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Power quality in Electron Beam Melting machines

A power quality and characteristics analysis

Bachelor's thesis in Electrical Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
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Cover: A GE Additive Arcam EBM Spectra H machine.

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Abstract

The subject of Power Quality (PQ) is a fairly new and broad topic in the electrical industry. Poor PQ can affect both customers as well as the distributors, by reducing efficiency, decreasing life time of products and increasing current demands. The Electron Beam Melting(EBM) machine is an type of additive manufacturing machine. The manufacturer and creator of the EBM machine, GE Additive Arcam EBM is located is Gothenburg, Sweden but has customers all over the world. The purpose of this project was to better understand how the EBM machine could be affected by poor PQ and how the it affects the electrical grid. By analyzing PQ in the machine, GE Additive Arcam EBM aim to setup certain guidelines ensuring that the EBM machine would function as intended. The project is performed at GE Additive Arcam EBM's premises, where multiple EBM machines are connected to the same grid.

Through a series of measurements on different EBM machines the PQ data was gathered. There was an increase of harmonic content while the machine was printing compared to when idle. The power consumed by the EBM machine could possibly be lowered if the power factor would be adjusted. To test the machine's tolerance against disturbances a series of voltage sags was induced. The machine performed well under the test with no significant effects on any of the parts of the machine. An analysis of the EBM machine's high voltage supply was also performed. The power factor in the high voltage supply seemed to increase as the current produced increased. Even though reactive and active power is not considered PQ it is an important element when looking at grid strain. The EBM machine could improve its power factor to some aspect to improve the reactive power produced onto the grid. Following the standard EN50160, a standard set for the European Union regarding PQ, the EBM machine performed within the limits of the set PQ standard. The Swedish power grid is considered strong and therefore the currents consumed by the EBM machine did not cause any disturbances on the provided voltage. The conclusion of the performed tests is that the EBM machines tolerate disturbances in the shape of sags down to 66 % of nominal voltage and no significant disturbances on the electric grid produced by the EBM machines have been observed.

The results of the measured PQ data in this report was to better provide what could be improved in the EBM machine regarding PQ, not how they should be implemented.

Keywords: power quality, EBM-machine, electron beam melting, low voltage.

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Sammanfattning

Ämnet elkvalitet är ett ganska nytt och brett ämne inom elektronikindustrin. Försämrad elkvalitet påverkar inte bara kraftnäten utan även indirekt oss kunder. Försämrad elkvalitet kan minska effektiviteten, minska livstiden på elektronik och ge onödigt ökad strömkonsumtion som elnätet belastas med. Electron Beam Melting(EBM) maskinen är en typ av 3D-skrivare. Tillverkaren och skaparen av EBM, GE Additive Arcam EBM har sitt kontor och fabrik i Göteborg, Sverige. GE Additive Arcam's kunder använder deras maskiner över hela världen. Syftet med det här arbetet var att förstå hur EBM maskinerna kan påverkas av dålig elkvalitet och dessutom hur EBM maskinerna påverkar elnätet. Genom att analysera elkvaliteten i EBM maskinerna skulle GE Additive Arcam kunna bestämma riktlinjer för deras kunder för bästa kvalitet. Detta arbete utfördes på GE Additive Arcams lokaler där flera EBM maskiner är inkopplade på samma nät. Elkvaliteten undersöktes genom att ett antal mätningar utfördes på olika EBM maskiner. Under utskrift i maskinen ökade övertonerna något jämfört med under tomgång av maskinen. Den skenbara effekten skulle kunnas minska något om effektfaktorn förbättrades. För att testa toleransen mot störningar så inducerades ett par spänningsdippar in i maskinen. Det var inga signifikanta påverkningar på EBM maskinen under det testet. Utöver de andra testen så utfördes även en analys utav högspänningsaggregatet. Det som kunde ses under användning av aggregatet var att effektfaktorn ökade då strömmarna ut från aggregatet ökade. Även om aktiv och reaktiv effekt inte har något med elkvalitet att göra så är det en väldigt viktigt faktor när man tittar på elnätets belastning. EBM maskinen skulle kunna förbättra sin effektfaktor och därmed minska belastningen på elnätet. Genom att följa en Europeiska standarden EN50160 så resulterade EBM maskinens elkvalite som godkänd och inom riktlinjerna för god elkvalitet. Det är värt att poängtera att Sveriges elnät är sett som ett starkt nät och har väldigt bra elkvalitet, därför påverkades inte spänningarna så mycket utav strömmarna som belastades från EBM maskinen. Slutsatsen av mätningarna är att EBM maskinerna klarade av de spänningsstörningar som testades, tex spänningsdipp till 66% av nominalspänning. EBM maskinerna påverkade inte heller nätet noterbart då de inte gav upphov till störningarna under användning. En utav avgränsningarna i denna rapport var att mätresultaten från elkvalitetmätningarna skulle endast ge förslag på vad som kunde förbättras ej hur dessa förbättringar bör utföras.

Den här rapporten är skriven på Engelska.

Nyckelord: elkvalité, elkvalitet, EBM-maskin, lågspänning.

Acknowledgements

This Bachelors thesis has been completed at GE Additve Arcam EBM in Mölnlycke, Sweden, together with the Division of Electric Power Engineering at Chalmers University of Technology. GE Additive Arcam EBM is a company that builds electron beam melting machines in the additive manufacturing industry. The thesis work is regarding the power quality in the EBM machines and their charactiristics. The thesis work was performed by Victor Lidskog and Oskar Falk, two Bachelor of Science in Electrical Engineering students at Chalmers University of Technology. The thesis covers 15hp per person, which is part of the total 180hp.

We would like to thank our supervisor at GE Additive Arcam EBM, Fredrik Ekåsen for helping us in the field of Power Quality and being a fun and supportive supervisor. We would also like the thank Carl Hellestam who setup the thesis work for us to complete at GE Additive Arcam EBM.

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We would like to thank Jonny Carlsson at Unipower AB for taking the time to teach us about power quality and everything surrounding it. Also letting us use the Unilyzer 900 and the compatible computer programs which made this thesis possible.

Victor would like to thank his wife Rachael for moving countries for Victor to be able to finish his Bachelor. Thank you for the endless support and for always believing in me.

Oskar would like to thank Laura and Luna for endless support and inspiration. Without you this would not have been possible.

Victor Lidskog, Gothenburg, June 2021
Oskar Falk, Gothenburg, June 2021

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Terminology

Abbreviations:

A	Ampere
AC	Alternating Current
BC	Breakout Cable
CAT	Category
CNC	Computer Numerical Control
DC	Direct Current
DPF	Displacement Power Factor
EBM	Electron Beam Melting
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
GE	General Electric
GUI	Graphic User Interface
HV	High Voltage
Hz	Hertz
IDE	Integrated Development Environment
IH	Individual Harmonic
PBF	Powder Bed Fusion
PF	Power Factor
PQ	Power Quality
RMS	Root Mean Square
RVC	Rapid Voltage Change
THD	Total Harmonic Distortion
THDI	Current Total Harmonic Distortion
THDU	Voltage Total Harmonic Distortion
V	Volt
VA	Volt Ampere
VAr	Volt Ampere reactive
W	Watt

1 Introduction

Chapter one includes the background for this project. After the background the purpose, goals and limitations will be explained and chapter one is closed with the problem description.

1.1 Background

The company GE Additve Arcam EBM is a manufacturer of Electron Beam Melting (EBM) machines. These machines are sold all over the world to customers, many of them have multiple EBM machines connected to the same grid and together with other large industrial machines. In Sweden the Power Quality problem might not be as big of a concern but in other countries the PQ may cause issues. The company is interested in finding out how the EBM machine is affected by the PQ of the grid and if the EBM machine could cause poor PQ once being connected. By measuring the PQ in the different EBM machines the company can then put certain requirements on customers to ensure the best quality manufacturing from the EBM machine.

1.2 Purpose

There is limited knowledge of the PQ when using multiple EBM machines and together with other industrial machines. By analyzing the information and data from the PQ measurements the company will be able to set certain power grid requirements for future customers to ensure that the EBM process will achieve its highest quality. The measurements will also be able to provide the company with knowledge of how to improve the currents consumed from the electrical grid by updating power quality factors and balance in a 3-phase system.

1.3 Limitations

The results of the PQ measurements performed in this project provide information on what could be improved in order to better the PQ of the machines. How these improvements could be implemented, however, will not be a part of the scope of this project.

Some of the tests and measurements have not been performed on an actual working machine while printing, but on a prototype used for testing in the laboratory. This machine is in most aspects identical to a fully functional EBM machine except that it lacks the ability to perform the printing process. This limitation is due to the fact that in case there is any damage on the machine, the cost would be significantly less, compared to if a fully functional machine were to be used.

During the measurements the only naturally, from the power grid, occurring disturbances detected were harmonics and transients. The EBM machine was also artificially exposed to voltage sags by connecting it to a manual transformer. Hence, the tolerance to disturbances of the machine has not been tested for the following: frequency deviations, unbalance, voltage swells, flicker or rapid voltage chance, since there was no resources for performing such tests.

1.4 Problem Description

From the section 1.2, the problem description can be built up. The questions to be answered during this project can be seen in the bullet point underneath:

- What does the EBM machine send out on the grid?
- How does the EBM machine affect the PQ?
- Is the load unbalanced or balanced?
- What currents and voltages are sent into the machine?
- How is an EBM machine affected by different kinds of disturbances?
- What are the characteristics of the HV-supply?

1.5 Report Outline

In the following chapters a brief theoretical background will be described to understand the subject further. After the theory, the method used to measure the PQ is described. The different measurements and data are then explained and introduced. Last the results, conclusion and a discussion is reported to conclude the report.

2

Theory And Technical Background

To put this report in context some of the fundamental theory and background is explained in the following chapters.

2.1 Introduction To Single And Three Phase

The EBM machine uses alternating current(AC) wave and to understand power quality better a brief introduction to single and three phase power needs to be explained.

2.1.1 Single Phase Power

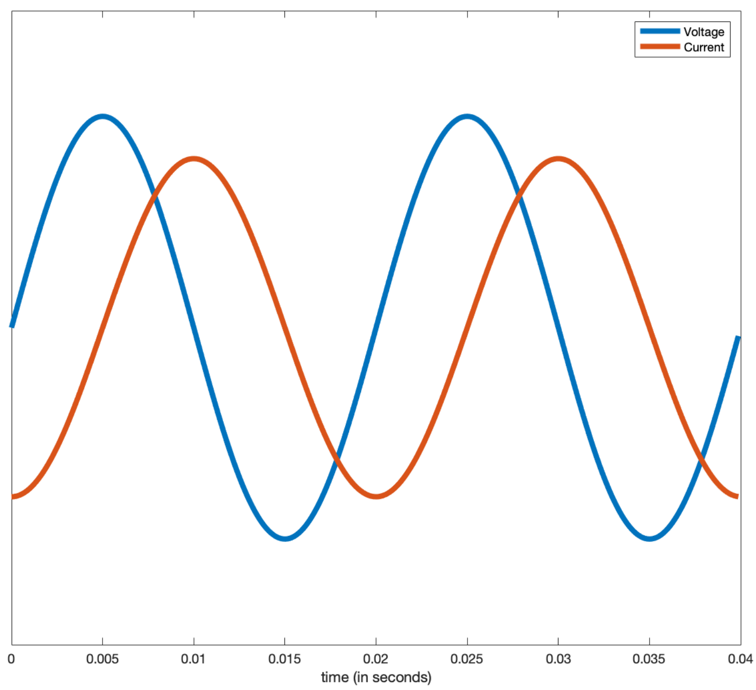


Figure 2.1: Single phase voltage and current forms in an inductive circuit

In Sweden a single phase AC voltage provided from the power grid is a sinusoidal wave with the frequency 50Hz and a peak value of 325V[4]. This means that the wave repeats itself 50 times during one second, making its period $1/f = 0.02$ seconds as seen in figure 2.1. The amplitude, voltage Û and current Î can be described in a time function as equation 2.1.

$$\begin{aligned} u(t) &= \hat{U} sin(\omega t - \alpha) \\ i(t) &= \hat{I} sin(\omega t - \beta) \end{aligned} \tag{2.1}$$

In equation 2.1, ω is the angle rotation which is 2πf, where f is the frequency of the signal. When calculating with linear single phase circuits the complex method $j\omega$is used. Since the frequency, with small variation, is kept at 50Hz the current and voltage can be used as phasors, where U and I is the root mean square value (RMS) of the signal[4]. The RMS value of an AC signal is the equivalent value of what a direct current (DC) signal would have, the rest of the report we will only use RMS values.

$$\begin{aligned} U &= \frac{\hat{U}}{\sqrt{2}} \angle - \alpha \\ I &= \frac{\hat{I}}{\sqrt{2}} \angle - \beta \end{aligned} \tag{2.2}$$

The angle α is set as the reference, so that $\alpha = 0°$, β is then the angle between the current phasor and the voltage phasor. In single phase systems, since the angle between the current and voltage can be different from 0°, a concept of active and reactive power is introduced. The total power consumed from the power grid is called apparent power and is denoted with an S.

$$\begin{aligned} S &= U \cdot I^* \ [VA] \\ S^2 &= P^2 + S^2 \ [VA] \\ P &= U \cdot I \cdot cos(\phi) \ [W] \\ Q &= U \cdot I \cdot sin(\phi) \ [VAr] \\ \phi &= \beta - \alpha \ [degree] \end{aligned} \tag{2.3}$$

As seen in equation 2.3, U and I is the complex phasors from equation2.2. The apparent power S is measured in VA or volt-ampere, power is measured in W or watts and reactive power is measured in VAr or volt-ampere reactive. The power and reactive power depend on the angle φ, which in its turn depends on α and β. α as mentioned earlier is usually set to 0°, therefore the active and reactive power depend on the currents angle β which is the amount the current is lagging or leading from the voltage.

