. Active power reduces, the larger the phase shift. Phase angle is between current and voltage.

Reactive power (Q)

The portion of power from a power source that is not useful from a system that is doing work. Reactive effect is measured in Volt-amperes reactive (VAr). It is calculated from these equations:

(3) Single-phase: $\boldsymbol{Q = UIsin\,\varphi}$
(4) Three-phase: $\boldsymbol{Q = \sqrt{3}UIsin\,\varphi}$

Where U is the voltage and I the current. The reactive power is the energy per second that goes into the electrical field in a capacitor or the magnetic field of an inductor.

Apparent power (VA)

The real effect that a device requires from a power source is termed apparent power. It is measured in Volt-amperes (VA) and is the voltage on an AC system multiplied by all the current that flows in it. The equation is:

(5) $\boldsymbol{S = UI = \sqrt{P^2 + Q^2}}$

The relation between P, Q and S can be shown from the triangle in figure 4.

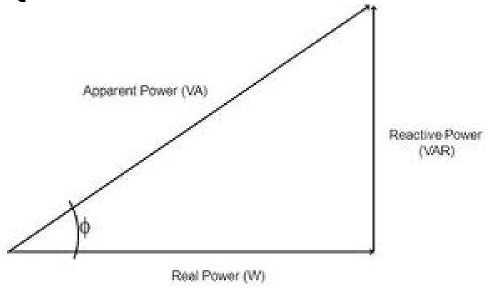


Figure 4: Power triangle showing the relation between active-, reactive- and apparent power

Short-circuit power

Short-circuit power is the electrical power which occur during normal operating voltage at a point in the network, just before the short circuit occurs. A short circuit I_k occurs when the fault occurs. A strong network has a high short-circuit power, whereas a weak network has a low short-circuit power.

RMS

Root mean square. It is the process used to determine the average power output. Used for example to set the value of alternating voltage and corresponds to the value needed to develop the same effect as a constant DC voltage. Equation below describes the formula for calculating the RMS for a single-phase system with a peak voltage of 325V.

(5) $\boldsymbol{RMS = \frac{Peak\ voltage}{\sqrt{2}} = \frac{325}{\sqrt{2}} \approx 230\ V}$

Resistance (R)

Resistance that indicates the current limiting capability in an electrical circuit with DC. Ohms law below gives a relation between resistance, voltage and current. Resistance is measured in ohm.

(6) $\boldsymbol{R = \frac{U}{I}}$

Reactance (X)

A form of opposition that electronic components exhibit to the passage of alternating current because of capacitance (X_c) or inductance (X_L). Resistance and reactance combine to form impedance. The capacitive and inductive reactance is found using equations below:

(7) $\boldsymbol{X_C = \frac{1}{2\pi * f * C}}$ (ohm)
(8) $\boldsymbol{X_L = 2\pi * f * L}$ (ohm)

Where f is the frequency, C the capacitance and L the inductance.

Impedance (Z)

The total resistance of an electrical circuit with AC called impedance. Impedance is a vector (two-dimensional) quantity that consists of two independent scalar: resistance and reactance. The two resistors are perpendicular to each other and form the impedance complex number Z. The relation between R, X, and Z can be described from the triangle below:

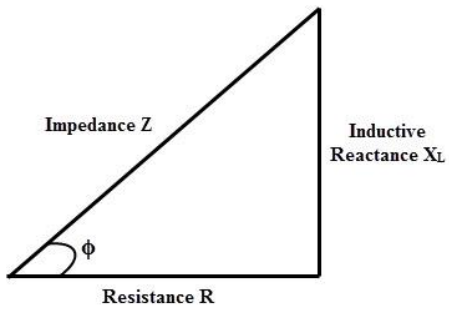


Figure 5: Triangle showing the relation between resistance (R), reactance (X) and impedance (Z)

Load

Load is used to describe the power output a customer retrieves from the network. All electrical appliances that require current contributes a load that consumes energy.

Connection point (anslutningspunkt)

The point at which electrical energy is transferred between the electrical network and customer equipment.

Power protector (reläskydd)

A device that detects abnormal conditions in the system and gives signals indicating the problem.

Junction (sammankopplingspunkt)

The point in the electrical network where more than one user are connected. At this point one can both supply and consume electricity.

Unbalance

The voltage of the three-phases is not equal.

THD (total harmonic distortion)

A measure of harmonics.

Harmonics

Voltage and current components having a frequency, which is an integer, multiple of the frequency of 50Hz. Harmonics are a result of non-linear electrical loads and are a frequent cause of power quality problems [1].

4. Theory

This section presents the basic theory behind concepts such as power grids, power distribution, microgeneration, solar cells, electrical environment, power quality, voltage fluctuations and asymmetry. This section also deals with rules and regulations that the electrical companies must follow so they can deliver a good power quality.

4.1 Power grids

Today’s Swedish electricity network consists of three levels: the national grid, regional grid and the local grid. These three grids together are approximately 552000 km and consists of 329500 km underground cables and 215000 km aerial cables. The electrical network has a delivery performance of 99,98% and is owned by approximately 170 companies, where each company has their right within their geographically area to provide electricity to customers. The national grid, however, has only one owner: the state enterprise and authority Svenska Kraftnät (SvK), which maintains and develops the basic infrastructure. The national grid consists of 15 000 km high voltage cables of 220 kV and 400 kV [6].

The regional network consists of a voltage around 130 kV, whereas in the next grids, the voltage is transformed down to at least 40 kV and then about 10 kV on distribution stations. In the transition to the low voltage station, the substation transforms the voltage down to 0,4 kV, which then connects to the customers connecting points. The regional and local networks are owned by private or public operators that have the obligation to make the network available to consumers in a specific geographical area. [6]

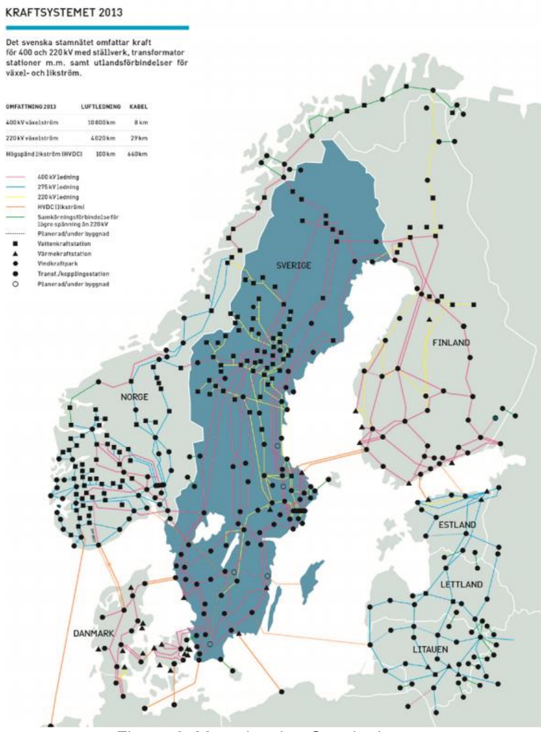


Figure 6: Map showing Sweden’s power system.

4.2 Power distribution

To transfer electricity over long distances means losses in energy and cost. That is the reason why the national grids voltage are up to 400 kV three-phase alternating current at the power plants. Transport cables that have low voltage levels, must increase the current level to transfer the same amount of power, which also generates greater energy loss as heat. These losses turn into large voltage drops along the cables, and a potential difference occurs. The voltage drop increases along the cables the higher the impedance is. This generally means that a powerful cable has low impedance and can provide all customers along a radial network with the same voltage, while poorer cables drop a lot of voltage so that customers who live far out in the network receive lower voltage. To counteract an unacceptable low voltage at customers, the transformer has a slightly higher voltage. Main voltage depending on the current and impedance can be described by the following equation:

(9) $\Delta U = \sqrt{3}RIcos\varphi + \sqrt{3}XIsin\varphi$

Where R is the resistance, X the reactance, I the current and α the phase angle.

Example:

A customer lives far away on a weak network. The network has a voltage drop from 230V at the transformer to 220V at the connecting point. To counter this, the transformer's voltage has been increased to 240 V, which in return provides the customer with a voltage of 230 V. See fig. 7 respective 8:

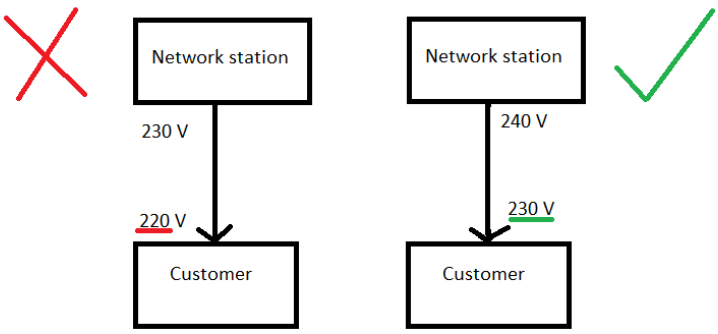
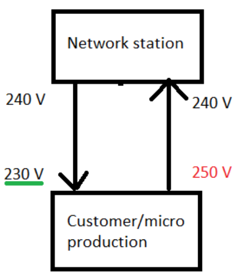


Figure 7: A picture over the voltage drop problem that can occur on weak networks.

Now assume that the customer owns solar cells and can produce electricity, then sell the surplus to the grid. When the sun shines, the customer will get an increased voltage at the connection point since the transformer already is above rating voltage (märkspänning). Check figure below:



Sunlight can vary a lot due to rapid weather changes, giving the customer rapid voltage changes between, for example 230V to 250 V. Keep in mind that this example is oversimplified.

Figure 8: Scenario if customer is using PV-system

Power distribution grids that contains many electrical motors have an energy storage in the machine's rotating mass, which means that the grid has an "inertia" that opposes rapid voltage changes. This stabilizing phenomenon is found primarily in large grids and works better the higher short circuit power the grid has.

The grids at local level are often constructed in different ways depending on what kind of environment they are placed in. The distance between customers and the load they want, place different demands on grid dimensioning. Electricity use varies on different season and times for villas, apartments and offices. All these factors put different demands on power quality, and therefore it must be adjusted accordingly [15].

4.3 The storage power (Sammanlagringseffekt)

When constructing the network grids, it is important to use well-dimensioned cables to avoid overload, but a well-dimensioned grid is not cost effective. It is therefore better to construct grids out from the power that might flow in each specific area. However, constructing cables out of the total maximum effect that the customers consume within an area is rarely necessary. The probability that all customers have their maximum power demand at the same time is small. Instead, one use something called the storage effect, which describes the relationship between the maximum demand of all customers at the same time and the maximum possible power in a system. It can in the simplification be described by the following equation:

(10) $$Storage\ effect = \frac{Maximum\ power\ demand\ of\ customers\ at\ the\ same\ time}{Maximum\ possible\ power}$$

It shall be mentioned that several micro-production together can create a negative interaction that can create interference outside the limit values or reinforce each other. This means that it is important to check the local conditions of the network before connecting a large proportion of micro-production in the same neighbourhood. This phenomenon also contributes to a complicated discussion about who is responsible and liable for any grid reinforcements [2].

4.4 Electrical environment

Being able to maintain a good electrical environment is a requirement in today's society. Dependence on advanced electronics is constantly increasing and use of sensitive electronic equipment, which can both disrupt and be disrupted from other devices.

4.4.1 Power quality

The definition of power quality is formulated in the Swedish legislation and is based on a number of European standards. The concept refers to the quality of the electricity supplied from a grid station to a customer, thereby judging the electricity capacity to satisfy a user's needs. A summary for all the parameters affecting the power quality are described in figure 9.

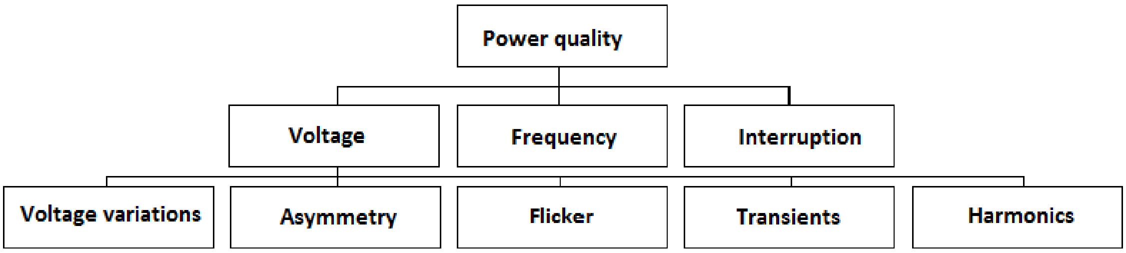


Figure 9. Schematic representation of the parameters that defy power quality [20].

The power quality can be determined by comparing the differences in waveform, frequency and voltage symmetry with a corresponding ideal grid. The differences that arise can be divided into non-periodic processes: voltage variations, over and under voltage, transients and flickers, while the periodic processes summarizes harmonics in current and voltage. These disruptions arise from the connections in power grid, connections and disconnections of loads, lightning, non-linear loads, or power production from for example solar or wind power [14].

4.4.2 EMC

Electromagnetic Compatibility (EMC) describes the electrical equipment regulations ability to function satisfactorily without affecting or being affected by its electromagnetic environment. An equipment's EMC describes how well the components work is in its electromagnetic environment (immunity, according to the standard EN 61000-6-1) and how much influence the equipment's interference contributes (emission, according to standard 61000-6-3). EMC is therefore about how to avoid these problems [1].

4.4.3 Grid quality

Describes the grids ability to withstand voltage fluctuations during changes in load and production. A weak power grid gets disturbances easier than a strong power grid. A good grid power is thus an important parameter for achieving a high power quality. In a low-voltage grid, the strength depends on transformers, area of cables and impedance. High impedance leads to a weak grid, while high short-circuit power contributes to a strong network, as mentioned earlier [1].

4.4.4 Flicker

Flicker is a measure of repeated variations (fluctuations) in a voltage, which results in that light from lamps behaves like a pulse or flash. It requires a voltage change of 1-2 V with 230 V supply for the eye to detect flicker as flashes. This disturbance is caused by frequent disconnection and connection of loads, often combined with a weak grid. Sources that may cause flicker can be heat pumps, induction cookers, rolling mills, welding machines etc. Flicker is measured with two different measurements, Pst, which stands for short term flicker and is measured with 10 minute interval, and Plt, which means long term flicker, and is measured during an interval of 2 hours [1], [2].

4.5 Voltage fluctuations

Voltage fluctuations are defined as repetitive or random variations in the magnitude of the supply voltage. An ideal voltage should be completely sinusoidal, have precise nominal effective value, an exact nominal frequency and be fully balanced between the three-phases. Voltage fluctuations occur in the power grid due to changes in the output terminals of the connected customers, so called load dependent voltage variations that disrupts the smooth voltage curves. The magnitude of the variation is due to the major changes taking place at the network loads, and the grid can during certain periods get too high or too low voltages. Power grids with low impedance get smaller and slower variations, while grids with long cables and high impedance can have bigger variations.

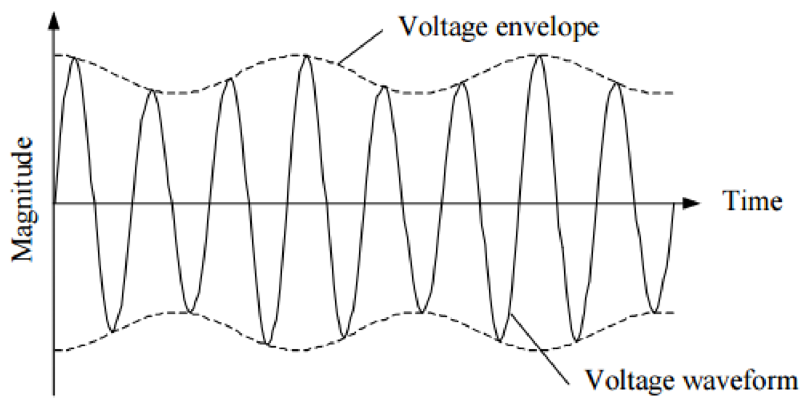


Figure 10. Illustration of voltage changes [7]

In a situation with increased amount of photovoltaic systems, the voltage variations also occurs because of the bidirectional power flow that occurs when customers have a surplus of electricity. Short voltage variations can also occur when skies shade the panels and the production from solar cells gets a sudden stop [7].