Depending on what load is attached to the pure sine wave the current will lag or lead the voltage. In purely capacitive loads the current leads the voltage due to that the capacitor is voltage stiff, hence the angle $\beta = 90°$ before the voltage as seen to the left in figure 2.2. With inductive loads the current lags the voltage due to that the inductor has a current stiff characteristic, thus the angle β = -90° after the

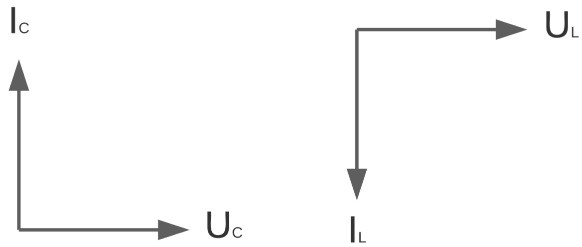


Figure 2.2: Left, capacitive phasors. Right, inductive phasors.

voltage as seen in figure 2.2 right[4]. An inductive load therefore consumes reactive power (negative VAr) while a capacitve load produces reactive power (positve VAr).

A purely resistive load has no phase angle between current and voltage and thus only consumes active power (positive W), if W is negative then it is producing active power, for example a generator.

2.1.2 Three Phase Power

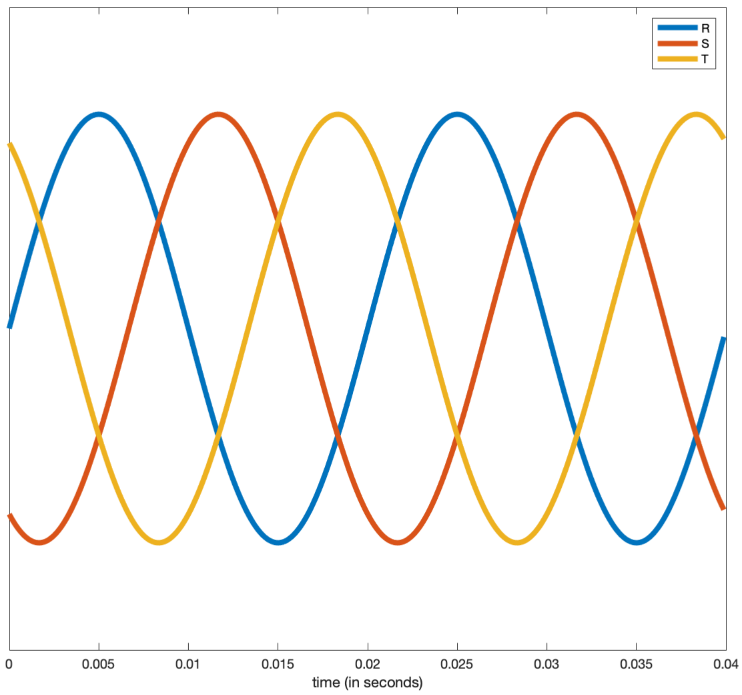


Figure 2.3: Three phase wave forms, 120 degrees separated

Building onto the single phase knowledge, the three phase is very similar. The three phases, RST or ABC or 123 or UVW, is the same sine wave with the frequency 50 Hz but the phases are shifted 120° apart from each other as seen in figure 2.3.

Voltage measured between phase to phase is usually called line-voltage and in Sweden the line-voltage is 400V RMS. The voltage between phase and neutral is called phase-voltage and in Sweden the voltage is 230V RMS[4].

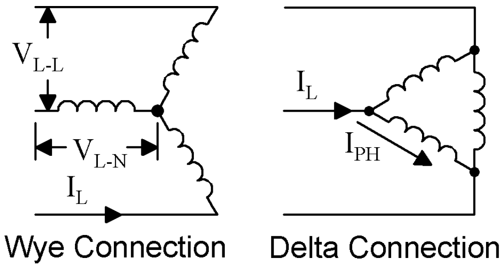


Figure 2.4: Delta and Wye connections from CC

The loads for the phase systems should be balanced for best quality and can be connected in two different ways, Δ (delta) and Y (Wye). In a Δ connection the impedance is 3 times as high as in Y and also the voltage is the line-voltage which is 1.73 times larger as the phase-voltage, but current is 1.73 times smaller[4]. If the load is symmetrical in 3 phase the power consumed can be calculated as in equation 2.4.

$$P = 3 \cdot U \cdot I \cdot cos(\phi) \; [W] \tag{2.4}$$

If complex phasors are used to calculate the power in 3-phase then the equation is as seen in 2.5, where U and I are complex numbers.

$$\begin{aligned} S_{3phase} &= 3 \cdot U_{complex} \cdot I^{*}_{complex} \; [VA] \\ S_{3phase} &= P[W] + Q[VAr] \end{aligned} \tag{2.5}$$

2.1.3 Power Factor

An important understanding in AC power systems is power factor(PF) and displacement power factor(DPF). The DPF is taken from the φ as seen in equation 2.3, this is the angle between the voltage and the current phasors [5]. This means how much power vs reactive power is used in a system. As seen in equation 2.6, DPF is then a number between 0 and 1, where 1 is pure power and 0 is pure reactive power.

$$\begin{aligned} DPF &= cos(\phi) \\ PF &= \frac{I_{s1}}{I_s} \cdot DPF \end{aligned} \tag{2.6}$$

The PF is affected by harmonics, as seen in equation 2.6, the fundamental current is divided by the total current. If the total current is a pure sine wave then the fundamental current is equal to the total current and PF = DPF. But due to harmonics the total current is not the same so the PF is decreased from the PF.

2.2 Power Quality

Power quality is a fairly new definition used in the field. Since switch mode power supplies and other non linear loads are being used more frequently, the quality of power has become poorer and a need for the term Power Quality has emerged. PQ can have a lot of different meanings but the most common use is to describe the quality of the voltage and/or current waveform accessible from our wall outlets, provided from the power grid.

The root of power quality can be split up in four categories as seen below:

1. The Unpredictable events
2. The Electric utility
3. The Customer
4. The manufacturing regulations

The unpredictable events consist of natural factors, such as weather, geomagnetically induced currents (GIC) and other unpredictable events. These usually happen on the Electric utility side. More than 60% of the PQ problems originate from this category[6].

The next category is the electric utility. Faults from the utility side can be forced outages due to maintenance at the source of the supply or other activities leading poor PQ. The electric utility can also induce poor PQ in the transmission lines[6].

The customer can induce poor power quality depending on how they use the power that comes from the grid. Different loads such as switch mode power supplies, fluorescent lights and more generate harmonics which then put a strain on the grid. Using equipment with poor power factor will increase the reactive power used which will also cause a strain on the grid[6].

The manufacturers of the equipment that the costumer uses have a large responsibility for maintaining good PQ on our grid and not causing strain with poor PF and high harmonics. The manufacturer must comply with standards to fulfill the EMC and EMI restrictions. The more low quality electronics out on the market the bigger strain the grid will suffer.

PQ can be divided up into different disturbances which affect the power grid. In the next section these disturbances will be explained more.

2.3 Disturbances

The following is a description voltage disturbances according to standards and regulations in PQ. This chapter will describe the different disturbances to give a better understanding of what happens during these disturbances and the effects of them.

2.3.1 Voltage Sags

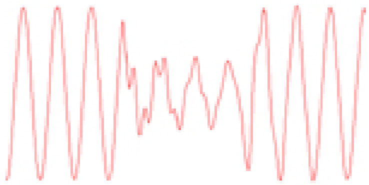


Figure 2.5: A voltage sag. From [1] used with permission

Voltage sags, sometimes also referred to as dips, are rms-voltage drops of 10 % or more. Their time duration is more than one cycle (which is 20 ms in a 50 Hz grid). Common causes of sags are for example: thunder, pumps, starting an inductive motor, short-circuits and line-to-ground faults. Consequences of a voltage sag can for instance be energy deficit that can lead to disturbances or damages in electronic devices, such as computers and control systems, or machine failures and shut-downs [1].

2.3.2 Voltage Swells

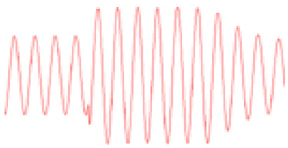


Figure 2.6: A voltage swell. From [1] used with permission

Voltage swells are, in a way the opposite of a sag, in that the voltage increases by at least 3 % for a duration of at least 1 cycle (20 ns). Common causes of swells are for example: poor grounding, connections and disconnections of capacitor banks and reactors. If voltage swells occur often they can lead to damaged insulation material which can result in a damaged electrical device [1].

2.3.3 Transients

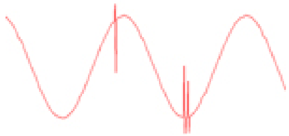


Figure 2.7: An example of multiple transients AC voltage. From [1] used with permission

A transient is a faster change in voltage, compared to sags or swells [1]. They are defined as a change shorter than a cycle and are commonly caused by lightnings, capacitor banks being connected or disconnected or switches. Possible consequences are damaged equipment, disturbances in electronics such as computers and control systems[1].

2.3.4 Harmonics

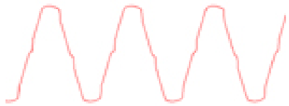


Figure 2.8: Distortion caused by harmonics on a sine wave. From [1] used with permission

AC currents and voltages are composed of various harmonics. The first harmonic is referred to as the fundamental frequency and the following harmonics are integer multiples of the fundamental frequency. E.g if the fundamental frequency is 50 Hz, the harmonics will be integer multiples of 50 Hz, i.e the second harmonic will be 2*50= 100 Hz, the third, 150 Hz and the forth, 200 Hz etc. The most common harmonics odd multiples of the fundamental frequency. When these harmonics add up they form a distorted sine wave such as the one seen in figure 2.8. The source of harmonics is any non-linear load such as switching power supplies, computers, fluorescent lamps and frequency converters. The possible consequences are many e.g. overheating of motors, currents in neutral line, efficiency decrease in engines, energy losses and disturbances in control systems. [1]

2.3.5 Unbalance

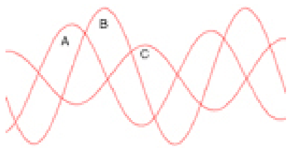


Figure 2.9: A visual representation of unbalance on three phases. From [1] used with permission

Unbalance occurs when the phases in a three-phase system are unequally loaded, resulting in different voltage magnitudes, and/or when the angle between the phases differ from 120 degrees [6, p. 14]. Sources of unbalance can for instance be heavy 1-phase household appliances like washing machines and dishwashers, twisted transmission lines, trains or arc furnaces. Common consequences are currents in neutral conductor, production of harmonics and decreases in efficiency in 3-phase motors [1].

2.3.6 Flicker

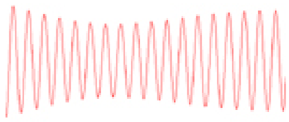


Figure 2.10: Flicker, voltage varying from nominal value. From [1] used with permission

The phenomenon when voltage fluctuates repeatedly is called flicker. This typically happens in weak grids when loads are connected and disconnected frequently. The effect of flickering can be observed in flashing or pulsating light bulbs, which can be irritating psychologically to people. Common sources of disturbance are for example induction cookers, heat pumps, rolling mills and welders. An economical effect of flicker is a decrease in production [1].

2.3.7 Power-Frequency Variations

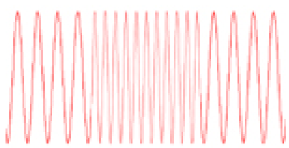


Figure 2.11: Power-Frequency variations. Nominal frequency first, then higher, then nominal. From [1] used with permission

Power-frequency variations, or simply frequency deviations, are disturbances that affect the frequency of the power grid, i.e. frequencies that differ from 50 or 60 Hz .

These kinds of disturbances, although not particularly common, tend to propagate widely, through the whole power grid [1]. Power-frequency variations occur when there is an imbalance between the generation and demand of power, which causes the rotational speed of electro-mechanical generators to vary [6, p. 20]. An example of this is when a large power plant is abruptly connected or disconnected. If a motor or a generator has frequency protection, it could be disconnected. [1].

2.3.8 Summary of types of disturbances

Table 2.1: Summary of types of disturbances

Disturbance:	Sources:	Consequences:
Voltage sags	thunder, pumps, inductive motor, short-circuits	damages in electronic devices
Voltage swells	poor grounding, connections of capacitor banks	damages to insulation material and devices
Transients	thunder, capacitor banks being connected or switches	damaged equipment, disturbances
Harmonics	non-linear loads, switching, computers	overheating in motors, neutral-line currents, efficiency decrease
Unbalance	Heavy 1-phase machines, twisted transmission lines	currents in neutral line, harmonics, decrease in efficiency
Flicker	induction cookers, heat pumps, welding	psychological irritation
Rapid voltage change	induction cookers/ motors, welding, and switching	psychological irritation
Power Frequency Variations	imbalance between the generation and demand of power	Disconnected motors and generators

2.4 Standards

For the ease of understanding what is good and what is poor PQ, some standards have been introduced in the field of PQ. Two standards in Europe that can be followed are IEC6100-2-4 and the EN50160. To understand the standards more a brief introduction to them is described in this chapter.

This report will only use the EN50160 as reference but it is good to have knowledge about a few more standards related to the subject.

2.4.1 EN50160

EN is an European standard, and EN50160 is created and designed by CENELEC which is the European Committee for Standardization (CEN) and Electrotechnical standardization (ELEC). The EN50160 is set to describe and specify the different disturbances in a system. The standard is set to better understand and have a measurement of if the PQ is at an adequate level.
The range is considered to be low voltage which ranges from 0V to 1kV. The voltage characteristics in the EN50160 report is not intended to be used for EMC standards.

2.4.2 IEC61000-2-4

IEC is the International Electrotechnical Commission [7]. The IEC is a non-profit organization which creates standards for all over the world to ensure good quality products. Currently 170 countries are together with the IEC.

The IEC61000-2-4 just like EN50160 is set to ensure good quality power from grid to costumer and but also provide a standard to keep costumers strain on the grid to a minimum. The IEC61000-2-4 sets certain limits for the different disturbances to check if the PQ pass or fail in that area.
The standard is concerned for disturbances in the range 0Hz-9kHz, nominal voltages up to 35kV and nominal frequency 50-60Hz. The report set standards regarding EMC and EMI.

2.5 Measurement Equipment

This sub section will explain the different measuring equipment used to achieve the measured data. All the equipment was calibrated according to standards as seen in Appendix B .

2.5.1 Unilyzer 900 Power Quality Analyzer

The equipment used to measure power quality in this report was the Unilyzer 900 from Unipower AB, Sweden. This is a costumed tool for measuring power quality. The Unilyzer measures and detects disturbances as mentioned earlier chapter 2.3. This device can be used to measure according to different standards from chapter 2.4, such as IEC61000 and EN50160. You can also customize the sampling and saving times for the unilyzers data as well as changing the range for sags, swells and more. The unilyzer fulfills the IEC61000-4-30 Class A power quality measurement standard which ensures a high quality and reliability in its advice and conclusions. The Unilyzer 900 was calibrated by Unipower before received, see Appendix B

Figure 2.12: Unipowers Unilyzer 900. From [1] used with permission

Table 2.2: Unilyzer 900 specifications

Specs:	Voltage Channel	Current Channel
Inputs	3	3
Level	0-1000V RMS	0-50A, 0-1000A
Resolution	24bits	24bits
Sampling rate	5000 samples/cycle	5000 samples/cycle
Input impedance	4MΩ	Galvanic isolated
Bandwidth	40kHz	40kHz
Category	CAT III 1000V, CAT IV 600V	-
Accuracy	IEC 61000-4-30 Class A (<0,1%)	IEC 61000-4-30 Class A (<0,1%)

Standards:
IEC 61000-4-30 ed.3 Class A.
IEC 61000-4-7 Class I.
IEC 61000-4-15 F3.

2.5.2 PQ Online

PQ online is a graphical user interface (GUI) used together with the Unilyzer 900 for real time visualisations. In the GUI there is a live Oscilloscope to view the live voltages and currents. The PQ online can also show live calculations such as active power, reactive power and apparent power drawn. The GUI can be accessed over wifi module or connected through usb. Once a measurement period is done the data can be downloaded through PQ Online and uploaded to PQ Secure which is explained in next subchapter.

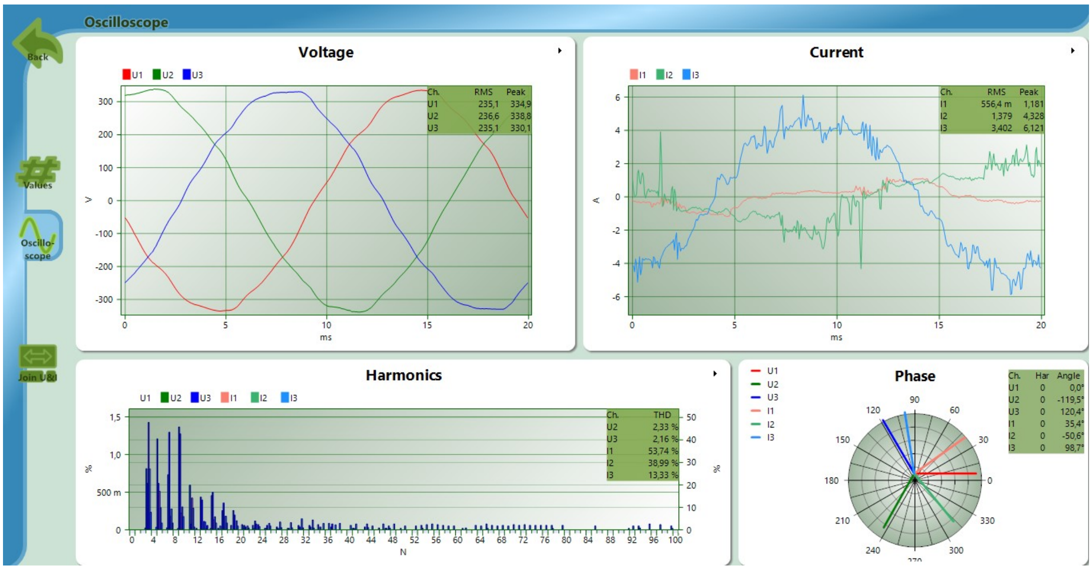


Figure 2.13: Snapshot from PQ Online. Upper left: Voltages measured. Upper right: Currents measured. Lower left: FFT of the harmonics. Lower right: Phasor diagram.

As seen in figure 2.13, PQ Online has a live oscilloscope to see voltage and current waves. The angle between the phasors can be seen in the lower right corner of the figure. The harmonics are also shown and can be selected for currents and/or voltages.

2.5.3 PQ Secure

Once a measurement is completed and downloaded from the Unilzyer using PQ Online, the data can be read using the GUI PQ Secure. This GUI has multiple functions and options to view all different disturbances and measurements. PQ Secure can create full PQ reports according to different world standards as mentioned in 2.4, for example EN50160 standard or IEC61000. PQ Secure is compliant with standard such as IEEE 1159.3, IEC 60255-24 and IEC 61000-4-30.

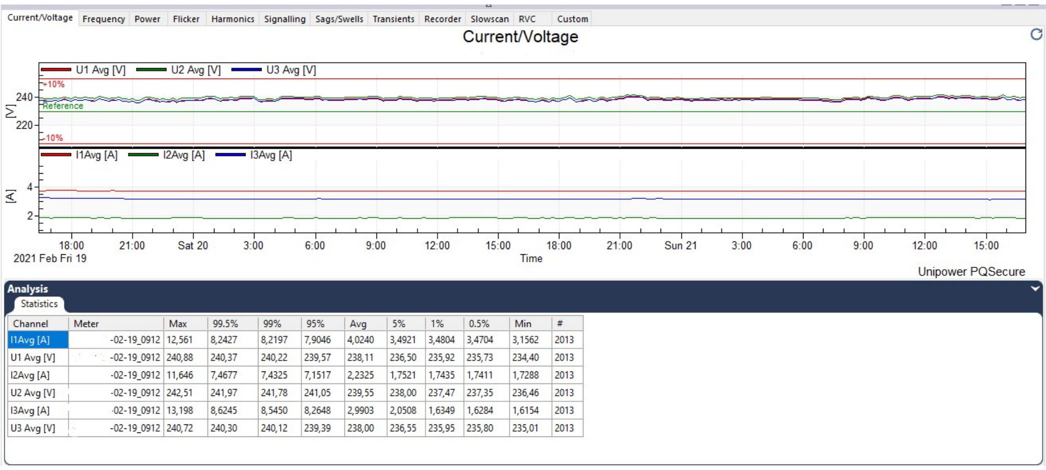


Figure 2.14: Snapshot from PQ Secure. Top: Average values of voltages and currents. Bottom: Analysis of voltages and currents on all three phases.

As seen in figure 2.14, the GUI has multiple tabs on top where the user can can see all collected data. The tabs consists of:

1. Current/Voltage
2. Frequency
3. Power
4. Flicker
5. Harmonics
6. Signalling
7. Sags/Swells
8. Transients
9. Recorder
10. Slowscan
11. RVC
12. Custom

Most of these are explained in chapter 2.3 Disturbances. By clicking on the tab the GUI shows within what limit the measured data should be to stay within the desired standard.

2.5.4 Current Transducer

The current transducers used were the clamp on ammeters. The ammeters were calibrated by Unipower before received, see Appendix B. The current ammeters have a rating for up to 50 A RMS and a CAT III rating.

Figure 2.15: Current clamp-on ammeter Art.No.40-1110.
From [1] used with permission

2.5.5 Voltage Transducer

The voltage transducer used to measure the power quality in this report was vampire clips. These clips are to ensure safety and not have any exposed conductor material while measuring. The vampire clips have a thin needle which pierces the insulating material and thus connecting to the live conductor material. Once the vampire clips are removed there is no conductor material exposed for electrical shock risk.

The vampire clips were calibrated by Unipower before recieved, see Appendix B. The voltage transducers used have a rating for up to 1000V RMS.

Figure 2.16: Vampire clips Art.No.40-2031(Red), Art.No.40-2041(Black).
From [1] used with permission

2.6 Electron Beam Melting - EBM

In this section there will be an introduction to the additive manufacturing and the EBM manufacturing. First explaining what additive manufacturing is and closing with how EBM works and what it is.

2.6.1 Additive introduction

Additive manufacturing is a manufacturing method used to create products and parts [3]. Comparing additive manufacturing with subtractive manufacturing, the additive create parts/products by adding a material layer by layer until the finished product is achieved. The subtractive removes material from solid blocks to achieve the final product, for example CNC machining. The additive manufacturing is also known as 3D-printing. By building a product layer by layer the final product can have more complex shapes and wastes less material compared to the subtractive manufacturing.

Additive manufacturing can be split up in seven sub categories as seen below [3]:

1. Powder Bed Fusion
2. Binder Jetting
3. Directed Energy Deposition
4. Material Extrusion
5. Material Jetting
6. Sheet Lamination
7. Vat Polymerzation

The most known method no 4. Material Extrusion, this method feeds material through a heated nozzle which is attached to an arm which can move in x,y and z direction. This is a traditional 3D-printer which most people have seen.

2.6.2 Powder Bed Fusion - PBF

EBM is under the manufacturing process 1. Powder Bed Fusion, PBF. In this process a thin layer of material in powder form is spread out on a table in a chamber, as seen in figure 2.17. The powder is then heated up with different techniques to adhere to the layer beneath. The table then moves down in Z direction and a new layer of powder is spread out. The process is then repeated until the final product is achieved. Once the build is complete the excess powder is vacuumed to reveal the final product. After this the last excess powder is blasted away to retrieve the final product.