According to the Energy Supervisory Authority (EIFS 2013:1), a short voltage rise is defined as a temporary increase in the voltage effective value (RMS) to over 110% of the reference voltage. Similarly, short voltage drop is defined as a temporary lowering of the voltage RMS under 90% of the reference voltage.

The limit for slow voltage changes is reached when a ten minutes value of the RMS value exceeds or falls below 90% and 110% of the reference voltage during a period corresponding to a week.

Restrictions on short voltage reductions for voltages less than or equal to 45kV can be seen in table 1. Area A in the table represent the area that is considered acceptable for interference and no action is necessary. Area B is the area where the grid owner must take steps to improve the quality so the condition is fair for the electricity user. Area C is unacceptable.

U (%)	t (ms)				
	$10 \le t \le 200$	$200 < t \le 500$	$500 < t \le 1000$	$1000 < t \le 5000$	$5000 < t \le 60000$
$90 > u \ge 80$	A	A	B	B	B
$80 > u \ge 70$	A	A	B	B	B
$70 > u \ge 40$	A	B	B	B	C
$40 > u \ge 5$	B	B	B	C	C
$5 > u$	B	B	B	C	C

Table 1. Limits for short-duration voltage variations.

Chapter 7, § 8 of the EIFS 2013: 1 also states that it shall not occur any momentary voltage increases with such residual voltage and duration presented in area C in table 2. In case of short voltage reductions, the grid owner is responsible for the disturbances that occur to the client.

U (%)	t (ms)		
	$10 \le t \le 200$	$200 < t \le 5000$	$5000 < t \le 60000$
$u \ge 135$	C	C	C
$135 > u \ge 115$	B	B	C
$115 > u \ge 111$	A	B	B
$111 > u \ge 110$	A	A	A

Table 2. Limits for short-term voltage increases.

A rapid change in voltage is defined as a change in the Voltage RMS value that is faster than 0.5% per second, and where the voltage RMS value is between 90-110% of the reference voltage during an entire process. These are further divided into stationary and maximum voltage changes, where $\Delta U_{stationary}$ is the difference between the RMS value before and after the change. ΔU_{max} is the the maximum voltage change during a voltage change course, check figure 3. These are limited in number for one day where they are added to the number of voltage changes in the range of A in table 1 and 2.

Rapid voltage changes	Maximum number per day
$\Delta U_{Stationary} \geq 3$ %	24
$\Delta U_{max} \geq 5$ %	24

Table 3. Limits for rapid voltage changes.

Worth noting is that short voltage changes are temporary variations of the voltage RMS value of at least ± 10 V of the reference voltage, while a rapid voltage change is defined as a change of the RMS value in the range of ± 10 V of the reference voltage, but the variation must be faster than 0.5% per second [15], [16].

4.6 Unbalance

In the ideal case, the power is distributed symmetrically between the three-phases with sinusoidal voltage. However, asymmetry occurs in reality, as the low voltage grid often gets an unbalanced power distribution from the customers load, while in mid and high voltage grids unbalance is caused by uneven impedances [1], [2]. The key idea of symmetrical component analysis is to decompose the unbalanced system into three sequence of balance networks. The three sequence networks are known as the [22]:

- Positive sequence
- Negative sequence
- Zero sequence

Check figure 12 for example.

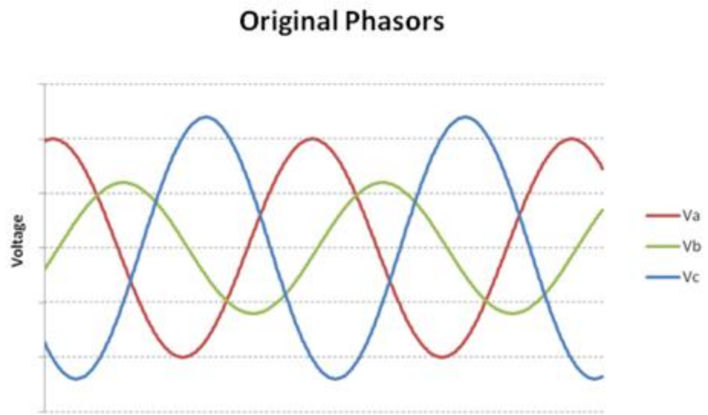


Figure 11. Illustration of three unbalanced voltage waveforms.

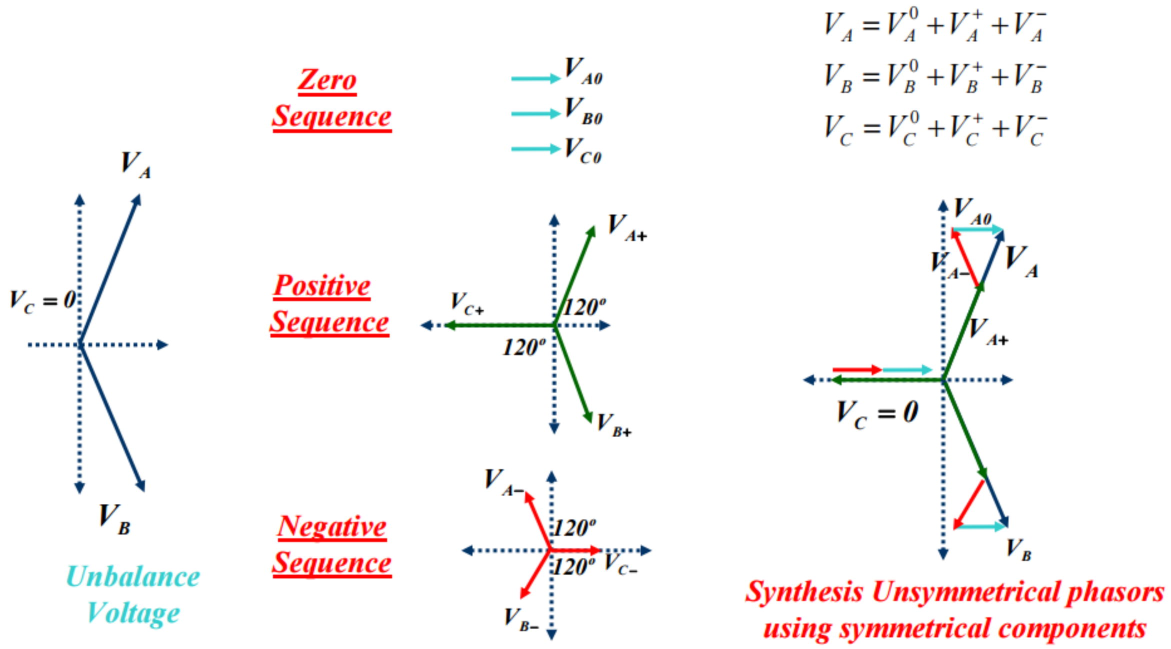


Figure 12. Example of symmetrical components. Decomposing an unbalanced system.

The limit of voltage unbalances exceeds when a ten-minute value of voltage asymmetry reaches 2% for a period equivalent to one week. According to the Energy Supervisory Authority (EIFS 2013:1), chapter 7. One of the consequence of asymmetry is the shortened life expectancy of electrical appliances, impaired efficiency, heat loss and breakdowns, which in turn can lead to downtime and can cost a lot for both customers and companies.

4.7 Microgeneration

Microgeneration refers to small-scale energy in electric power. It may include wind, solar or hydroelectric power. These three sources of energy provide renewable electricity. The technology behind the solar power is rapidly being developed. There will be new demands on the grid when the microgeneration will increase. Giving away good power quality is a prerequisite. The definition of microgeneration requires a fuse size of maximum 63 A, which limits the installed power to 43,5 kW at 230/400 V. From an economical perspective, the interest in microgeneration will become self-sufficient in electricity. Electricity has a higher purchase price than the selling price. The reduced costs for the purchase of electricity helps to offset the constructions cost [2].

4.8 Solar cells

Solar cells convert sunrays into electricity. Photons of the light excites the electrons and form a current. It is estimated that a small photovoltaic plant of 14 m^2 with a maximum power of 2 kW can generate approximately 1600 to 2000 kWh per year. In 2009, the Swedish average house had an annual use of electricity at 6000 kWh, a solar panel of this size could supply a third of it.

According to Svenskenergi, 20% of all Swedish house owners are considering to invest in their own electricity production from solar panels or small wind turbines in the five upcoming years. In addition, more than a third of those are living on the farm, or in a villa in rural areas are considering investing in their own generation. Furthermore, research has shown that the biggest driving force for owning an electricity production is the ability to save money, followed by environmental reasons. In 2013, 19MW solar panels were installed in Sweden [8].

Figure 13. Picture of solar panels of one of the customers.

4.10 Inverters

Inverters are needed to convert DC into AC. Each solar panel system has one or more inverters that sends AC to the main breaker box at houses. Solar panels efficiency depends largely on the inverter and the choice of the inverter size is selected depending on the quantity of electricity from the solar panels.

It is the choice of the inverters that determine if the panels are connected to single or three-phase. Connecting three single-phase inverters on each of the phases is not equivalent to the installation of a three-phase inverter. A scenario where three solar panels are placed in three different directions, or subjected to various degrees of shading can explain this. In this situation, each solar panel is producing different amount of electricity, which gives unbalance between the phases.

4.11 Total harmonic distortion

Harmonics are voltage or current components with a frequency which is an integer multiple of the waveform's fundamental frequency 50 Hz. Non-linear loads can draw current that is not perfectly sinusoidal, which might give a distorted waveform. Total harmonic distortion (THD) can be calculated by equation 11.

$$(11)\ THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1}$$

Multiplying the result with 100 will give a percentage comparing the harmonic components to the fundamental component of a signal. Higher percentage means more distortion [1], [21].

4.12 Solar cells future

Increased production of electricity from solar cells can reduce costs for photovoltaic systems. According to a report from Elforsk one can expect a reduction in costs for the whole system of about 14% for each doubling of installed power. According to Elforsk, the capacity in the world is expected to be about 200-800 GWp by 2020 and 800-2000 GWp by 2030. If the solar market continues to expand further, the issue of resources can be a challenge that will affect the technology. Continued development of the solar cells will largely be influenced by how the price of electricity changes during the coming years.

Figure 14. “The future is here” [9].

5. Result

This section presents the results obtained with respect to different factors, namely voltage drop, voltage variations, asymmetry, harmonics, and how all of these are affected by the sunlight.

5.1 Simulation: Sunlight and parameters from three-phase solar panel system

Figures below are showing how sunlight affects the different parameters in power quality. Parameters such as power, voltage, current, unbalance and flicker. Each figure has been made out of the RMS value of true power each customer produced during the time measurements took place. The solar radiance is from Helsingborg obtained from Öresundskraft. Keep in mind that whenever the power is negative, the customer is producing electricity, and consuming when it is positive.

5.1.1 First customer with three-phase solar panel system (29th March – 3rd April)

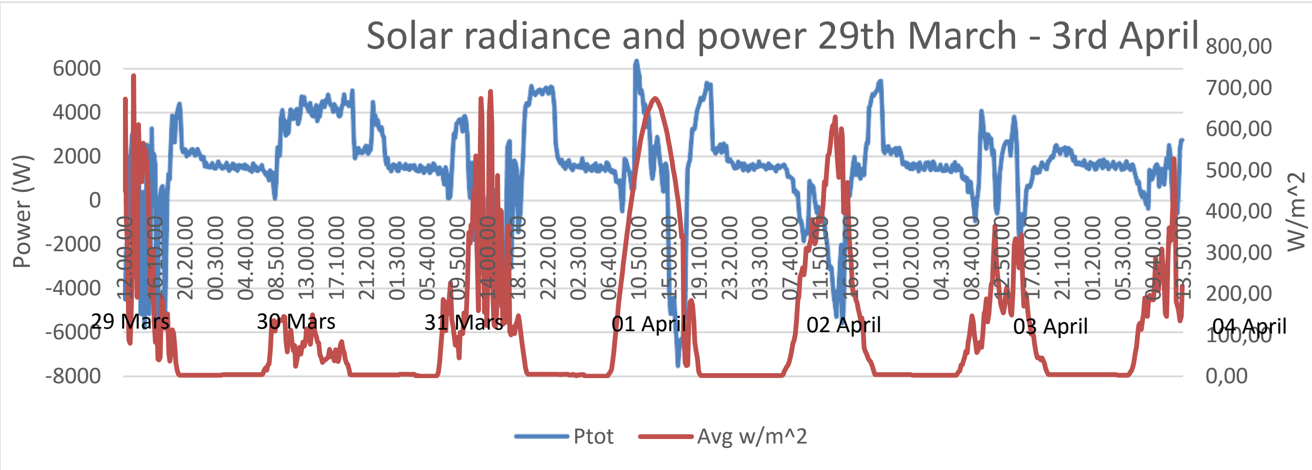


Figure 15. Solar radiance (secondary axis) compared with power values (primary axis) from the first customer's solar panels. Measurements took place from 29th March to 04th April.

Notice that the sunlight is as strongest from 1200-1500. It should be noted that the customer produced most power 1st April from 1500 – 1600, at around -7500 W. The power is positive most of the time, meaning that the customer consumed more energy than producing. Reasons and more in depth analysis are found in the Analysis chapter.

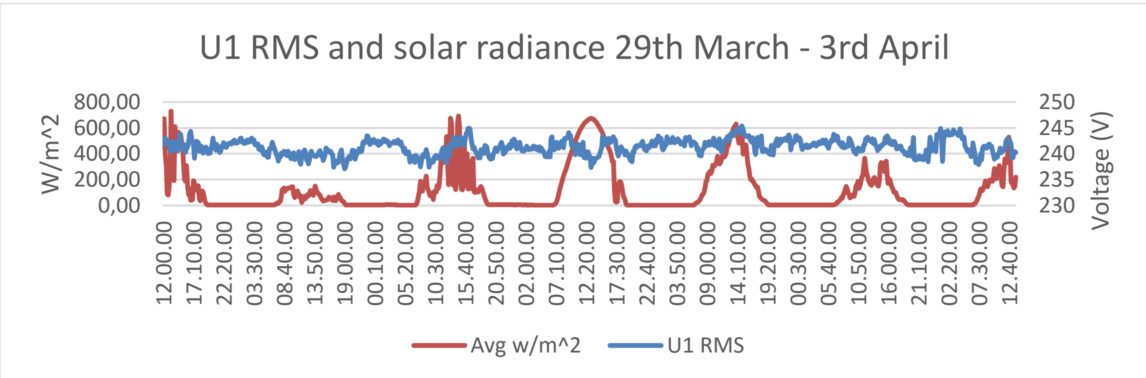


Figure 16. U1 RMS (Voltage) compared with solar radiance. Measurements took place from 29th March to 04th April.

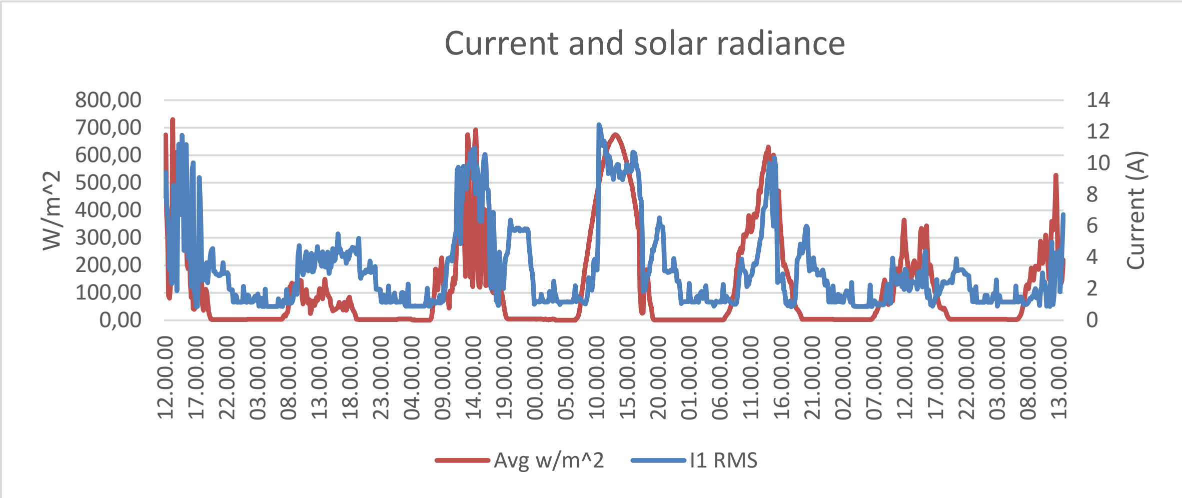


Figure 17. Current (A) compared with sunlight values from Helsingborg. Measurements took place from 29th March to 04th April.

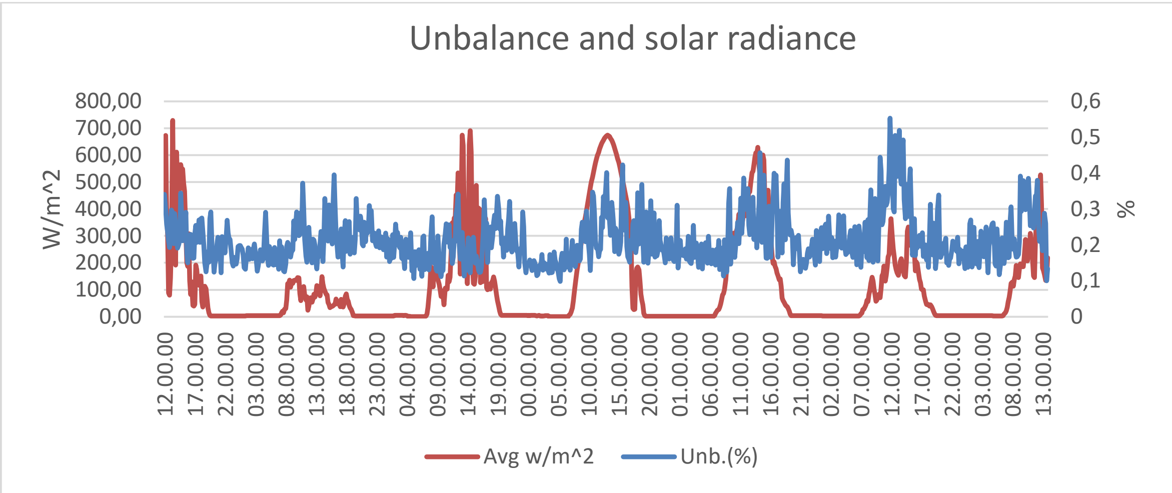


Figure 18. Unbalance (%) compared with solar radiance. Unbalance values are under the limit, which is 2%. Measurements took place from 29th March to 04th April.

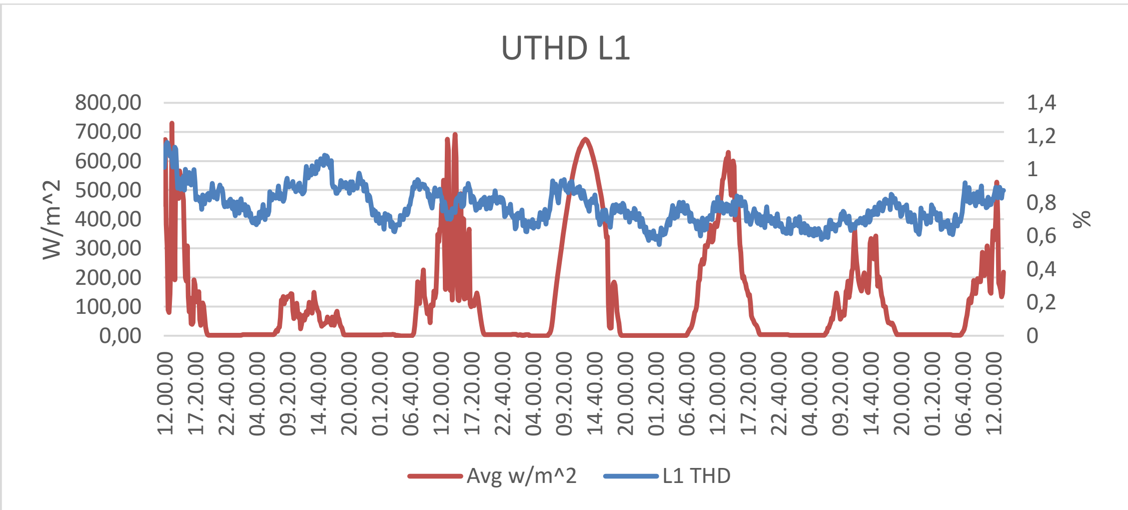


Figure 19. Harmonics UTHD for the first phase (L1) compared with solar radiance.

5.1.2 Second customer with three-phase solar panel system (11th April – 13th April)

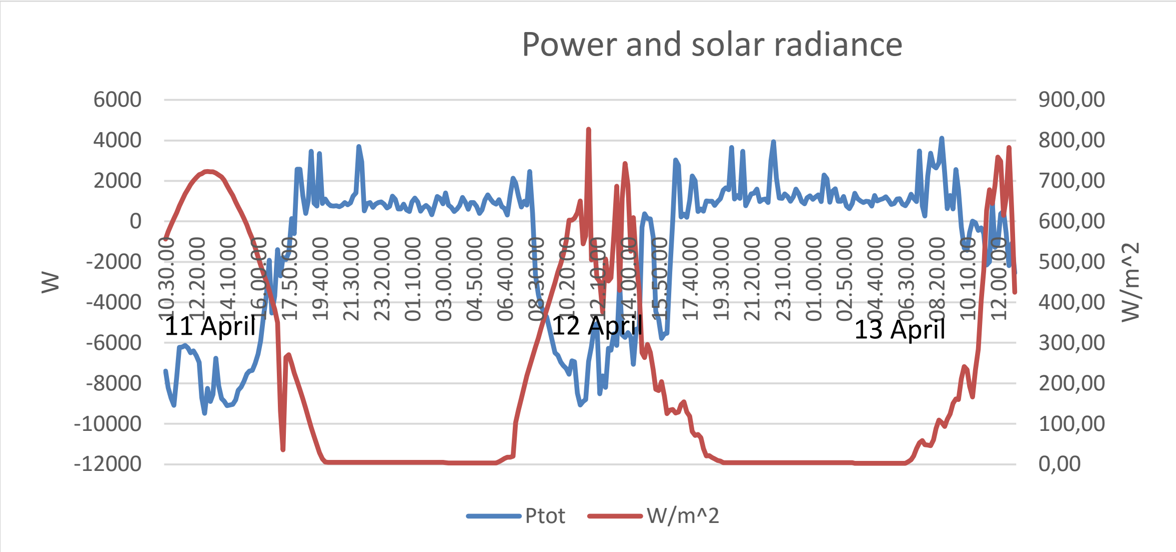


Figure 20. Second customer's effect compared with solar radiance.

Second customer's graph is more accurate than the first customer's. First of all there was better weather during this time (11th April – 13th April) compared to the weather from 29th March – 3rd April. Another factor that affects the power is the equipment the customers are using. Equipment that consumes electricity affects the production.

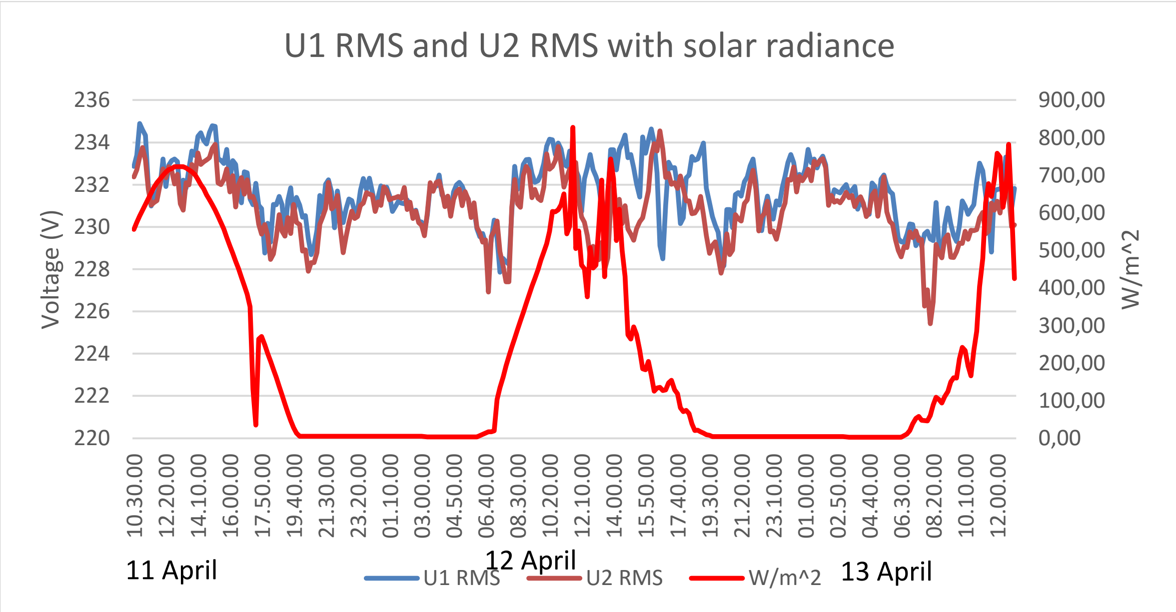


Figure 21. Voltage of two phases (U1 and U2) compared with solar radiance.

The customer has an electrical car that charges mostly at night. But on which phase does the car charge?

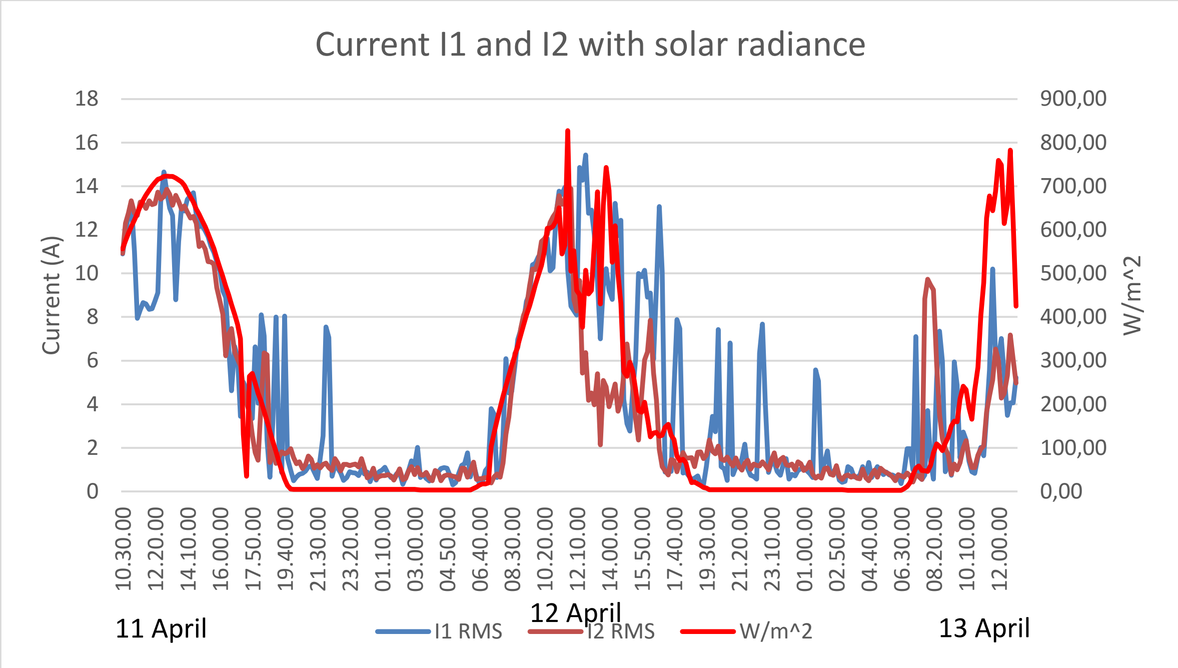


Figure 22. Current from two of the phases (I1 and I2) compared with the solar radiance.

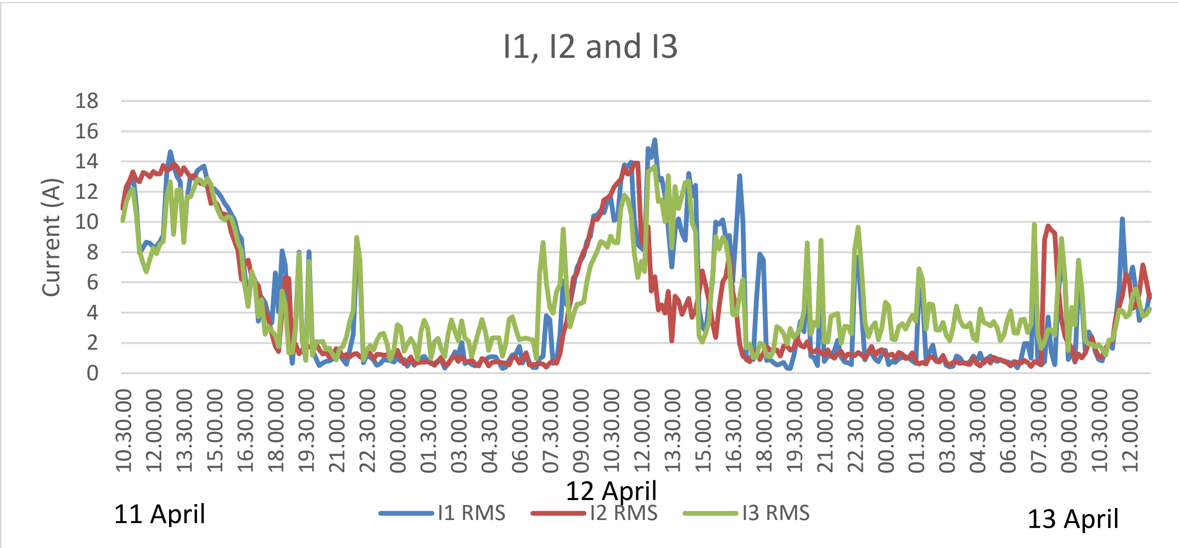


Figure 23. Current for all three-phases.

The customer charges the car on one of these phases. As mentioned earlier, the electrical car is charged between 1800-0700. The customer also had two heat pumps. Heat pumps turn on and off to stabilize the temperature, which means that the current will drop and increase all the time. Judging from figure 23, I1 and I3 have this drop-increase graph leaving one ***guess*** that the car might be charging on phase two, since the other phases are connected to the heat pumps. Keep in mind that there might be other things too that are connected to these phases and they also affect the electricity, therefore this conclusion cannot be 100% accurate.