Some advantages of having PBF is that most builds need no or minimum support during the building process. Another advantage is that the used powder can be filtered and recycled for the next build. PBF also allows for a wide variety of material

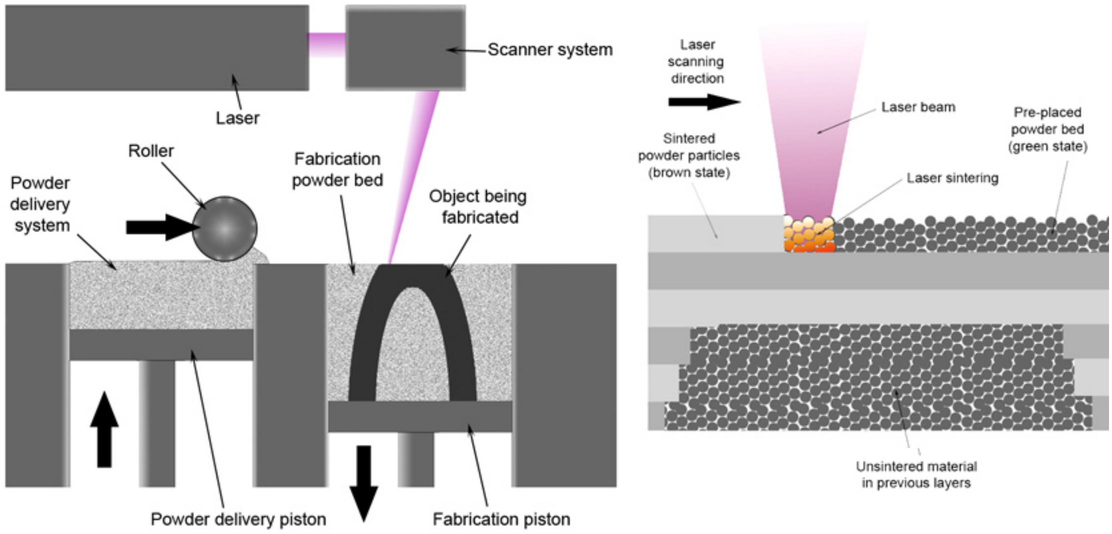


Figure 2.17: A type of Powder Bed Fusion.
From [2] CC BY-SA 3.0

choice, such as ceramics, plastic, titanium, copper and more.

A few disadvantages with PBF could be for example, long time for a print with all preparations and post processing, high power usage during prints, and surface texture could be grainy due to the fusing of powder.

This manufacturing process can be split up in five sub categories as seen below[3]:

1. Direct Metal Laser Sintering - DMLS
2. Selective Laser Sintering - SLS
3. Selective Heat Sintering - SHS
4. Electron Beam Melting - EBM
5. Direct Metal Laser Melting - DMLM

2.6.3 EBM Additive

EBM process uses a high powered electron beam to melt the powder layers together [3]. The electron beam heats up the powder layer until the optimal temperature for the material is acquired, the beam can be seen in figure 2.18. This process melts the powder layers together therefore achieving an additive manufacturing. The additive manufacturing is completed in a vacuum chamber to ensure a controlled environment for the material powder and the electron beam.

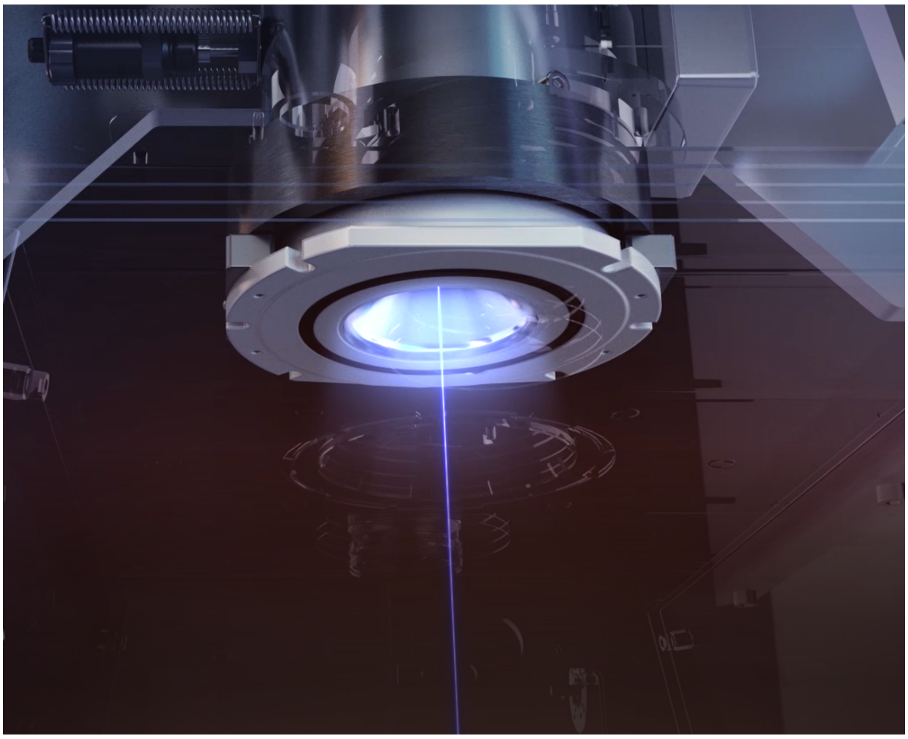


Figure 2.18: Electron beam. From [3].

Since the excess powder is sintered together the designer can stack multiple products on top of each other to maximize the building capacity and therefore reducing price and increasing efficiency per part. Once the product is finished the excess material is blasted away and the excess powder can be filtered and reused/recycled for next build. Since the electron beam is controlled electromagnetically, and there is no mechanic control of the electron beam therefore EBM process can be very fast and accurate. EBM melts the material before which ensures that the layers are fused together. EBM manufacturing results in a more homogeneous composition and has a lower porosity in the final product compared to other PBF processes.

Since the EBM is a PBF process the need for support structures are minimum or not needed at all. The EBM can also due to its control with magnetic fields appear to be in more than one spot which this increases speed of prints and is more time efficient, this is called multi beaming. Since the EBM is able to work with metal materials the manufacturing cost of customized parts is cheaper and faster compared to other metal manufacturing.

Some examples of areas and applications where the EBM manufacturing is used today is:

- Aerospace - Complex geometric designs, robust aerospace products.
- Automotive - Using aluminium alloys for customized parts.
- Healthcare & Orthopedic - E.g. Hip implants, complex dental implants.

3
Method

The method for this project has been split up into multiple phases to achieve the desired goals and meet all requirements. The different phases will be explained in this chapter.

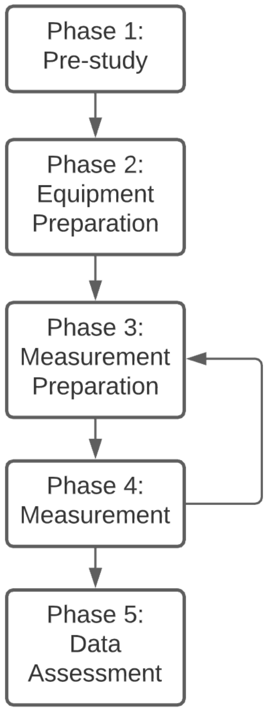


Figure 3.1: Different phases in project.

As seen in figure 3.1 there are five phases. Phase 3-4 are repeated multiple times for noticing patterns of PQ measurements.

3.1 Phase 1: Pre-study

The subject of PQ is a very specific and niche subject. Therefore a pre-study in the field had to be carried out. While a student of electrical engineering is assumed to have basic knowledge of single and three phase AC, they are not assumed to be familiar with the theories behind PQ.

The website Unipower [1], had the basic terminologies and standards to get a basic understatement for PQ measurements. The book [6], Power Quality in Power Systems and Electrical Machines, was also found using keyword Power quality in Chalmers library database. Using keywords as, "Power Quality" and "Power Quality analysis" to find other thesis work provided help for how to measure PQ and what key details to look for.

3.2 Phase 2: Equipment Preparation

As described earlier the measurement equipment used was the Unipower Unilyzer 900 with current and voltage transducers. To be able to measure the voltage and current on the machines, the 3-phase conductors needed to be accessed. To access the conductor the protective casing on the 3-phase wire had to be removed. To not cause any permanent damage to the machine a breakout cable was created.

This cable was connected between the 3-phase connector on the wall and the EBM machine and thus being able to measure input current and voltages.
To simulate voltage sags in the machine a 3-phase variable transformer had to be used. The variable transformer was to be wired up in Y connection. By adjusting the knob on the transformer a voltage drop could be induced into the EBM machine.

3.3 Phase 3: Measurement Preparation

To measure the current and voltages the breakout cable was connected from the wall outlet to the machine. Once the breakout cable was installed the Unilyzer could be started to and connected to PQ online. In PQ online the live oscilloscope was used to ensure that the correct phase transducers was connected to correct phase by checking the phasors angles.

The Unilyzer could then be setup with desired settings for saving date and trigger limits for transients and other disturbances. Once all desired settings was setup the measurement could be started.

3.4 Phase 4: Measurement

During the measurement phase the Unilyzer is saving the data according to settings. By connecting to the Unilyzer over the wifi module during a measurement you can check live measurements and download saved data until current time, the meter will continue to save data until the measurement is turned off. Measurements are usually measured at a minimum of 2-3 days, since printing time is around 40 hours on average.

3.5 Phase 5: Data Assessment

Once the measurement is completed the data can be downloaded using PQ online. The Unilyzer 900 can then be reset and either continue measuring or start new measurement. The data is then analyzed in PQ Secure. Any disturbances recognized during the measurement period is then available in PQ Secure. By comparing the single-line of the EBM machine and log files for the build, different conclusions can be drawn which could lead to improvements or desires.

4

Equipment preparation

This chapter will briefly describe how the breakout cable and transformer was prepared.

4.1 Breakout Cable

The breakout cable was used to be able to measure safely between the machine and the 3-phase outlet. Since the EBM machine is connected via a 32A 3-phase connector and fuse the wire had to be sized accordingly. The wire used for the breakout cable was $6mm^2$. The wires were connected properly to the 3-phase connector using the following table as a guide, table 4.1

Table 4.1: 3-phase connector table

Color:	Designation:	Description:
Brown	L1/R	Phase 1
Black	L2/S	Phase 2
Gray	L3/T	Phase 3
Green/Yellow	GND	Protective Earth
Blue	N	Neutral

To ensure no loose connection a small tug on wire was performed. To be able to attach the current and voltage transducers, about 30cm of the protective casing had to be removed. As seen in figure 4.1.

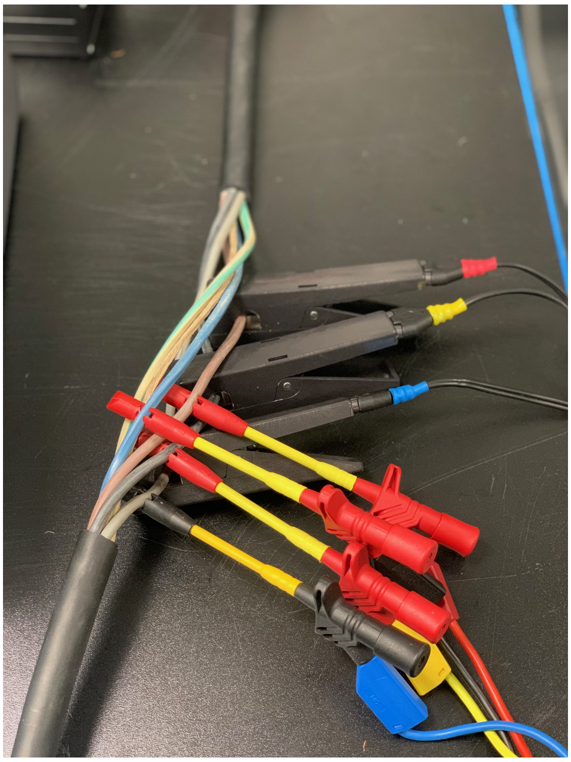


Figure 4.1: Breakout cable with voltage and current transducers connected. Brown = Phase 1, Black = Phase 2, Gray = Phase 3, Blue = Neutral, Green/Yellow = Ground.

Once the protective casing was removed the wires was inspected to ensure that no open copper could be seen. As a final safety precaution the continuity was tested between each wire and connector to ensure that the connector was safe to use. The continuity was tested also to ensure that correct wire was connected to correct housing. The wires were properly connected and the breakout cable was completed.