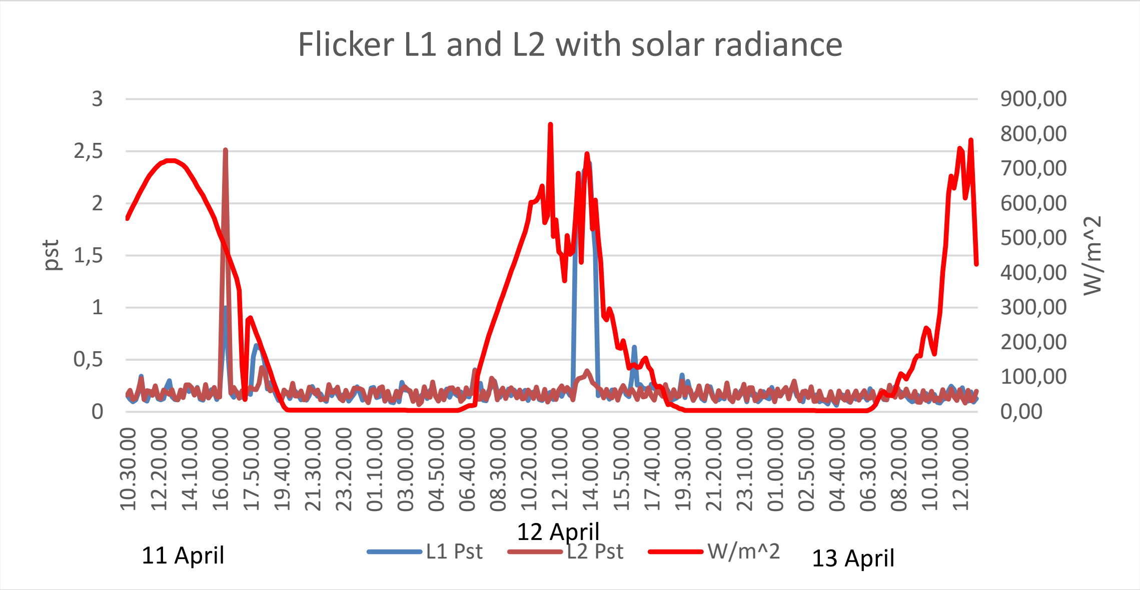


Figure 24. Flicker from L1 and L2 compared with the solar radiance. Note that there are some high flicker values in some areas.

Figure 24. Has some high flicker values in some areas. There must have been some voltage variations during these times (check figure 25).

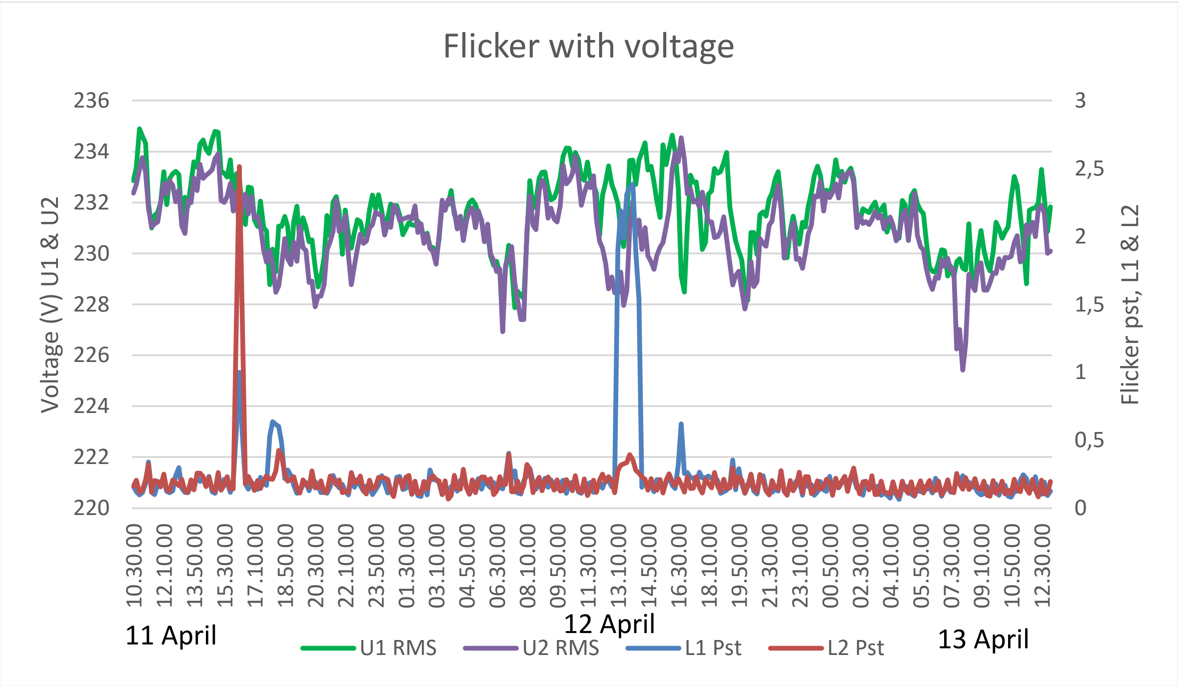


Figure 25. Flicker compared with voltage.

Production:

Before (kWh)	After (kWh)	Total production (kWh)
10796,8	10947,3	**150,5**

Table 4: Table showing the production from 11th April to 13th April.

Consumption:

Before (kWh)	After (kWh)	Total consumption (kWh)
11326	11364	**38**

Table 5: Table showing the consumption from 11th April to 13th April.

Sold energy

Before (kWh)	After (kWh)	Total sold (kWh)
6823	6935	**112**

Table 6: Table showing the amount of energy sold (to Öresundskraft) by the customer from 11th April to 13th April.

Table 4-6 shows the values of energy the customer produced, consumed and sold during these three days the measurements took place. The customer produced and sold more energy to Öresundskraft than what he consumed. All these values were noted before and after the measurements took place.

5.1.3 Third customer with single-phase solar panel system (15th April – 18th April)

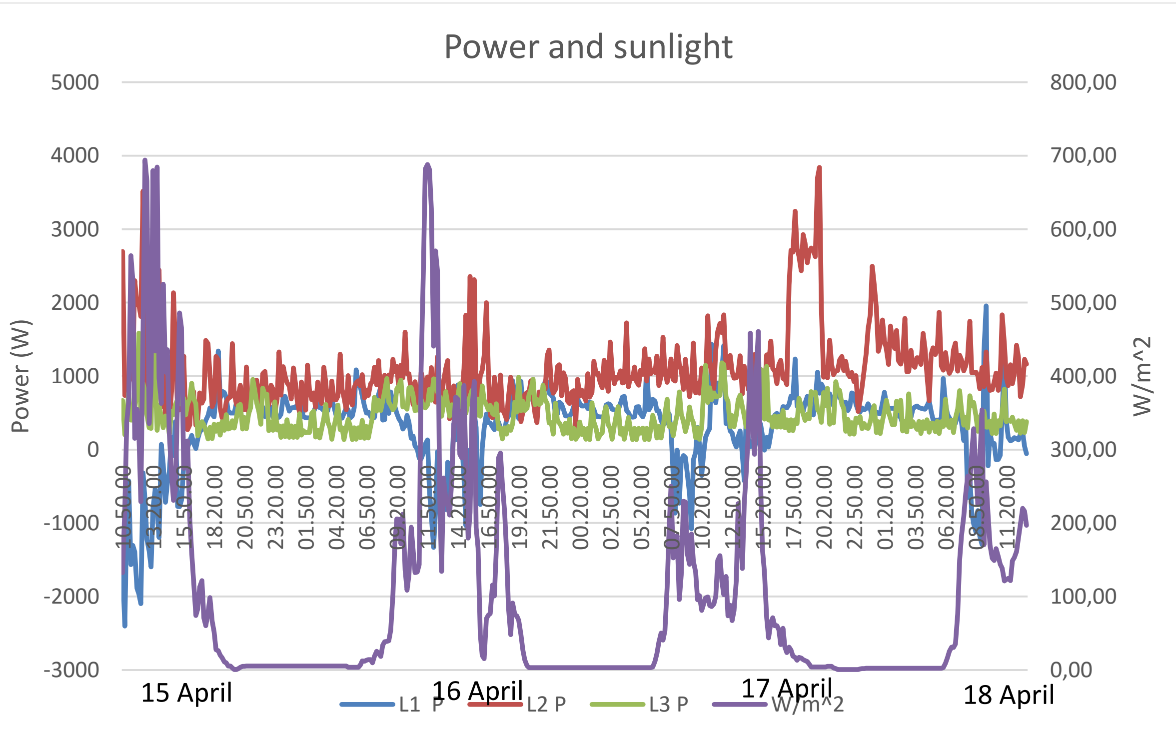


Figure 26. Power of the three-phases compared with the sunlight

The owner did not know on which phase (L1, L2 or L3) the solar cells were connected to. Figure 26 shows the true power of all the three-phases. Which graph correlates best with the sunlight? Whenever the sunlight intensity is high, the owner is producing the electricity, which means that the power will be negative. The only phase that matches with this criterion is phase L1. Figure 27 gives a closer view of L1 and sunlight.

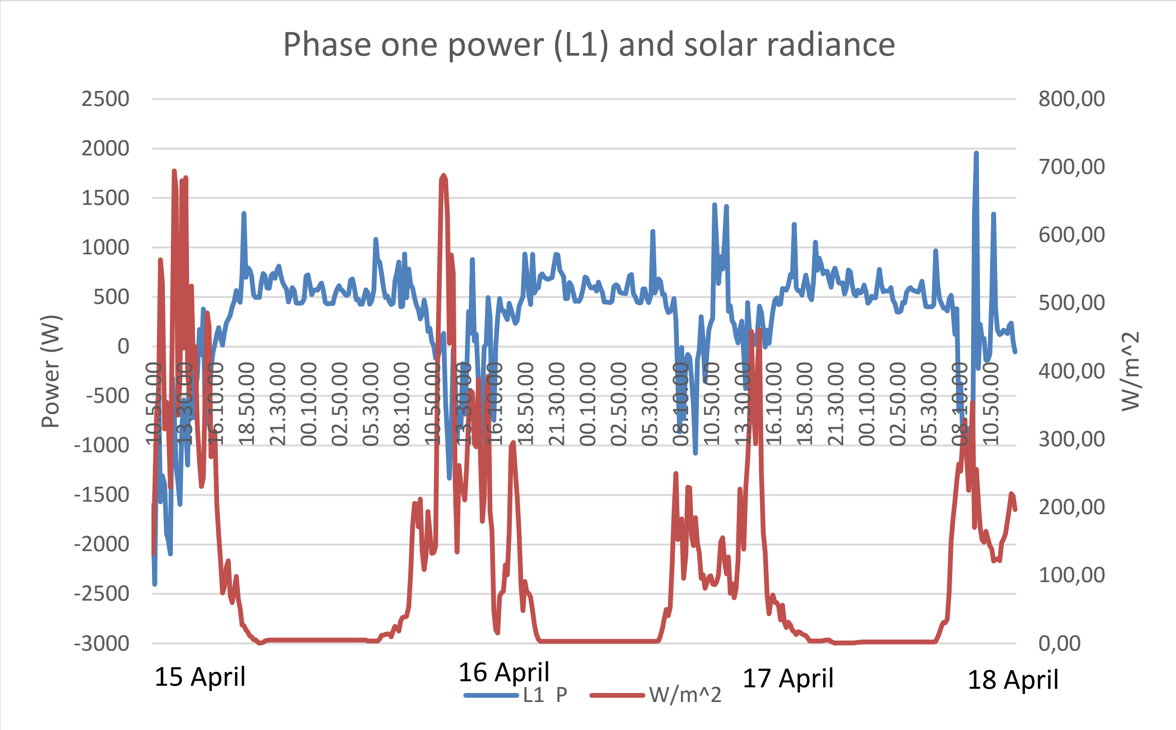


Figure 27. Power from L1 compared with solar radiance.