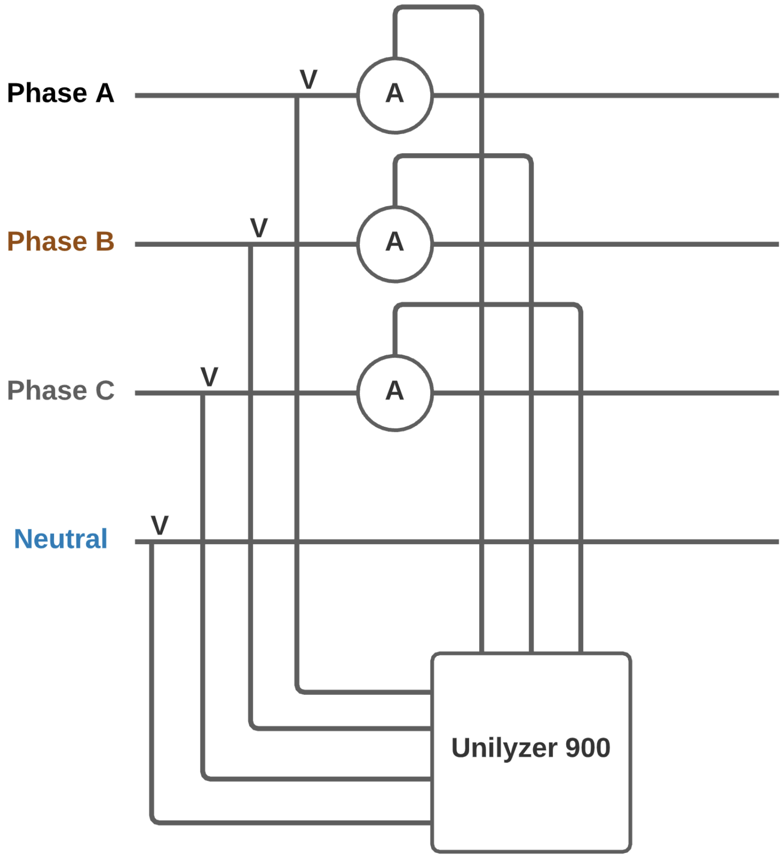


Figure 4.2: How the transducers was connected to the different phases from the Unilyzer 900. A is current clamps and V is voltage vampire clips.

The connections from the Unilyzer 900 to the breakout cable can be seen in figure 4.2.

4.2 3-Phase adjustable transformer

To be able to induce voltage sags into the EBM machine an adjustable transformer was used. The transformer had to be wired up to fit the desired need. The transformer was connected in a YN-yn connection and the wire size used for the transformer was the same as the BC, 6mm^2. The continuously variable voltage autotransformer used was a RS-WCV-10-E3, that can be seen in the figure below, **??**.

Figure 4.3: The adjustable transformer. RS-WCV-10-E3.

5

First Measurement Sequence: No Load

To better understand the measurement equipment and test the breakout cable, a first measurement without any load was completed. This chapter will explain more what was accomplished during the first measurement.

5.1 No Load Preparation

To ensure that the breakout cable was working properly and measure the voltage from the grid, a no load measurement was setup. The breakout cable was connected to the 3-phase outlet and the Unilyzer's transducers were attached to the conductors. The order of the transducers from the Unilyzer matters, so to ensure that the correct transducer was connected to the correct conductor the live oscilloscope in PQ online was used.

5.2 No Load Measurement

The no load measurement was tested a couple of times. Mainly to familiarize with the Unilzyer but also to check the quality from the grid.

The total measured time in first measurement sequence was 48hours over 2 measurements.

5.2.1 First Test

The first test was setup with storage intervals of 10 min apart. The test ran for 60 minutes. In PQ Online the oscilloscope was tested as well as its different calculation tools. Once the first test was completed the measured data was saved and uploaded into PQ Secure.

5.2.2 Second Test

The second measurement with no load was completed after the measurement of the lab machine M1 had failed the limit for 15th individual harmonic according to PQ standard EN50160. To ensure that the harmonic problem was not caused by the machine a second no load test was completed.

The second test was setup with 1 minute storage intervals and ran for about 45 hours. Once the measurement was completed the data was saved and uploaded into PQ Secure.

5.3 No Load Data Assessment & Result

Once the measurements were completed the data was uploaded into the GUI PQ Secure for data assessment.

5.3.1 First Test

The first test with no load was a very simple data file with only voltages since there was no load. The data provided no important information since it was over such a short time. The measurement was only completed to understand the equipment more and try PQ Online and PQ Secure.

5.3.2 Second Test

The priority of the second test with no load was to check for the under laying 15th individual harmonic. Since the other information from this measurement was of as much interest they were not assessed as deeply. By creating a report according to the standard EN50160 we were able to assess if the PQ from the grid held the standard.

As assumed in the individual harmonic analysis the 15th harmonic did not pass the set standard for EN50160. As seen in table 5.1, an outtake from the EN50160 report, 95% of the time the 15th harmonic for phase 2 and 3 exceeds the set limit.

Table 5.1: 15th individual harmonic analysis

#:	Limit[%]:	95%U1[%]:	95%U2[%]	95%U3[%]	Result
15	0.5	0.24	0.79	0.93	Failed

With this data assessment we can conclude that the 15th harmonic is an under laying harmonic in the building coming from the line side of PQ. Therefore the 15th harmonic problem will be disregarded from future measurements. The rest of the data collected during the measurement sequence seemed normal and following the set standard.

It is worth noting that in PQ standards the 15th harmonic limit is acknowledged for being set too high. This will be discussed in later chapter 9.1.1, conclusion and discussion.

6

Second Measurement Sequence: EBM Machines

This chapter will describe the measurements completed on the EBM machines. The measurements were completed during the machines multiple stages such as, idle, printing and open chamber door. The measurement were made on three different EBM machines, as seen in table 6.1

Table 6.1: Machine Names

Name:	Type:	Breaker Size (A):
Machine 1	Lab test machine	32
Machine 2	Spectra L	32
Machine 3	Spectra H	32
Machine 4	Q20plus	32

Machine 1(M1) is a laboratory machine and hence not a fully functioning one. It is setup in a lab environment to test certain aspects of its performance, such as electron beam and other electrical parts. Measurements done on M1 were done to test the Unilyzer with a load to be able to see both voltages and currents. M1 was also used to ensure that the BC and Unilyzer would not affect or damage the machine. Since this was a test machine the damage would a lower economical impact compared to the other machines.

Machine 2(M2), Machine 3(M3) and Machine 4(M4) are fully functioning machines. During the measurements the machines would use all its parts and the Unilyzer was able to measure the different PQ aspects.

6.1 EBM Machine Measurement Preparation

The different EBM machines were connected the same way. First the EBM machine was turned off by the main switch, then the 3-phase connector was then disconnected from the wall socket. After this the Unilyzer voltage and current transducers were connected onto the BC before attaching to the live socket. Lastly the BC was then connected between the machine-connector and the wall socket. To ensure safety and trip hazard the wires from the Unilyzer were then zip tied in a secure position to ensure that the device and the transducers would not be disconnected during the measurement.

6.2 EBM Machine Measurement

As mentioned the measurements were completed on four different machines. Each measurement will be described in this section.

6.2.1 Machine 1 Measurement

As mentioned earlier M1 is an EBM machine setup for testing, the machine cannot perform printing tasks but is setup to test other aspects of the machine. The M1 measurements were completed to further test the Unilyzer. Since the first test was made without a load there were no current measurements thus, by attaching M1 as a load we were able to analyze different currents to better understand the Unilyzer. Total time measured on M1 was 45 hours, over 2 measurements.

6.2.1.1 M1: First measurement

The first measurement on M1 was setup with 1 minute storage intervals and measured over 5 hours. This measurement was tested through PQ online to see that the Unilyzer was able to measure currents and voltages. The main focus for the first measurement was to understand the Unilyer 900 more and seeing the different calculations made in PQ online and PQ Secure. During the measurement the machine performed some tasks such as, start up, operate the vacuum pumps and start HV supply.

6.2.1.2 M1: Second measurement

The second measurement on M1 was setup with 10 min storage intervals and measure over 40 hours. During this measurement the machine was in an idle stage where mostly the pumps for the vacuum were seen as the load over the phases.

6.2.2 Machine 2 Measurement

Machine 2 is an Arcam Spectra L EBM machine. This machine is a fully functioning machine setup to test the different printing capabilities and quality of printing.

At this time the capability of the Unilyzer and its functions were fully understood. The different measurements were completed as the EBM machine completed full prints and other component tests. The Spectra L can be seen in figure 6.1.

Total time measured on M2 was 504 hours, over 4 measurements.

Figure 6.1: The Arcam EBM Spectra L. From [3]

6.2.2.1 M2: First measurement

The first measurement on machine 2 was setup with 1 minute storage intervals and measured over 47 hours and 15 minutes. During this measurement a full print was scheduled and performed.

6.2.2.2 M2: Second measurement

The second measurement on machine 2 was setup with 1 minute storage intervals and measured over 47 hours and 50 minutes. During the second measurement the machine was under a different set of component test.

6.2.2.3 M2: Third measurement

The third measurement on machine 2 was setup with 10 minute storage intervals and measured over 335 hours and 40 minutes. During this measurement a full print was performed. By measuring over a long time the different idle positions were observed to be able to understand the behavior and properties of the machine more.

6.2.2.4 M2: Fourth measurement

The fourth measurement on machine 2 was setup with 1 minute storage intervals and measured over 75 hours and 50 minutes. During the fourth measurement a full print was scheduled and performed.

6.2.3 Machine 3 Measurement

Machine 3 is an Arcam Spectra H EBM machine. This is also a fully functioning EBM machine. During the measured time the machine performed multiple tasks such as full prints and other components tests. The Arcam Spectra H can be seen in figure 6.2.

Total time measured on M3 was 291 hours, over 2 measurements.

Figure 6.2: The Arcam EBM Spectra H. From [3]

6.2.3.1 M3: First measurement

The first measurement on machine 3 was setup with 1 minute storage intervals and measured over 120 hours. During the first measurement a full print was scheduled and performed.

6.2.3.2 M3: Second measurement

The second measurement on machine 3 was setup with 1 minute storage intervals and measured over 171 hours.During the second measurement a full print was scheduled and performed.

6.2.4 Machine 4 Measurement

Machine 4 is an Arcam Q20plus EBM machine. This is also a fully functioning EBM machine. During the measured time the machine performed multiple tasks such as full prints and other components tests. The Arcam Q20plus can be seen in figure 6.3.

Figure 6.3: The Arcam EBM Q20plus. From [3]

6.2.4.1 M4: First measurement

The first measurement on M4 was setup with 1 minute storage intervals and was measured over 143 hours. During the measurement the machine performed a print and all the components of the machine were used.

6.3 EBM Machine Data Assessment & Result

In this section the different machines' measured result will be assessed.

6.3.1 Machine 1 Data Assessment & Result

In this subsection the data logged for Machine 1 will be assessed. A summary of the data logged during all the measurements can be seen in table 6.2. The data in the table is an average over the time measured.

Table 6.2: Summary of M1 measured data

Measurement#:	1:	2:
THDFU1:	2.55 %	1.96 %
THDFU2:	2.38 %	2.31 %
THDFU3:	2.16 %	2.10 %
THDFI1:	55.1 %	52.78 %
THDFI2:	37.8 %	38.91 %
THDFI3:	13.85 %	13.37 %
PFtot:	0.73	0.74
#Sags/Swells:	0/0	0/0
#Transients:	0	0
Hours.Minutes:	5.09	40.02

6.3.1.1 M1: First Measurement

As seen in table 6.2 there were no sags or transients measured in the first measurement. When observing the power tab in PQ secure we realized that the current clamps had its reference facing the opposite way which resulted the measured power to be negative which would mean that the machine was producing active power. Since the EBM is not a generator this was obviously not correct. By just changing the direction on the current clamps on the BC this problem was fixed.

Another issue that was realized watching the logged data was that phase 2 and 3 had been connected wrong on the BC. This problem was easily corrected as well by changing the vampire clips and current clamps. Knowing about the wrong reference for the current clamps and the switched phases we were still able to use the data gathered on the first measurement.

By selecting the max registered current for the 3 phases we were able to see fast peaks of currents and voltages. At startup of the HV supply there was an inrush current on all the 3 phases, which was predicted, as seen in figure 6.4. This inrush current lasted about 10 ms. By creating a EN50160 report in PQ Secure we were quickly able to see what the overall PQ looked like before diving in deeper. The machine passed the report except the 15th harmonic which was discussed in earlier chapter 5.3.2, so this could be ignored.

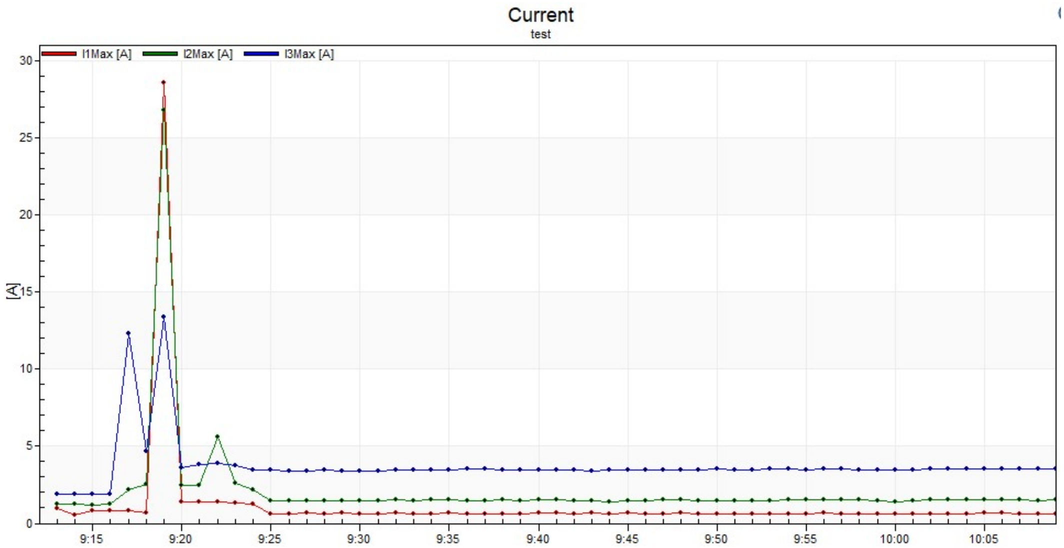


Figure 6.4: Inrush current in Machine 1, Max current registered on Y axis, Red=Phase1, Green=Phase2, Blue=Phase3, Time X axis.