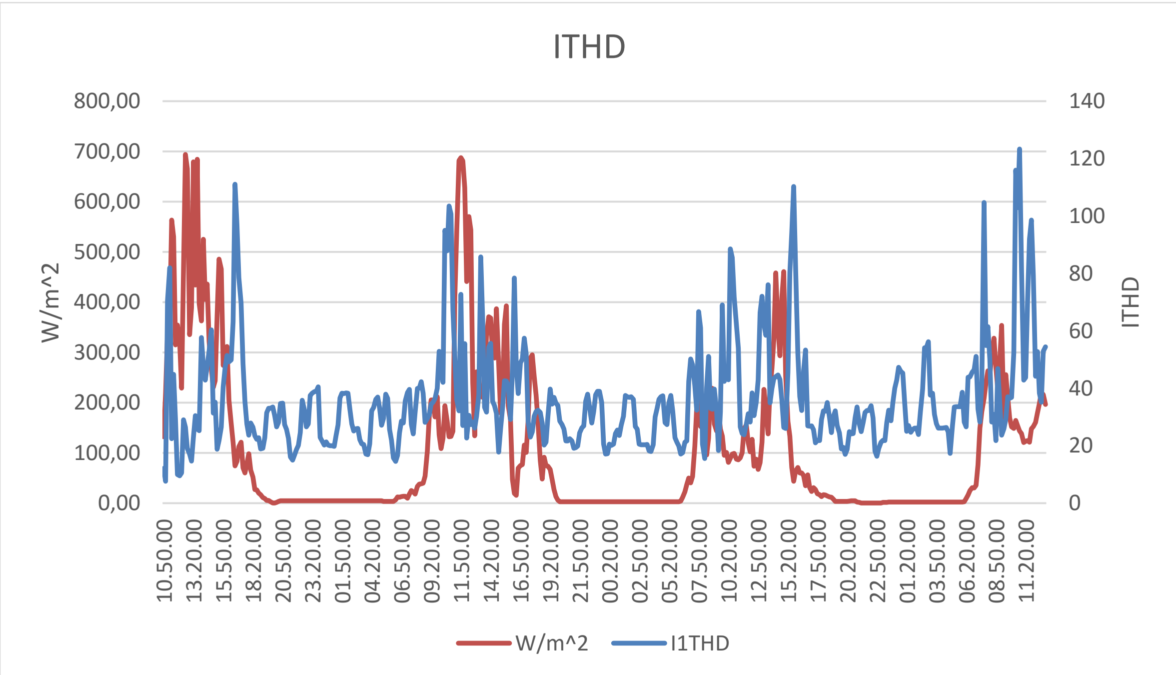


Figure 28. Harmonics for current I1 compared with solar radiance

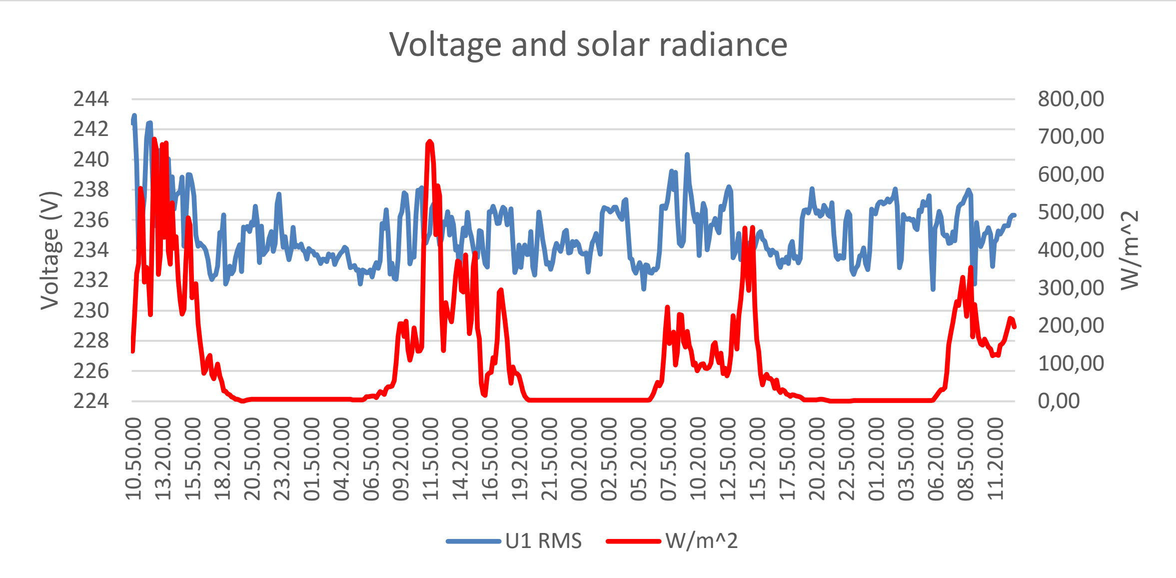


Figure 29. Voltage U1 compared with sunlight

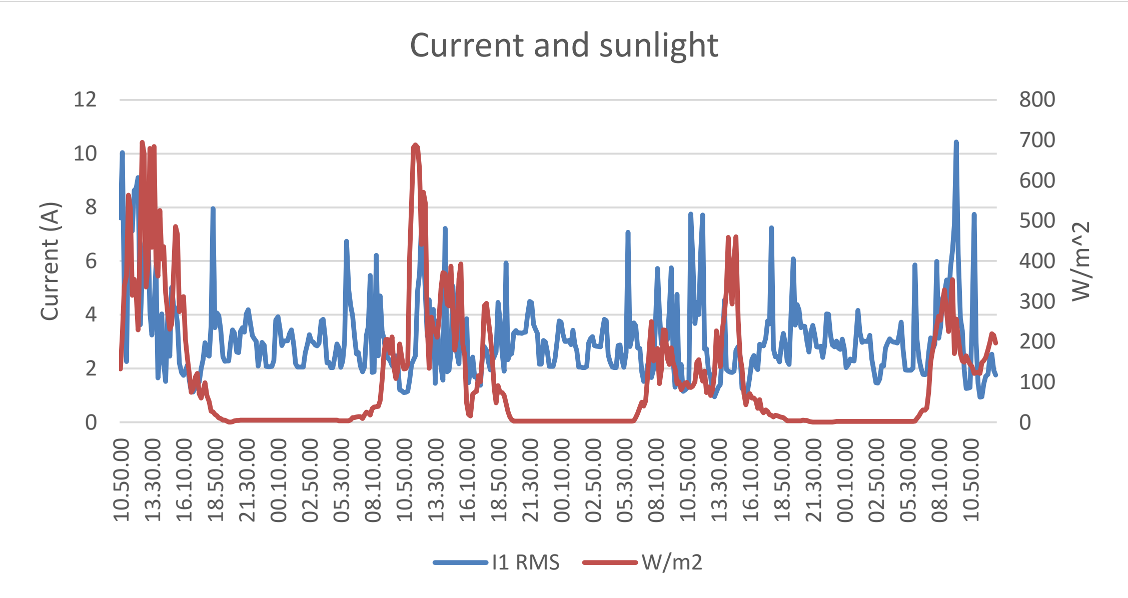


Figure 30. Current for the first phase compared with the sunlight.

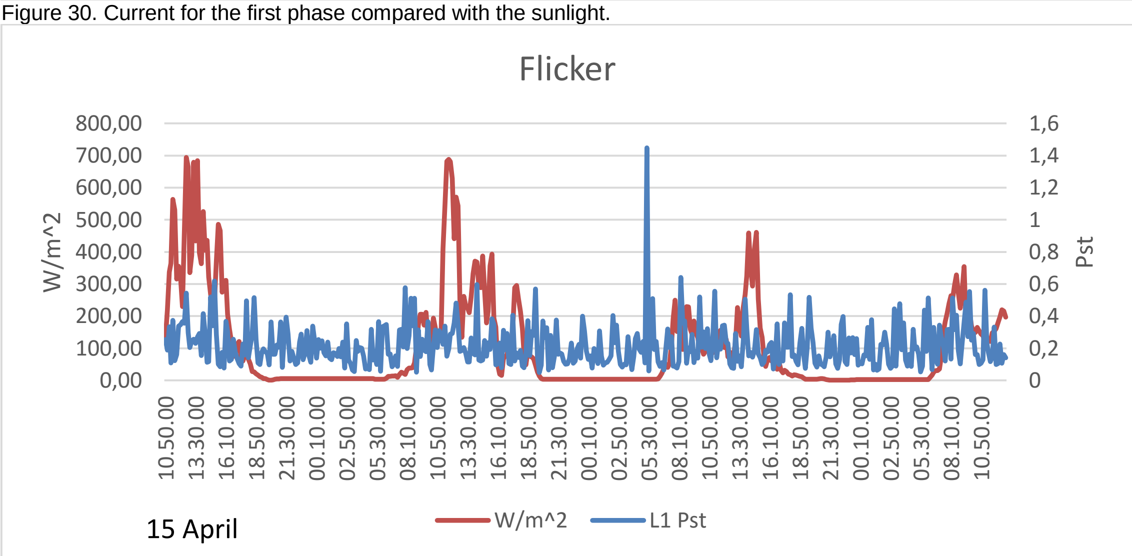


Figure 31. Flicker L1 compared with the solar radiance.

Production:

Before (kWh)	After (kWh)	Total production (kWh)
841	843	**2**

Table 7: Table showing the production of the third customer, measurements from 15th April to 18th April.

Consumption:

Before (kWh)	After (kWh)	Total consumption (kWh)
74672	74809	**137**

Table 8: Table showing the consumption of the third customer, measurements from 15th April to 18th April.

This customer consumed more energy than producing.

5.1.4 Fourth Customer with three-phase solar panel system (production only, 19th April – 22nd April)

This customer's system shows only the amount of production the solar panel system created. The graphs from this customer match really well with the solar radiance.

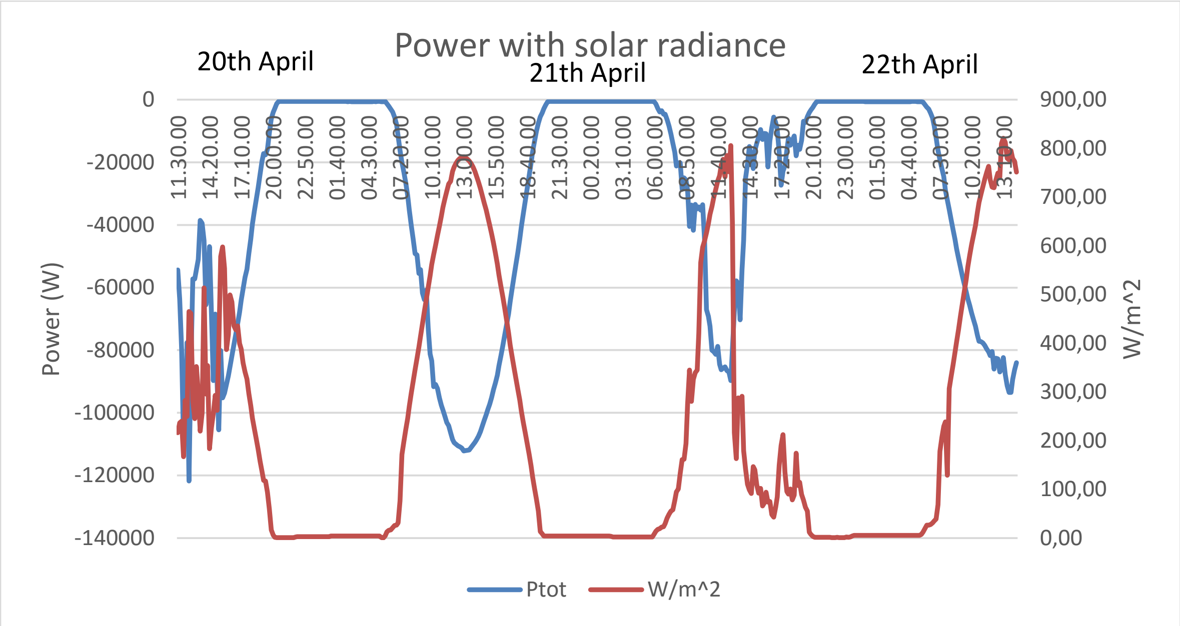


Figure 32. Power compared with solar radiance.

Notice from figure 32. How well true power and the sunlight values match. The reason is that this customer is only producing energy and consuming nothing.

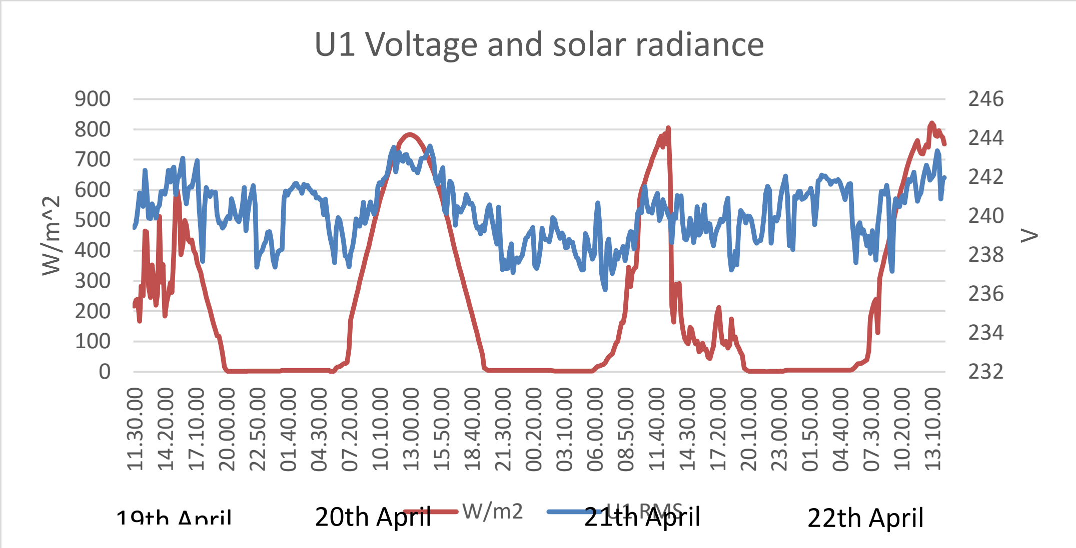


Figure 33. Voltage compared with solar radiance.

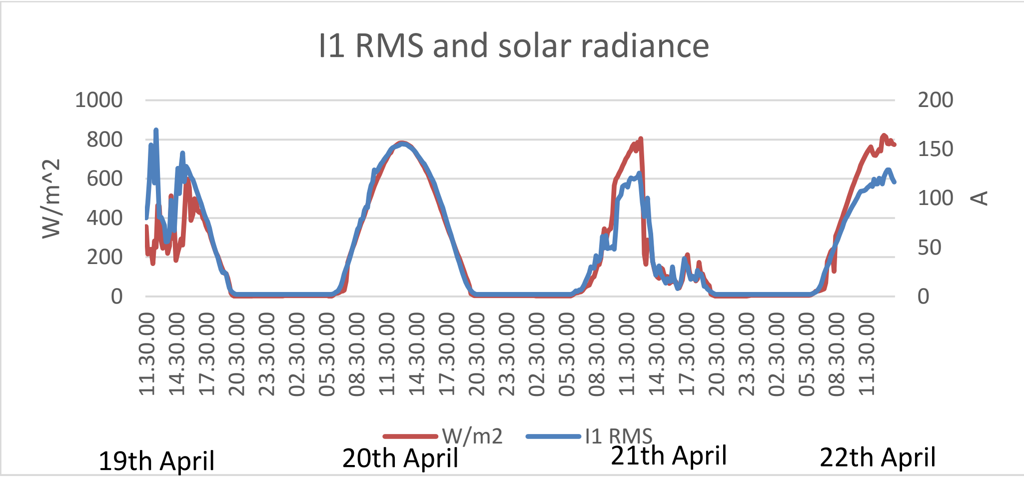


Figure 34. Current and solar radiance.

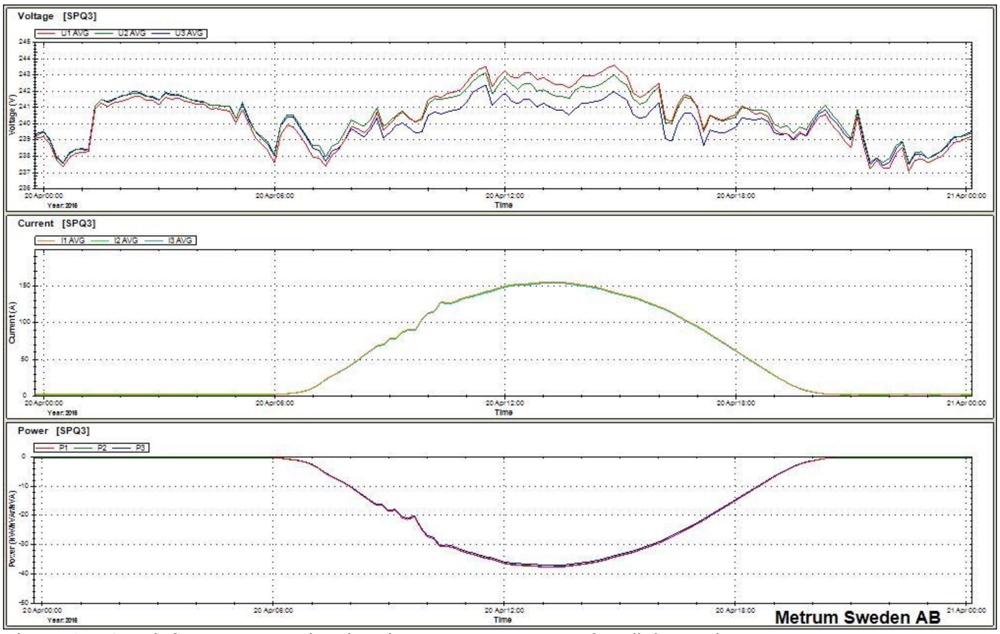


Figure 35. Graph from Metrum showing the same parameters for all three-phases.

5.2 Simulation: How solar panel systems with three-phase affect the power station

This simulation is from the second measurements. The main objective is to create a scenario where it shows what would have happen if all customers from Safirgatan had solar panels just as the second customer. How would it affect the power grid? There are 51 customers who are connected to the power station N151. Figure 36 shows all the blue cables that are connected from each house to N151 (red square in the middle). This simulation tests what would have happen to the voltage in “worst case scenario” if people had a solar panel system of 5 kW, 10 kW, 15 kW and 20 kW connected to their homes. Table 9 shows how the voltage would change if 0%, 22%, 35%, 45%, 75% and 100% of the customers would use solar panel system in that area.

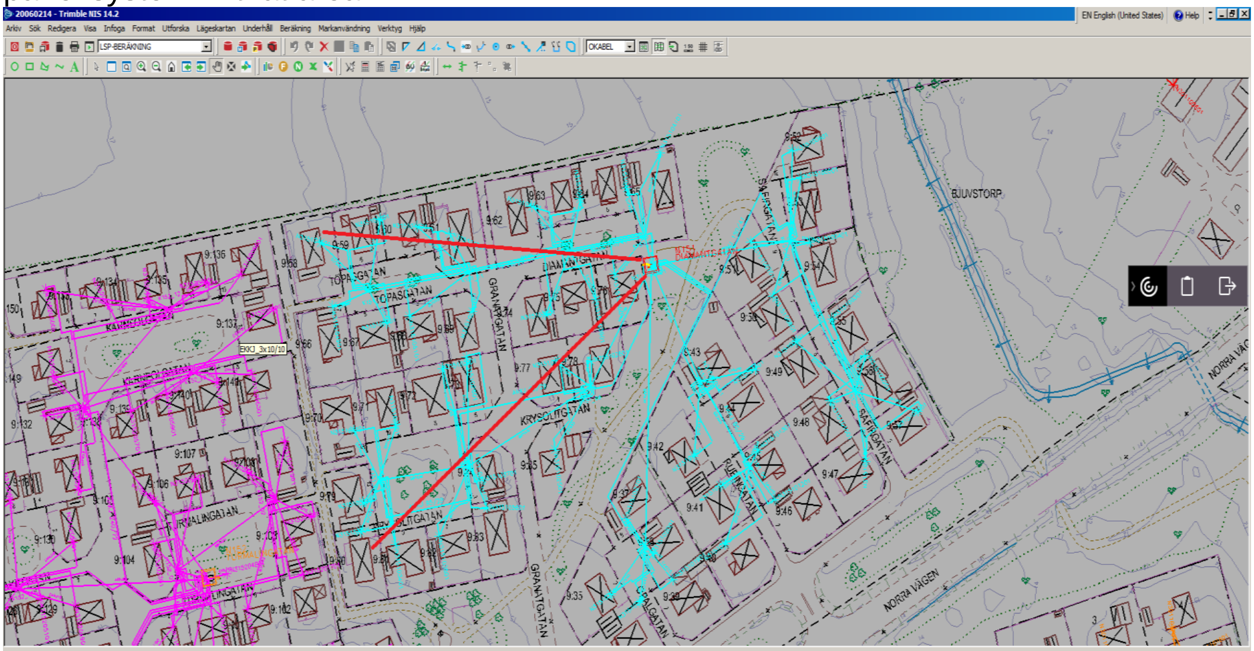


Figure 36. Picture where all customers (blue cables) are connected to the power station N151. The red lines represents the customers who live furthest away from the power station. Source: xPower.