As seen in table 6.2, the THDU is around 2 % average, where the limit for the THDU set by EN50160 is 8 % this is a good value.

By checking the individual current harmonics in PQ Secure, we were able to see that the 3rd harmonic on phase 1 was the largest at 49.5 % of the fundamental current. The top three individual current harmonics can be seen below.

1. I1-3(150Hz) = 49.5 %
2. I2-3(150Hz) = 26.6 %
3. I1-5(250Hz) = 21.0 %

The different causes of these harmonics will be discussed in the chapter 9 conclusion and discussion.

The total PF as seen in table 6.2, was around 0.73. The PF over the different phases however varied. The average PF for the different phases was, Phase1 = 0.7, Phase2 = 0.91 and Phase3 = 0.3.

Since the M1 is not a fully functioning machine the measurements could differ from the other machines. The main reason for measuring on M1 was to better understand the Unilyzer, PQ Online and PQ Secure.

6.3.1.2 M1: Second Measurement

During the second measurement, which was over a longer time, the machine was only in a idle stage. The current was constant for 40 hours and nothing really interesting happened. In an EN50160 report the machine passed the PQ limits except the 15th harmonic which was expected. There were no sags, swells or transients. As seen in table 6.2, the THDU and THDI is very similar to the first measurement. The top three individual current harmonics can be seen below.

1. I1-3(150Hz) = 47.59 %
2. I2-3(150Hz) = 28.57 %
3. I1-5(250Hz) = 19.31 %

6.3.2 Machine 2 Data Assessment & Result

In this subsection the data logged for Machine 2 will be assessed. A summary of the data logged during all the measurements can be seen in table 6.3. The data in the table is an average over the time measured.

Table 6.3: Summary of M2 measured data

Measurement#:	1:	2:	3:	4:
THDFU1:	2.60 %	2.72 %	2.67 %	2.31 %
THDFU2:	2.41 %	2.60 %	2.48 %	2.53 %
THDFU3:	2.03 %	2.07 %	2.08 %	1.97 %
THDFI1:	42.46 %	17.15 %	20.25 %	32.92 %
THDFI2:	68.78 %	27.87 %	31.46 %	53.25 %
THDFI3:	53.19 %	53.94 %	52.02 %	41.59 %
PFtot:	0.83	0.68	0.75	0.84
#Sags/Swells:	0/0	0/0	0/0	0/0
#Transients:	1	1	1	0
Hours.Minutes:	47.15	47.50	335.40	75.50

6.3.2.1 M2: First Measurement

This is the first measurement of a printing machine with all its parts operating. A EN50160 report was created to see the overall PQ of the machine. The machine passed the EN50160 standard except the 15th harmonic as mentioned previously. As seen in the summary in table 6.3, there were no sags or swells. There was one transient registered during the measured time.

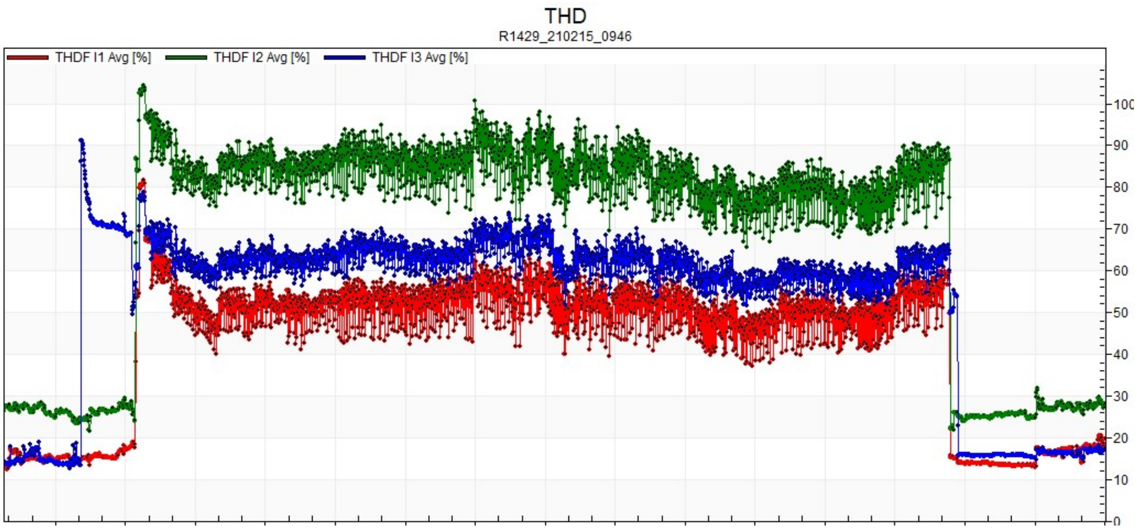


Figure 6.5: THDFI for M2 measurement 1. Red = Phase 1, Green = Phase 2, Blue = Phase 3. Yaxis = Percentage, Xaxis = Time.

During the printing phase of the measurement the THDI changes drastically.

- THDFI1=15 % → 46 %
- THDFI2=26 % → 87 %
- THDFI3=15 % → 62 %

This can be seen in figure 6.5. These harmonics will be discussed more in the conclusion and discussion chapter 9 of this report. A complete summary of the first measurement on M2 can be seen in table 6.4.

Table 6.4: Summary of first measurement data M2

	Full measurement average:	Printing session average:
THDI1:	42.47 %	51.46 %
THDI2:	68.79 %	83.39 %
THDI3:	53.20 %	62.11 %
PF1:	0.72	0.73
PF2:	0.49	0.56
PF3:	0.85	0.90
P1:	1.02 kW	1.16 kW
P2:	0.52 kW	0.64 kW
P3:	1.07 kW	1.30 kW
Q1:	-0.79 kVAr	-0.85 kVAr
Q2:	-0.60 kVAr	-0.67 kVAr
Q3:	-0.22 kVAr	-0.22 kVAr
Top 3 highest IH:		
1:	I2-5(250Hz): 40.55 %	I2-5(250Hz): 52.86 %
2:	I2-7(350Hz): 32.64 %	I2-7(350Hz): 40.63 %
3:	I3-5(250Hz): 30.35 %	I3-5(550Hz): 36.61 %

6.3.2.2 M2: Second Measurement

During the second measurement on the machine M2 there was no printing taking place. However, a set of tests were performed on the machine, which resulted in a variety of components of the machine being activated. When a EN50160 report was generated, the result was in line with the previous reports, i.e the machine passed the standards, again with the exception of the 15th harmonic. One transient was registered, but no sags or swells.

What stood out in this measurement compared to previous performed on M2 was the noticeably lower average values of THDFI on all three phases, as can be seen in table 6.5. This was due to the fact that there was no printing taking place. Another interesting event was a transient that was registered as indicated in figure 6.3.2.2.

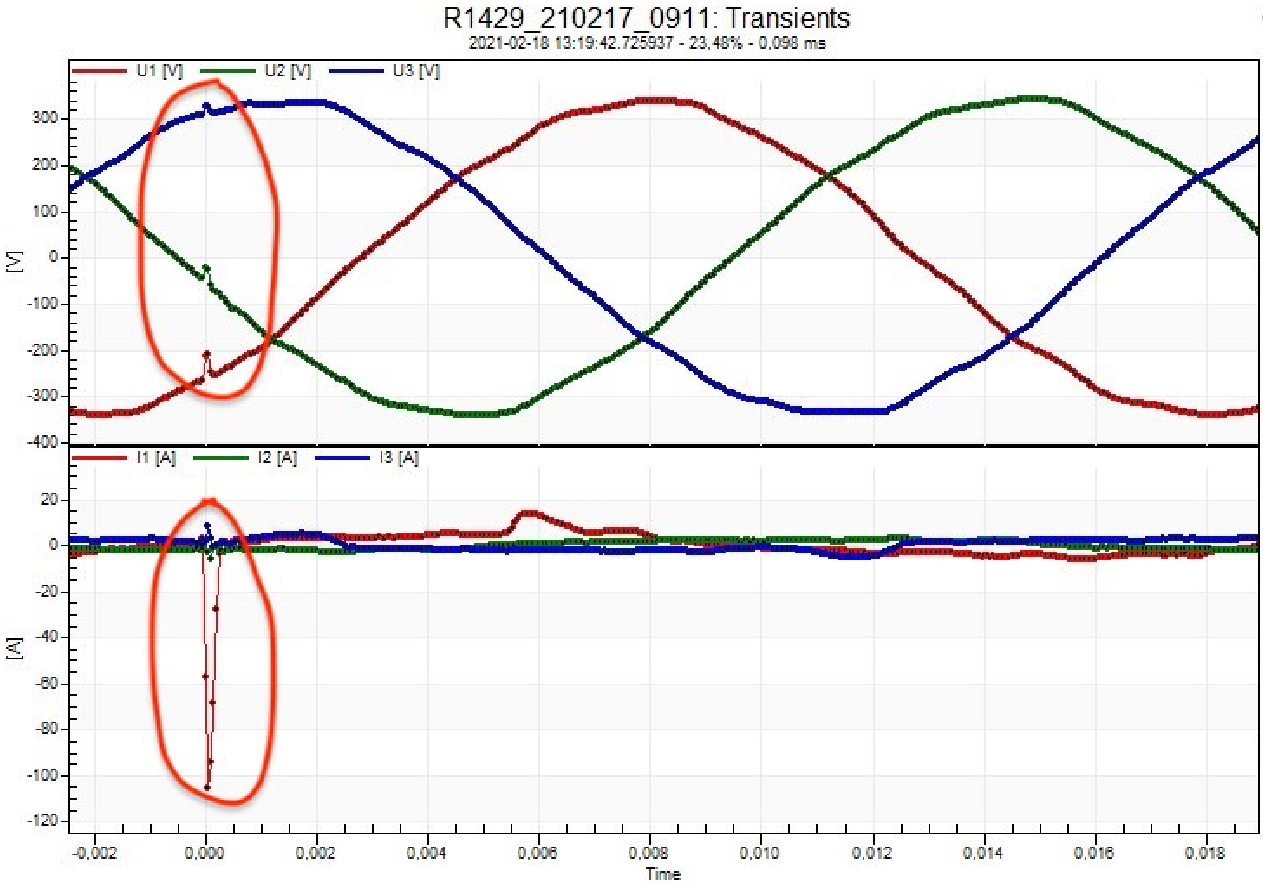


Figure 6.6: Transient during measurement 2 in Machine 2. Voltage curves above, Current curves below. Red = Phase 1, Green = Phase 2, Blue = Phase 3.

As seen in the figure , the large current spike creates a voltage rise over the source impedance which is the cause of the transient. A complete summary of the second measurement on M2 can be seen in table 6.5.

Table 6.5: Summary of second measurement data M2

	Full measurement average:	Printing session average:
THDI1:	17.15%	N/A
THDI2:	27.88%	N/A
THDI3:	53.94%	N/A
PF1:	0.67	N/A
PF2:	0.34	N/A
PF3:	0.63	N/A
P1:	0.60kW	N/A
P2:	0.15kW	N/A
P3:	0.46kW	N/A
Q1:	-0.65kVAr	N/A
Q2:	-0.41kVAr	N/A
Q3:	-0.23kVAr	N/A
Top 3 highest IH:		
1:	I3-3(150Hz): 33.68%	N/A
2:	I3-5(250Hz): 26.19%	N/A
3:	I3-7(350Hz): 23.36%	N/A

6.3.2.3 M2: Third Measurement

As before an EN50160 report was created at first to get a proper overview of the total PQ. The measurement passed the PQ standard with the execption of the 15th harmonic as discussed before.

Taking a look at the overall PQ there was no sags or swells, there was 1 transient, and the over all voltage harmonics within the limits of the PQ standard. Comparing this measurements with the measurements before we were starting to notice the different patterns of the machine. How the currents looked when the machine was printing and how the currents looked during the idle mode. By comparing the different current on the phases and the single line we were able to identify what the different loads were. Out of the total 335 hours measured, about 23 hours the machine was in print mode.

During the printing phase the harmonics on phase 2 are the largest, but over the whole 335hours the individual harmonics from phase 3 was the largest. This will be discussed more in chapter 9.

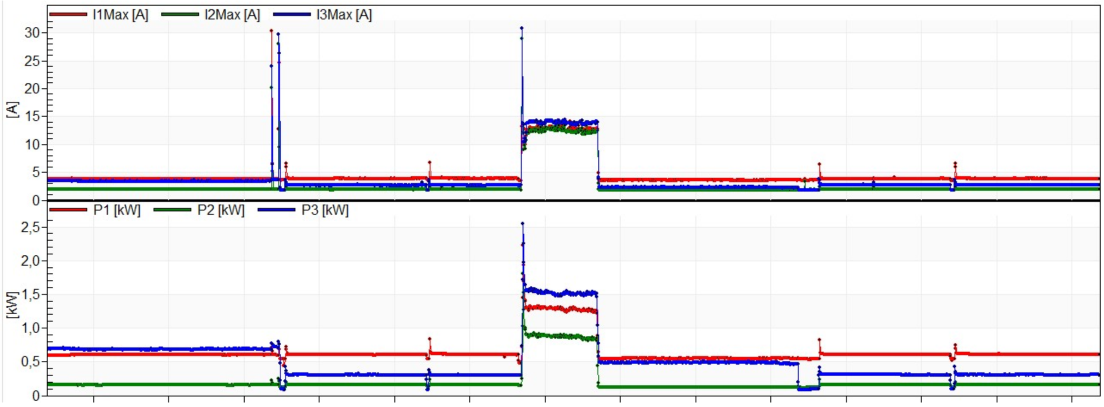


Figure 6.7: Graph from PQ Secure, Active power above, Currents below. Red = Phase 1, Green = Phase 2, Blue = Phase 3.

Over the 335 hours measured, only 1 transient was observed, which had a very small impact. It was a 24.32% transient on phase 3. Another thing to register is the current drawn from the different phases and the active power consumed. The currents during the printing phase is pretty well balanced between the phases but the active power consumed has some difference between the phases and phase 2 and phase 3 differ by a factor 2 as seen in figure 6.7, this is something due to the PF from phase 2 and the current THD. This is something that will be discussed further in the discussion chapter 9. A complete summary of the measured data can be seen in table 6.6.

Table 6.6: Summary of third measurement data M2

	Full measurement average:	Printing session average:
THDI1:	20.26%	59.55%
THDI2:	31.46%	91.32%
THDI3:	52.02%	66.54%
PF1:	0.67	0.78
PF2:	0.36	0.67
PF3:	0.71	0.95
P1:	0.62kW	1.28kW
P2:	0.20kW	0.87kW
P3:	0.51kW	1.52kW
Q1:	-0.65kVAr	-0.86kVAr
Q2:	-0.42kVAr	-0.72kVAr
Q3:	-0.20kVAr	-0.17kVAr
Top 3 highest IH:		
1:	I3-3(150Hz): 30.49%	I2-5(250Hz): 63.05%
2:	I3-5(250Hz): 27.32%	I2-7(350Hz): 46.13%
3:	I3-7(350Hz): 21.96%	I3-5(250Hz): 42.57%

6.3.2.4 M2: Fourth Measurement

As the other measurements an EN50160 report was created to see the overall PQ from this sequence. During this measurement there was 0 sags/swells, 0 transients and no interruptions. The PQ passed all the disturbance limits except the individual harmonics due to the 15th harmonic as expected.

Since this measurement was measured over about 75hours during which the machine was operating about half of the time. As the earlier measurements completed on M2 during the print phase the THDI increased significantly compared to during idle mode. With the THDI2 highest at 75%, THDI3 second at 57% and THDI1 lowest at 46%.

By checking the power harmonics you can determine if the harmonics are coming upstream(from grid to load), or downstream(load to grid). If the power harmonics are positive its upstream and if the power harmonics are negative its downstream. During a very short time the 5th power harmonics(250Hz) on phase 2 was negative as seen in figure 6.8, this meaning the load created the harmonics. An important note is that the maximum negative power harmonics was 14Watt, this is a very small value and due to that there is not very large voltage harmonics. Also worth noting that the power harmonic is almost 0 watts during the other time of the measurement. This will be discussed more in the chapter 9 discussions.

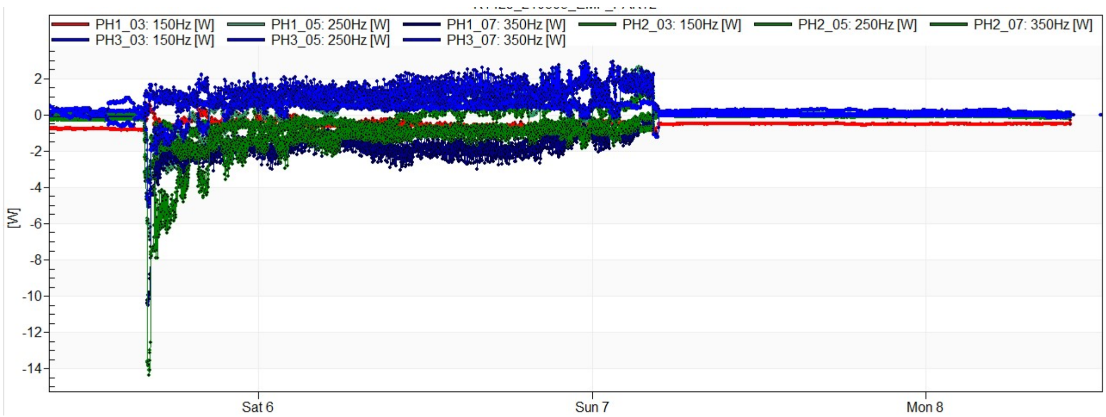


Figure 6.8: Power harmonics during measurement 4 on M2

During the printing part of the measurement, the most active power is consumed on P3=1.35kW, second P1=1.16kW and last P2=0.57kW. The reactive power consumed during the printing phase was, Q1=0.85kVAr, Q2=0.65kVAr and last Q3=0.18kVAr. This is due to the power factor and the harmonics on the different phases. A complete summary of the fourth measurement on M2 can be seen in table 6.7.

Table 6.7: Summary of fourth measurement data M2

	Full measurement average:	Printing session average:
THDI1:	32.92%	48.53%
THDI2:	53.25%	80.67%
THDI3:	41.59%	56.35%
PF1:	0.70	0.74
PF2:	0.44	0.58
PF3:	0.88	0.92
P1:	0.85kW	1.16kW
P2:	0.40kW	0.69kW
P3:	0.87kW	1.32kW
Q1:	-0.73kVAr	-0.85kVAr
Q2:	-0.53kVAr	-0.67kVAr
Q3:	-0.12kVAr	-0.19kVAr
Top 3 highest IH:		
1:	I2-5(250Hz): 29.03%	I2-5(250Hz): 54.81%
2:	I3-5(150Hz): 23.72%	I2-7(350Hz): 39.01%
3:	I2-7(350Hz): 23.06%	I3-5(250Hz): 33.76%

6.3.3 Machine 3 Data Assessment & Result

In this subsection the data logged for Machine 3 will be assessed. A summary of the data logged during all the measurements can be seen in table 6.8. The data in the table is an average over the time measured.

Table 6.8: Summary of M3 measured data

Measurement#:	1:	2:
THDFU1:	1.67 %	1.98 %
THDFU2:	2.14 %	2.05 %
THDFU3:	1.89 %	1.96 %
THDFI1:	53.15 %	22.49 %
THDFI2:	81.67 %	34.42 %
THDFI3:	57.83 %	32.06 %
PFtot:	0.85	0.81
#Sags/Swells:	0/0	0/0
#Transients:	0	0
Hours.Minutes:	120.02	171.08

As seen in table 6.8, there was no voltage transients, voltage sags or voltage swells. The THDFI differ between the two different measurements and thats due to that during measurement 1 there is a very long print compared to measurement 2 where the machine was only printing for a short time of the whole measurement. Since the values are an average this will result in a different value of the two measurements. The table will be discussed more in the following sub chapters.

6.3.3.1 M3: First Measurement

At first a EN50160 report was created to check the overall PQ. The report passed the PQ limits except the individual harmonics, due to the 15th harmonic as mentioned before. There was 0 sags, 0 swells, 0 interuptions and 0 transients during the 120hours measured. The measured data was within the limits of the standard EN50160.

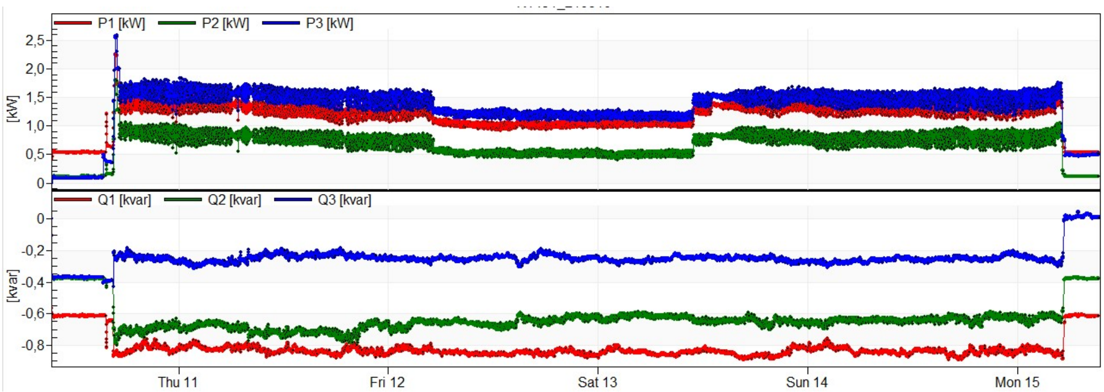


Figure 6.9: Active and reactive power in M3.

Looking into the characteristics of the machine. There was an inrush current once the machine was turned on and one before printing, which was expected. The over all load looked balanced during printing, I1=10.1A, I2=8.4A and I3=10.3A. The active and reactive power during the measurement can be seen in figure 6.9. During the printing phase the active and reactive power was measured to be:

- P1=1.24kW ,Q1=-0.83kVAr
- P2=0.71kW ,Q2=-0.66kVAr
- P3=1.66kW ,Q3=-0.25kVAr

A complete summary of the first measurement on M3 can be seen in the table below, table 6.9.

Table 6.9: Summary of first measurement data M3

	Full measurement average:	Printing session average:
THDI1:	53.15%	56.74%
THDI2:	81.67%	87.38%
THDI3:	57.21%	60.63%
PF1:	0.73	0.74
PF2:	0.57	0.60
PF3:	0.88	0.91
P1:	1.18kW	1.25kW
P2:	0.66kW	0.72kW
P3:	1.32kW	1.42kW
Q1:	-0.81kVAr	-0.83kVAr
Q2:	-0.63kVAr	-0.66kVAr
Q3:	-0.25kVAr	-0.25kVAr
Top 3 highest IH:		
1:	I2-5(250Hz): 52.31%	I2-5(250Hz): 57.23%
2:	I2-7(350Hz): 39.32%	I2-7(350Hz): 42.55%
3:	I1-5(250Hz): 32.73%	I1-5(250Hz): 35.83%

6.3.3.2 M3: Second Measurement

An EN50160 report was generated from PQ secure for the second measurement to check the over all PQ. The measurement passed the standard except the individual harmonic due to the 15th harmonic as discussed previously. During the measurement there was 0 sags, 0 swells and 0 interruptions. There was 0 transients registered.

During 24hours out of the total 171 hours the machine was printing. Looking at the inrush currents during start of pumps and other equipment the Unilyzer 900 was set to register a current trig. By doing this we were able to see how long the inrush current was and what exact moment it happened as seen in figure 6.10. In the figure the duration of the inrush current was around 10ms, so less than one period (20ms, 50Hz).

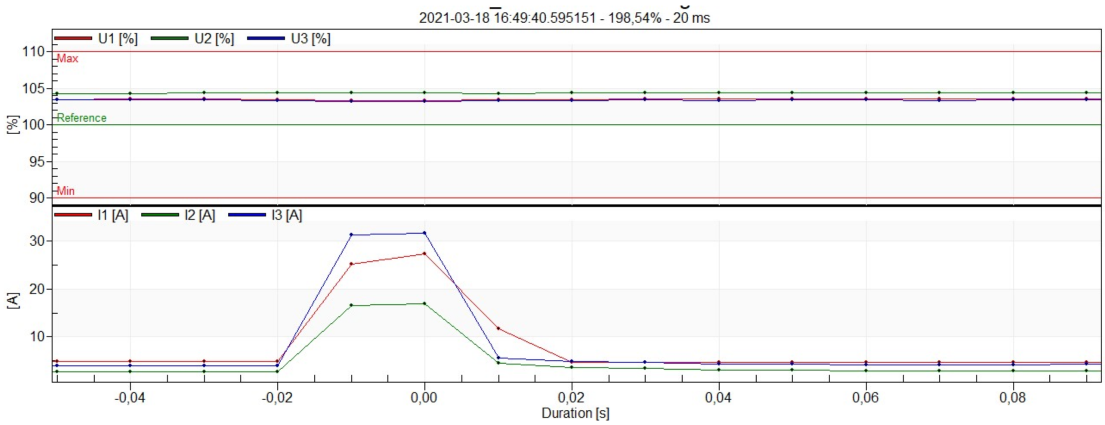


Figure 6.10: Duration of inrush current.