Power on solar panels (kW)	0 (0%)	11 (22%)	18 (35%)	23 (45%)	38 (75%)	51 (100%)
5 kW	230 V	232 V	233 V	235 V	236 V	238 V
10 kW	230 V	234 V	236 V	240 V	242 V	246 V
15 kW	230 V	235 V	237 V	243 V	246 V	254 V
20 kW	230 V	237 V	240 V	248 V	252 V	260 V

Table 9. Table showing how the voltage on power stations would change depending on how many customers are connected with the respective solar panels.

The reference voltage on power station is 230V, gotten from xPower. The red boxes indicate the voltage that goes above the limit in Sweden (253 V). These voltages will be disconnected according to the voltage standard to not spread disruption to the grid.

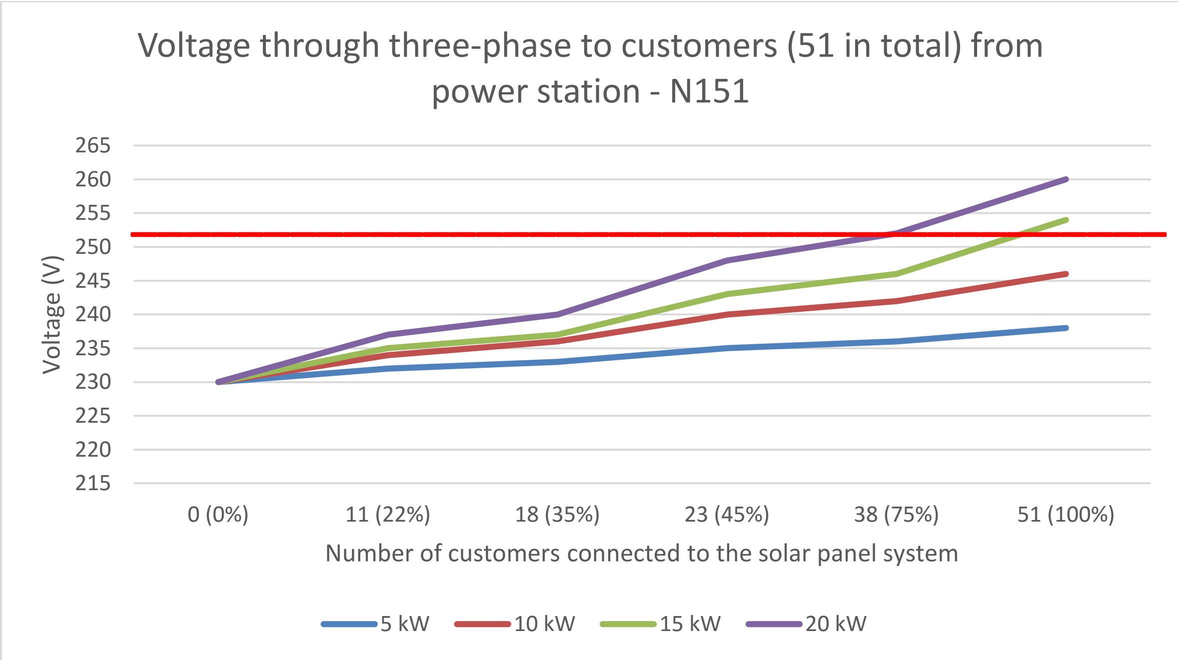


Figure. 37 The voltage of power station affected by the number of customers connected with solar panel system with different power. Red line indicates the limit (253 V).

5.3 Simulation: Difference between distances to power station

Upcoming results presents the difference on customers voltage depending on the distance between their houses to the power station. The scenario figures 38-39 are illustrating is the case when 100% of customers are using a photovoltaic system with 10 kW, and the voltage on the grid is 246 V (check table 9). Figure 39 and table 10 shows how much voltage the nearest and farthest customer will have. Notice that the customer that lives furthest away in that network area, is 171,75 meters away (customer 958) from the power station.

Customer	**Cable resistance (R)**	**Voltage change, 10 kW (V)**	**100% Connected 10 kW (V)**
Customer 965 (35 m)	0,05	1	247
Customer 958 (172 m)	0,11	2	248

Table 10. Voltage customers have (closest to furthest) when the reference voltage on the grid is 246 V, and 100% of the customers in that area are using solar panel system with 10kW.

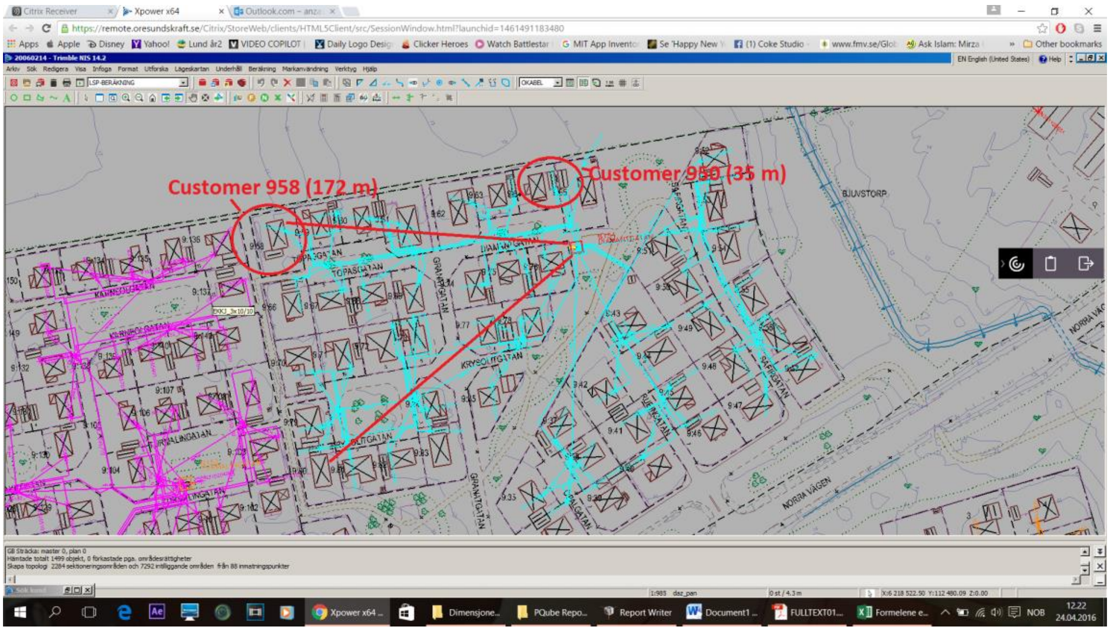


Figure 38. Picture of customer 965 (35 m) and 958 (172 m)

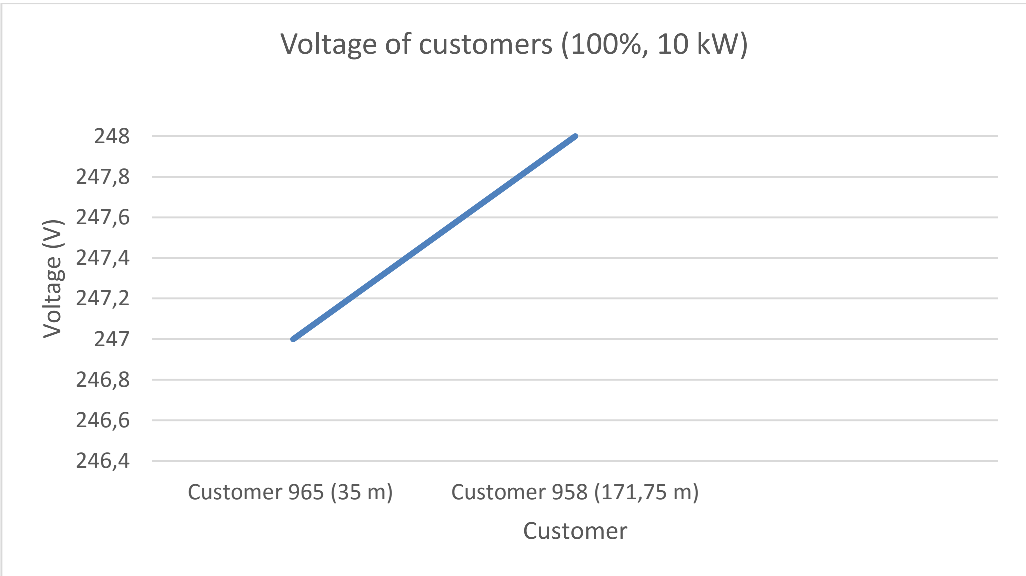


Figure 39. Voltage of customers depending on the distance from the power station when 100% are connected with 10 kW solar panel system.

Another scenario:

Same example as above, but now there is only **one** customer who is using a solar plant (5-20 kW), meaning all the other customers in the network area have no solar plants. The voltage in the power station is now 230 V. Figure 39.1 and 39.2 shows how the voltage would affect a customer living 35 m away from the power station respective 1000 m.

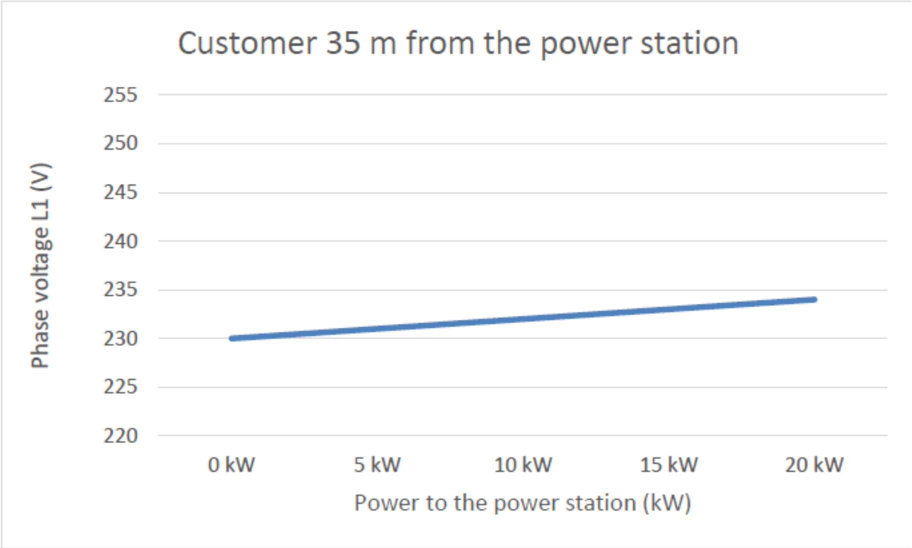


Figure 40. How voltage is affected for a customer living 35 m away from the power station while all the other customers have none PV-systems.

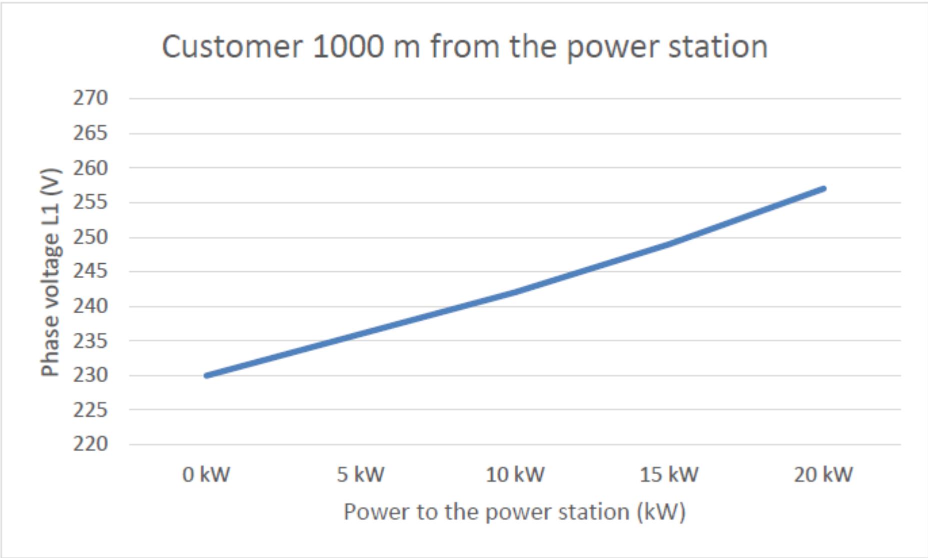


Figure 41. How voltage is affected for a customer living 1000 m away from the power station while all the other customers have none PV-systems.

5.4 Testing with PQube

PQube is a power quality recorder that measures sags/dips, swells, interruptions, voltage and current harmonics, flicker and rapid voltage changes. The main objective was to try some measurements with this new instrument. It was also something new for Öresundskraft. This instrument did some measurements at the last power station measurements were done at (19th April – 22nd April). Due to the system software that was locked (of unknown reasons), it was not possible to change the settings for PQube and set the limits according to the standards Öresundskraft follow. Therefore the graphs from Pqube have been made for the main voltage 400 V which was the standard (instead of 230 V), meaning it will be correct if all the voltage values from PQube are divided by $\sqrt{3}$.
Note that some tables show unknown, which is due to not being able to set the limits according to the standards.

EN50160 Requirement	**Measured L1 Voltage**	**Measured L2 Voltage**	**Measured L3 Voltage**	**Result**
95% of the time: 360,00V - 440,00V	**411,67V~418,77V**	**410,94V~417,84V**	**411,33V~418,22V**	**UNKNOWN**
100% of the time: 340,00V - 440,00V	**409,39V~420,03V**	**408,83V~418,86V**	**409,21V~419,49V**	**UNKNOWN**

Table 11. Measure voltage from PQube

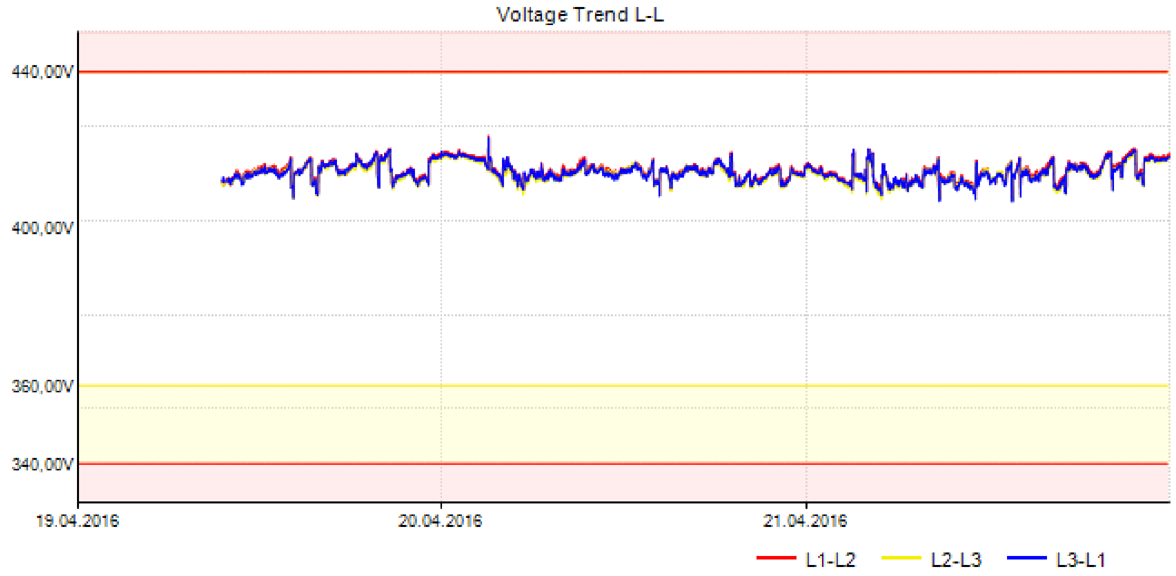


Figure 40. Voltage trend from PQube

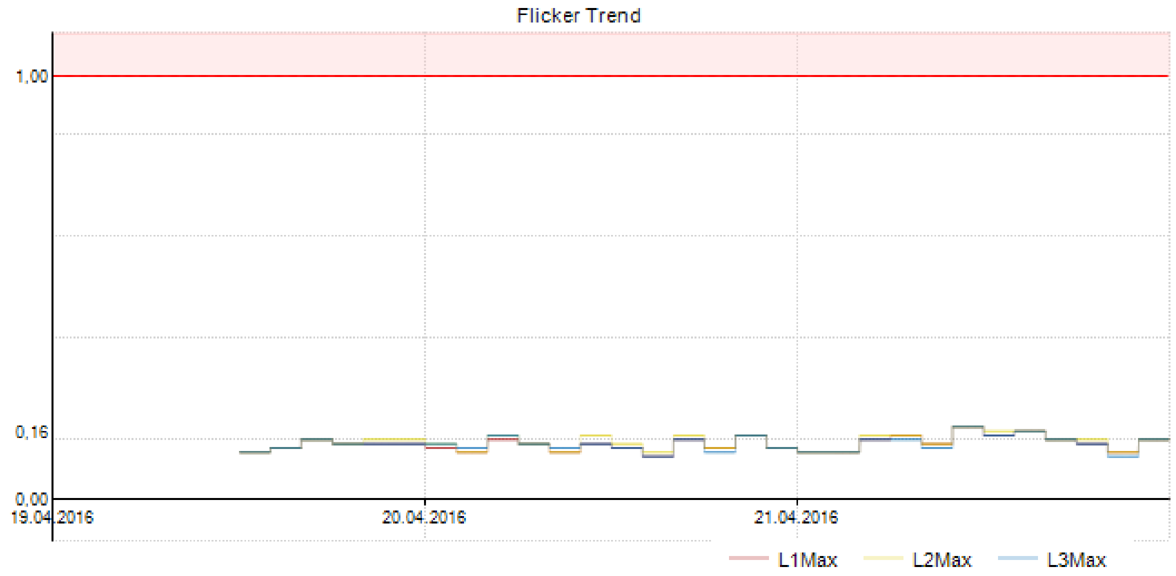


Figure 41. Flicker trend

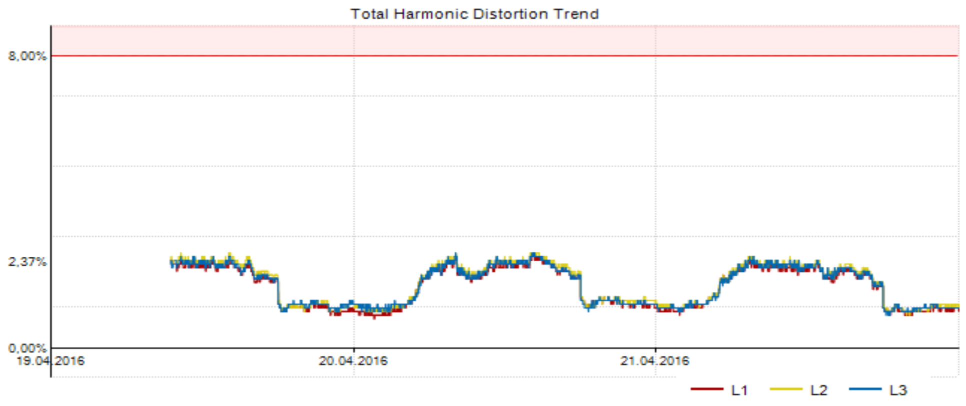


Figure 42. THD trend from PQube.

6. Analysis

This section analyses the results presented in section 5, Results. The analysis is to explain the conclusions that can be made about the voltage variations, current, parameters affected by sunlight, solar panel systems affecting the power grid and disorders.

6.1 Analysis: Sunlight and parameters from three-phase solar panel system

Sunlight affects many power quality parameters as shown in the graphs from result chapter. Whenever the solar irradiation is high, the customers starts producing their own energy. Looking at figure 15 and figure 20, it is shown that the true power starts going towards the negative axis whenever the sunlight is high. As explained earlier, the customer is producing energy when the power is negative.

In addition, the graph is not perfect since there are some areas where the sunlight is high, but the customer is still consuming energy. What can the reasons for that be? It all depends on what kind of equipment the customer is using. For example during afternoon, the customer might be making food where he might use the stove, oven or dishwasher. All these machines requires electricity, which concludes that the customer is consuming more energy during that time than producing. In addition, some of the customers had heat pumps; heat pumps turn on and off to stabilize the temperature. Heat pumps require a lot of electricity, something that also affects the energy consumption. Other customers had electrical car that needed charging, that also affects the energy consumption.

Another reason for why the solar radiance do not match so perfectly can be that the customers lived 5 km – 25 km away from Helsingborg. The solar radiance that Öresundskraft measured were from Helsingborg. It is a possibility that the weather in Helsingborg and at the customer’s place might be slightly different. There can for example be clouds difference, which resulted in reduction of sunlight.

Figure 32. shows only the production from the solar panels. Notice that the sunlight matches really well with the power and the reason is that there are no parameters showing what the customer consumed while the others had both consumption and production, something that restricts the sunlight of matching perfectly with the true power.

Conclusion: To get the solar radiance to match perfectly with the power quality parameters, one has to look at production only. Energy is produced when there is solar radiance and the current increases. Other factors that affect the current is equipment that requires electricity. Figure 25, respective figure 35 shows some flicker peaks, which might be a result of voltage fluctuations caused by loads that have been rapidly changing the active and reactive power demand.

6.2 Analysis: Difference between distances to power station

One can see from figure 39 how the voltage changes depending on how far away someone lives from the power station. The customers that lived 35 m and 172 m away from the power station had a voltage of 247 V, respective 248 V, which is still acceptable. Also from figure 39.1 – 39.2 one can see that the customer that lived 1 km away from the power grid had a huge voltage difference (27 V) compared to the one who lived 35 m away from the grid.

Conclusion: The distance to the power station plays a big role when it comes to the ability to resist voltage variations, as well as asymmetry. At a short distance to a transformer, the difference between single and three-phase is less significant, while the voltage variations are huge if the distance is longer.

6.3 Analysis: How solar panel systems with three-phase affect the power station

As shown in table 9 and figure 37, the voltage would start to go above the limit if all 100% of the customer used solar panel system with either 15 kW or 20 kW. That would make disruptions occur for most customers simultaneously because many share so many common cables. However, N151 has a relatively strong power station as one can see from figure 37 that it shall be able to handle all customers with 5 kW or 10 kW solar panel system.

As mentioned in section 1.4, limitations. It was not possible to do the same simulation with single-phase solar panel system, due to lack of time and equipment. However, according to other theses [17, 18, 19], and research done by universities and students, the acceptance in the grid against voltage increasement is less for single-phase compared to three-phase.

Conclusion: One can see that there is a greater acceptance on the grid of voltage increasement at three-phase compared to single-phase. One can also see those who live furthest away from the power station receive the largest difference between three-phase. One may also conclude that the power station N151 is a strong power station.

6.4 Analysis: Testing with PQube

PQube is a power quality recorder that is really easy to use. It has touch screen, is tiny, software-calibrated where engineers spent years of developing fully automated calibration systems. It also has lower price compared to other power quality recorders. Unfortunately, it was not possible to test it with all functions and features, but it still gave good results that can be extended in future.

Conclusion: PQube is really simple and easy to use which will give better result once all the functions are available. It automatically creates a word document where it saves all the power quality parameters with values and graphs, something that saves both time and work.

7. Conclusion

The objectives and issues that were set at the start of this thesis will be answered in this section as best as possible with regards to the conditions and restrictions that occurred during this project.

7.1 Answering the questions

The main question is what will happen in future during a sunny day when many customers within the same power network area, geographically located close together, have a solar panel system and all the plants have a surplus of electricity that must be output to the grid. Below are the other questions that were mentioned in section 1.3.

- ***How do solar cells connected with single- and three-phase affect the power quality?***

  The big difference between single and three-phase is that the power station is more negatively affected when single-phase solar panel systems are connected compared to three-phase. If single-phase systems spread out on all three-phases as evenly as possible, can more be installed before the impermissible values are reached. However, a certain asymmetry appears in single-phase systems, which is not desirable. In reality, it is almost impossible to say who, where and when in the power network will produce electricity, something that can give unbalance between the phases and it can be huge even if the panel systems are spread out in all phases.

  According to the measurements that were done during this work, one can see that the most common interferences are harmonics, unbalance, variations in the voltage and flickers. All of them were inside the limits, which does not make them a huge threat.

- ***What would happen if too many customers used solar cells connected to same network?***

  As discussed in section 5 and 6. Too many customers that are using solar cells connected to the same network can make a huge impact on the power station if it is not so strong. According to the simulation done in section 5.2, all customer that start producing their own energy will increase the voltage in power station, which can spread disruption to the grid. People, who are only using single-phase solar plants, might even disrupt more. Also, keep in mind that those who live further away from the power station create greater voltage variations.

- ***What are the reasons for a bad power quality?***

  Reasons for bad power quality are the following:

  Sensitive areas that have long wires with high impedance and low phase area can give bad power quality.
  A cause for disturbances in the power can be mainly due to the two-way power flow that can enter the low-voltage network when the microgeneration is connected, and when connected single-phase inverters are used. Asymmetry can occur in networks with many solar plants within one area. Customers and transformers also set conditions for the grid strength.

- ***What can be done to create a better power quality?***

  Some of the long term solution is that all actors involved must gather and spread knowledge about the difference between single- and three-phase. The industry must reach a common agreement so that recommendations reach customers and installers.
  If despite recommendations for three-phase, the customers choose to connect their microgeneration to single-phase, it is strongly recommended to allocate production evenly over the phases and supplement with an imbalance protection and power protection. Allocating production evenly across all phases also provides a better advantage because all larger amount of production is consumed locally in own plants and one does not need to think about unnecessary disconnections. Power companies are also required to disclose the value of impedance and short circuit power at the connection point to the customer so the electrician will be able to make the right judgement about the electrical design (2).

- ***How does the solar radiance affect the power quality?***

  Whenever there is sunlight, the solar panels will start producing energy. Sunlight might be the cause of minor flickers, disturbances or harmonics, but nothing major that exceeds the limits. How much energy someone produces depends all on how much sunlight there is. Is there is a clear sunny day, then the customers might produce a lot, while when it is a lot of clouds that are blocking the sunlight, one might not produce so much energy.

The conclusion is that the results do not show any serious problems with an increased proportion of solar cells, providing increased awareness of the need for an evenly distributed production and the extra vulnerable customers far into the power network. If knowledge about this continues to grow, there might be great opportunities to ensure a supply of electricity of good quality. With proper installation, proper equipment, proper plants in relation to the needs and proper integration with other systems, there are no barriers and limitations for the further developments of solar cells.

7.2 Future Developments

Suggestions for other future developments in this area are:

- A deeper examination regarding the impact of the transformer.

- Carry out measurements on a **real** area that has several solar panel systems in use and see how the voltage levels and power quality parameters look in practice.

- Investigate what happens in the overlying grids as solar cells are connected to the low voltage grid.

- Further investigation on how electric cars and other loads interact with microgeneration to balance the system.

- More knowledge and research is required when it comes to “mass plants” of solar cells, where one can take great lessons from Denmark and Germany that have had a rapid expansion of renewable energy with both positive and negative consequences. What requirements should be met to prevent the same problems that they have encountered in their power grids?

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Appendix A – Maps of customers and power grids

Figure 43: Map of the first customer and power grid.

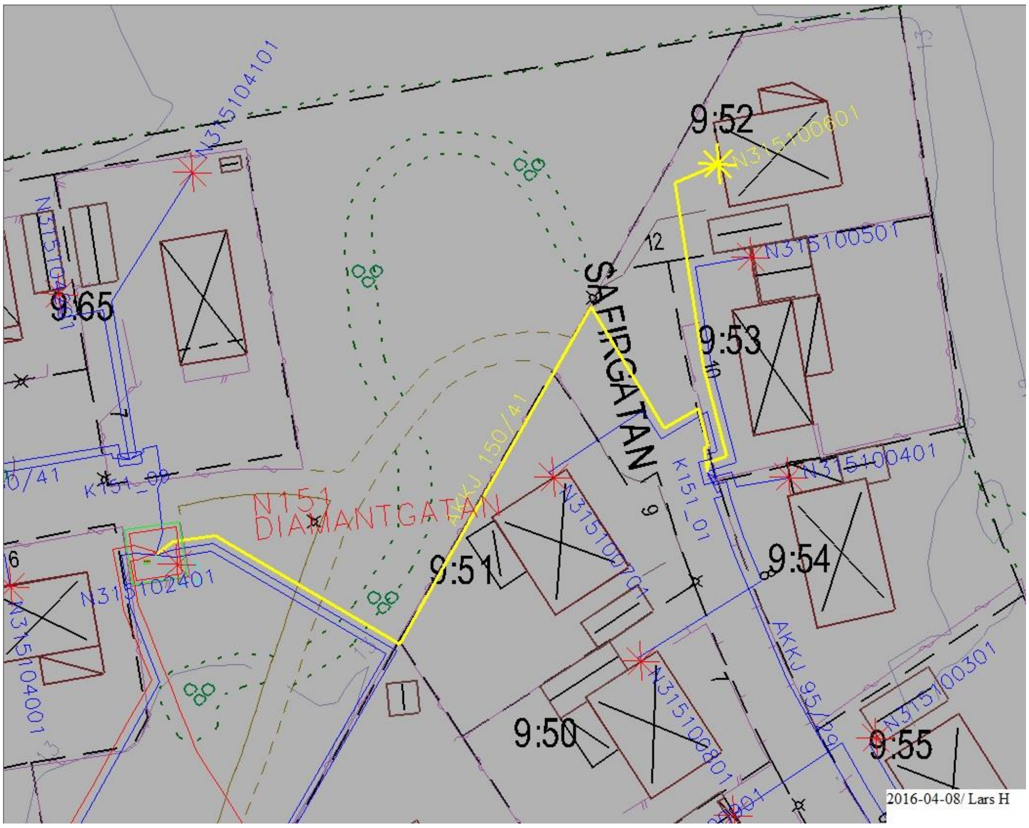


Figure 44. Map of the second customer and power grid.

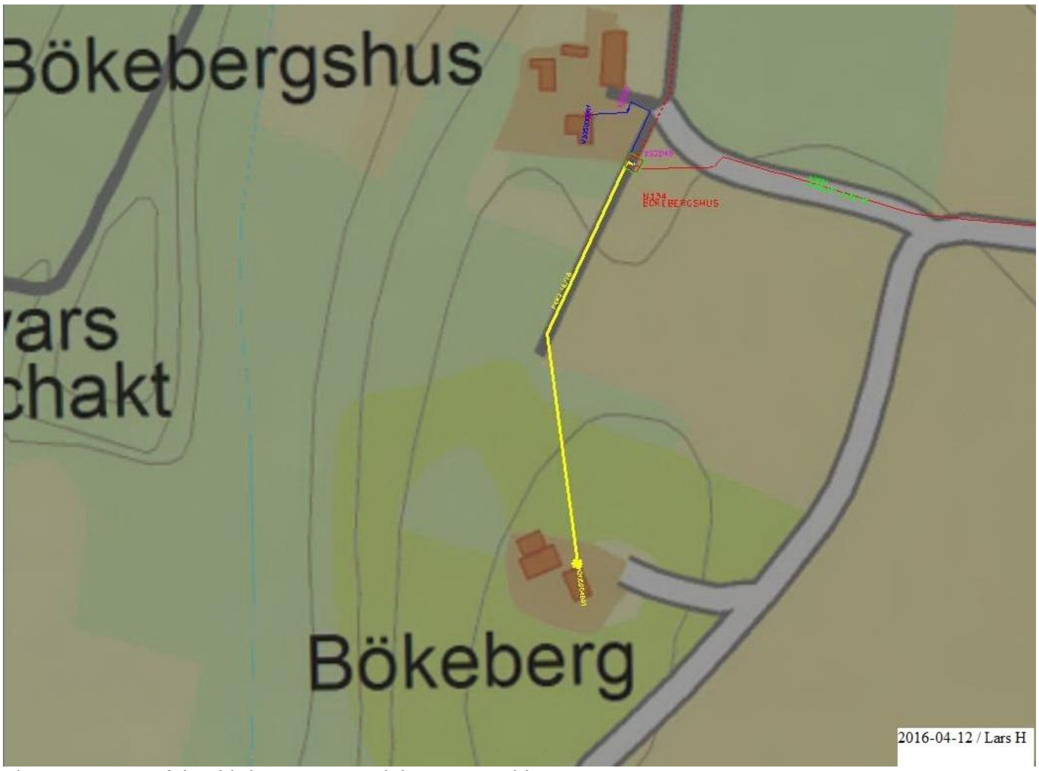


Figure 45. Map of the third customer and the power grid

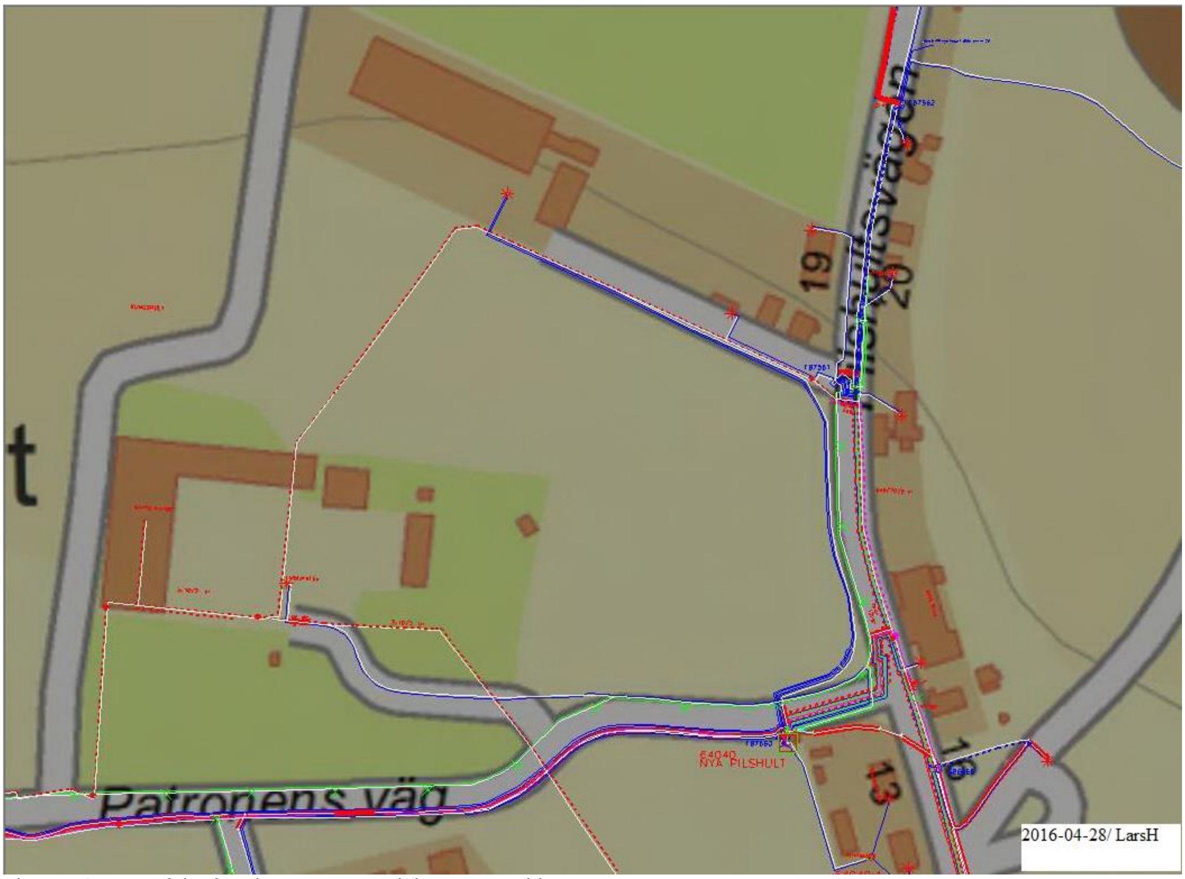


Figure 46. Map of the fourth customer and the power grid

Appendix B – Dimensions

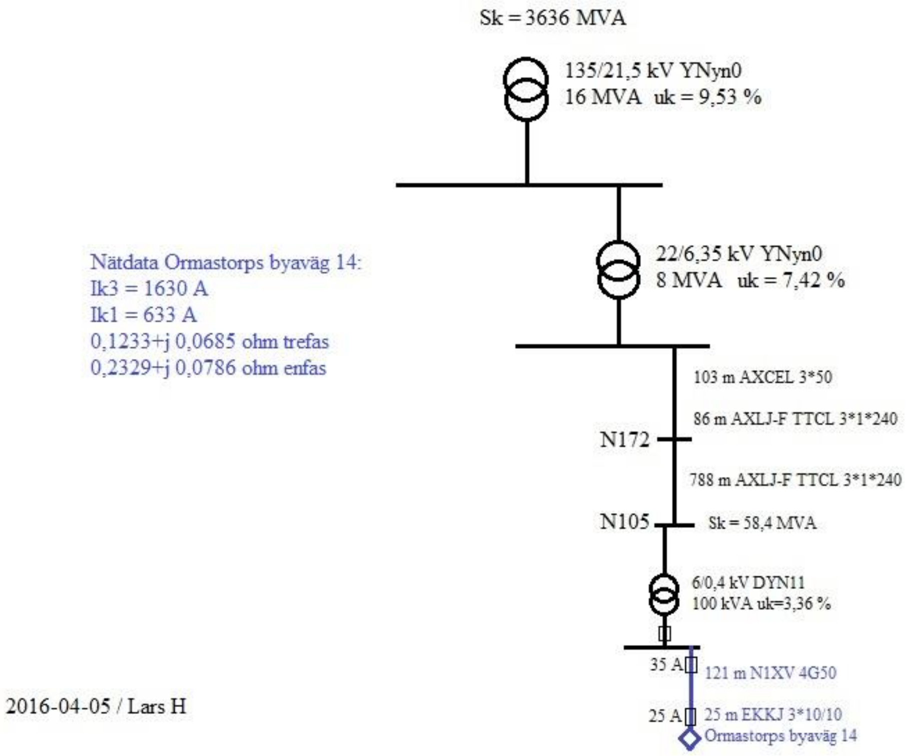


Figure 47. Power station data with impedance and schematic figure, Ormastorps byaväg.

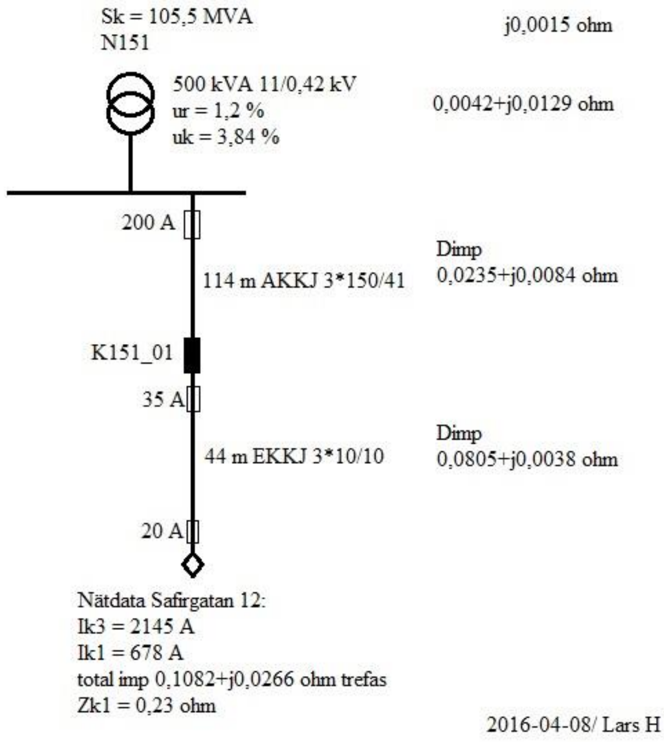


Figure 48. Power station data with impedance and schematic figure, Safirgatan.

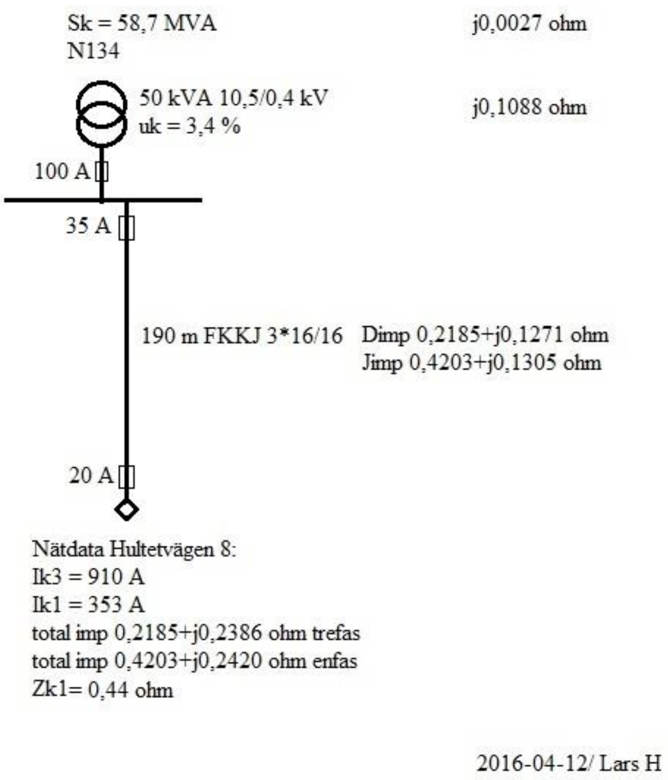
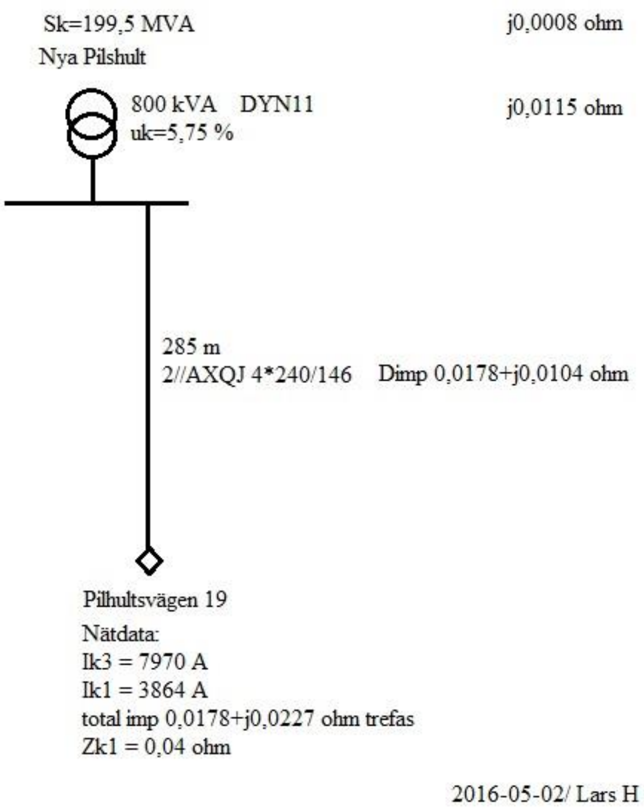


Figure 49. Power station data with impedance and schematic figure, Hultevägen



. Figure 50. Power station data with impedance and schematic figure, Pilhultsvägen

Appendix C – Simulation table and graph

		20000	144,337567		20kW							7,505553499	237,5056	23 kunder
		K151_12 (4 kunder)			Resistant fra 12 til 11	0,01			K151_11 (4 kunder)		Resistant fra 11 til 10	0,016		
		Effekt	Strøm			Sp.ändring 12			Effekt	Strøm	Sp.ändring 11-10	Sp.ändring nät	Sp.nät	
		5000	28,8675135		5000W	0,288675135			5000	28,86751346	0,461880215	0,75055535	230,7506	
		10000	57,7350269		10000W	0,577350269			10000	57,73502692	0,923760431	1,5011107	231,5011	
		15000	86,6025404		15kW	0,866025404			15000	86,60254038	1,385640646	2,25166605	232,2517	
		20000	115,470054		20kW	1,154700538			20000	115,4700538	1,847520861	3,0022214	233,0022	
		K151_10 (4 kunder)		Resistant fra 11 til 10	0,008		K151_00(3 kunder)		Resistan 00 til nät	0,004				
		Effekt	Strøm		Sp.änding 10-00		Effekt	Strøm		Sp.ändring 00 til nät		Sp.ändring nät	Sp.nät	
		5000	28,86751		0,23094008		5000	21,65064		0,08660254		0,31754262	230,3175	
		10000	57,73503		0,46188024		10000	43,30127		0,173205081		0,635085321	230,6351	
		15000	86,60254		0,69282032		15000	64,95191		0,259807621		0,952627941	230,9526	
		20000	115,4701		0,9237608		20000	86,60254		0,346410162		1,270170962	231,2702	38 kunder
K151_08 (5 kunder)		Resistant fra 08-07	0,02	K151_07 (5 kunder)		Resistans 07 ti	0,027		K151_06 (3 kunder)		Resistans 06 til nät			
Effekt	Strøm		Sp.ändring 08-07	Effekt	Strøm	Spändring			Effekt	Strøm	0,015	Sp.ändring nät	Sp.nät	
5000	36,08439		0,72168784	5000	36,08439182	0,974278579			5000	21,65063509	0,324759526	2,020725942	232,0207	
10000	72,16878		1,44337567	10000	72,16878365	1,948557159			10000	43,30127019	0,649519053	4,041451884	234,0415	
15000	108,2532		2,16506351	15000	108,2531755	2,922835738			15000	64,95190528	0,974278579	6,062177826	236,0622	
20000	144,3376		2,88675135	20000	144,3375673	3,897114317			20000	86,60254038	1,299038106	8,082903769	238,0829	51 kunder

Solceller

Power Station (W)	0 (0%)	11 (22%)	18 (35%)	23 (45%)	38 (75%)	51 (100%)
5 kW	230	232	233	235	236	238
10 kW	230	234	236	240	242	246
15 kW	230	235	237	243	246	254
20 kW	230	237	240	248	252	260

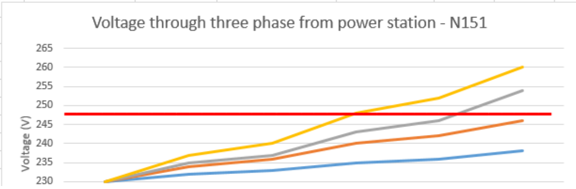


Figure 51. Table and measurements from the simulation over dimensioning.