A summary of the measured data can be seen in the table below, 6.10:

Table 6.10: Summary of second measurement data M3

	Full measurement average:	Printing session average:
THDI1:	16.81%	60.25%
THDI2:	26.54%	87.71%
THDI3:	16.93%	60.22%
PF1:	0.62	0.75
PF2:	0.34	0.61
PF3:	0.75	0.95
P1:	0.58kW	1.09kW
P2:	0.20kW	0.64kW
P3:	0.51kW	1.32kW
Q1:	-0.66kVAr	-0.85kVAr
Q2:	-0.43kVAr	-0.69kVAr
Q3:	-0.16kVAr	-0.19kVAr
Top 3 highest IH:		
1:	I2-3(150Hz): 17.84%	I2-5(250Hz) = 55.36%
2:	I3-5(550Hz): 17.25%	I2-7(350Hz) = 40.76%
3:	I3-3(150Hz): 17.15%	I3-5(250Hz) = 35.35%

6.3.4 Machine 4 Data Assessment & Result

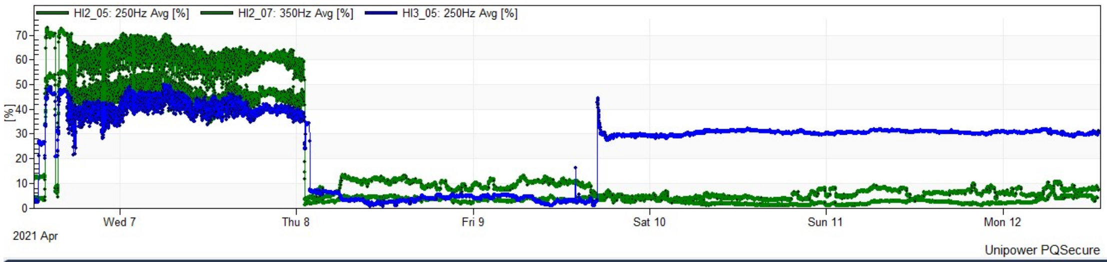
In this subsection the data logged for Machine 4 will be assessed. A summary of the data logged during all the measurements can be seen in table 6.11. The data in the table is an average over the time measured.

Table 6.11: Summary of M4 measured data

Measurement#:	1:
THDFU1:	2.10%
THDFU2:	2.14%
THDFU3:	2.07%
THDFI1:	28.61%
THDFI2:	40.60%
THDFI3:	54.06%
PFtot:	0.75
#Sags/Swells:	0/0
#Transients:	1
Hours.Minutes:	143.53

6.3.4.1 M4: First Measurement

An EN50160 report was created to check the PQ compared to the standard. The measured data passed limits according to the standard, except the 15th individual harmonic discussed before. There was 0 sags, 0 swells, 1 transient and 0 interruptions. The transient registered was a 23.68% transient on U2. The top three highest individual harmonics can be seen in the figure below, figure 6.11.



Channel	Meter	Max	99.5%	99%	95%	Avg	5%	1%	0.5%	Min	#
HI2_05: 250Hz Avg [%]	q20plus210406	72,978	70,995	70,244	65,047	16,918	1,2007	0,9686	0,8992	0,7179	8683
HI2_07: 350Hz Avg [%]	q20plus210406	55,737	54,484	54,001	49,757	16,397	3,3031	2,7670	2,5919	1,9973	8683
HI3_05: 250Hz Avg [%]	q20plus210406	49,817	47,864	47,183	44,065	25,525	2,3201	1,3242	0,9405	0,5235	8683

Figure 6.11: Highest individual harmonics measurement 1 M4.

The inrush current during turn on of pumps was registered at 31.43A and lasted for about 10ms. During 36 hours of the total 143 hours the machine was in printing mode. A summary of the most important data can be seen in the table below, 6.12:

Table 6.12: Summary of first measurement data M4

	Full measurement average:	Printing session average:
THDI1:	28.68%	53.58%
THDI2:	40.58%	96.79%
THDI3:	54.22%	70.11%
PF1:	0.59	0.71
PF2:	0.25	0.50
PF3:	0.50	0.88
P1:	0.81kW	1.38kW
P2:	0.25kW	0.72kW
P3:	0.55kW	1.49kW
Q1:	-0.93kVAr	-1.08kVAr
Q2:	-0.58kVAr	-0.82kVAr
Q3:	-0.44kVAr	-0.29kVAr
Top 3 highest IH:		
1:	I3-3(150Hz): 29.06%	I2-5(250Hz): 60.57%
2:	I3-5(250Hz): 25.52%	I2-7(350Hz): 45.85%
3:	I3-7(250Hz): 24.75%	I3-5(250Hz): 40.57%

7

Third Measurement Sequence: Induced Sags

As mentioned earlier in chapter 1.4, the question of how the EBM machine gets affected by disturbances some voltage sags was designed to be induced. The Swedish power grid is pretty stable so a transformer was used to induce these voltage sags.

7.1 Induced Sags Measurement Preparation

As mentioned in section 4.2, an adjustable 3phase transformer was used to induce sags into a machine. The transformer was connected as in figure 7.1. By having the Unilyzer on the load side of the transformer the Unilyzer is able to register when a sag occur.

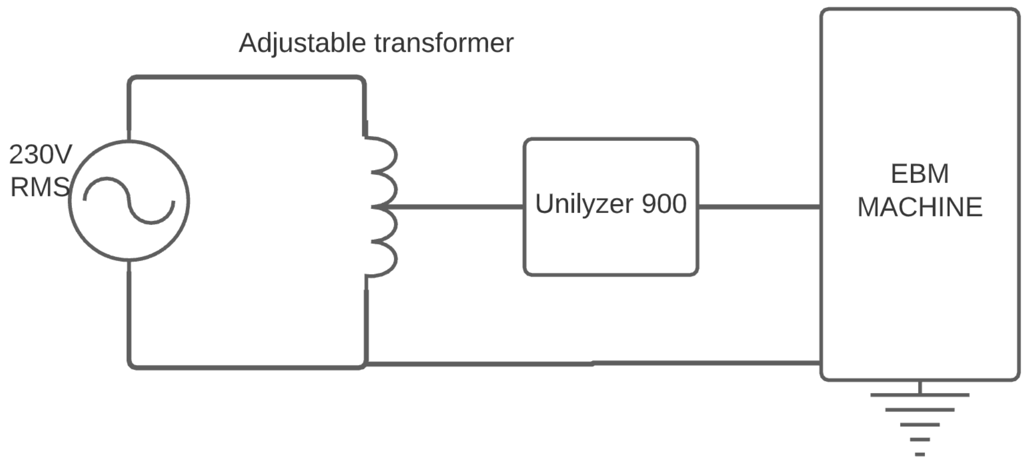


Figure 7.1: Transformer connection single line.

7.2 Induced Sags Measurements

The induced sags sequence was divided up into two measurements, a first one to test out the transformer with idle voltages and a second one measuring the sags in an EBM machine. Total time measured with induced sags sequence was 1hour.

7.2.1 First Measurement

The first measurement was setup with 1 minute storage intervals and was measure over 20 minutes. The first measurement was completed to test out the adjustable transformer and observe how the Unilyzer registers the different voltage sags. The measurement was completed without any load and only idle voltages from the grid was measured.

7.2.2 Second Measurement

The second measurement was setup with 1 minute storage intervals and measured over 40 minutes. The Unilyzer was connected to the adjustable transformer and Machine 1, the Arcam lab test setup machine. As mentioned before Machine 1 is not a fully functioning machine but has the most vital components of interest connected, when measuring PQ.

During the measurement a couple of sags was induced during different operation modes. First, 4 different depth sags was induced while the machine was in idle mode. In idle mode the machine has the Programmable Logic Controller (PLC), different vacuum pumps and other computer loads working.

After the first 4 sags was induced the HV supply was started as well and another 4 sags at different depth was induced. As seen in table 7.1, the desired sag depth and load. Since the adjustable transformer has a turn knob to control the output, to achieve a fast and accurate sag was a complicated task. The desired sag and measured might differ but the induced sag was completed as accurate as possible.

Table 7.1: Desired Induced Sags

Sag #:	Desired sag depth:	Load:
1	5%	Idle
2	10%	Idle
3	10%	Idle
4	15%	Idle
5	15%	Idle
6	20%	Idle
7	20%	Idle
8	10%	HV Supply
9	10%	HV Supply
10	15%	HV Supply
11	20%	HV Supply
12	25%	HV Supply

7.3 Induced Sags Data Assessment & Result

In this section the data logged for the induced sags will be assessed. First the induced sags without load and second the induced sags with EBM machine as load. A summary of the data logged during the induced sags sequence can be seen in table 7.2. The data in the table is an average over the time measured. Since the first measurement was measured without a load and only to test the adjustable transformer THDF, THDI and PFtot is not applicable.

Table 7.2: Summary of measured data

Measurement#:	1:	2:
THDFU1:	N/A	2.3%
THDFU2:	N/A	2.2%
THDFU3:	N/A	2.0%
THDFI1:	N/A	51.9%
THDFI2:	N/A	40.76%
THDFI3:	N/A	18.63%
PFtot:	N/A	0.76
#Sags/Swells:	41/0	12/0
#Transients:	8	14
Hours.Minutes:	0.20	0.40

7.3.1 First Measurement

The main objective for the first measurement was to test the Unilyzer to better understand the registration of sags. By creating a EN50160 report we were able to see that there was 41 sags registered with different characteristics. A snapshot from PQ Secure can be seen in figure 7.2. The other data gathered during the first measurement was irrelevant due to that there was no load and of no interest.

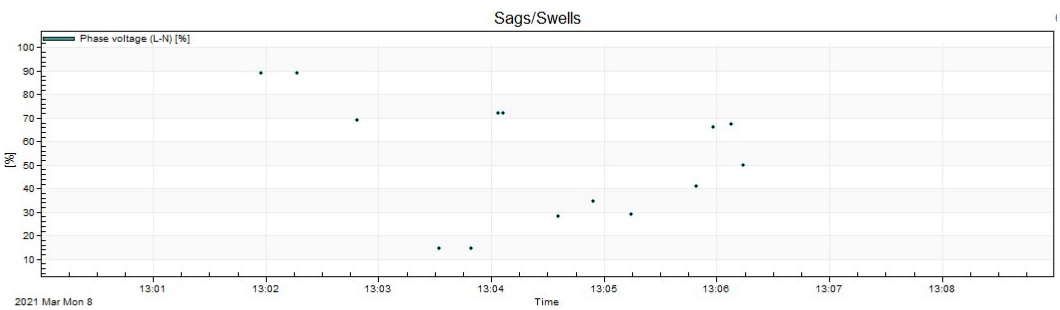


Figure 7.2: Registered sags in PQ secure. Each dot represents a registered voltage sag. Yaxis = Percentage, Xaxis = Time

7.3.2 Second Measurement

An EN50160 report was created to check the induced sags, 11sags was registered with different characteristics, only 11 was registered due to that according to EN50160 a sag is only below 10% so the first induced sag was below this limit. There was 14 transients registered during the measurement. A summary of the induced sags can be seen in table 7.3. As seen in the table the actual sag and the desired sag differ by some percent due to that its an analog manual turning knob which which affects the accuracy of the induced sags.

Table 7.3: Registered Induced Sags

Sag #:	Desired sag depth:	Actual sag depth	Duration	Load:
1	5%	7.01%	109.98ms	Idle
2	10%	12.53%	109.98ms	Idle
3	10%	10.86%	109.93ms	Idle
4	15%	14.37%	250.15ms	Idle
5	15%	11.64%	120.13ms	Idle
6	20%	20.56%	190.22ms	Idle
7	20%	16.8%	190.04ms	Idle
8	10%	16.87%	159.92ms	HV Supply
9	10%	16.14%	210.13ms	HV Supply
10	15%	21.4%	210.12ms	HV Supply
11	20%	28.97%	269.88ms	HV Supply
12	25%	33.86%	320.18ms	HV Supply

In PQ secure every sag registered was inspected as can be seen in figure 7.3, the lenght of the sag, the depth and an transient current after each sag was noticed. The different causes of the sags will be discussed in chapter 9. After each sag there was a voltage transient registered as well within 100ms after the sag, which is caused by the current transient.

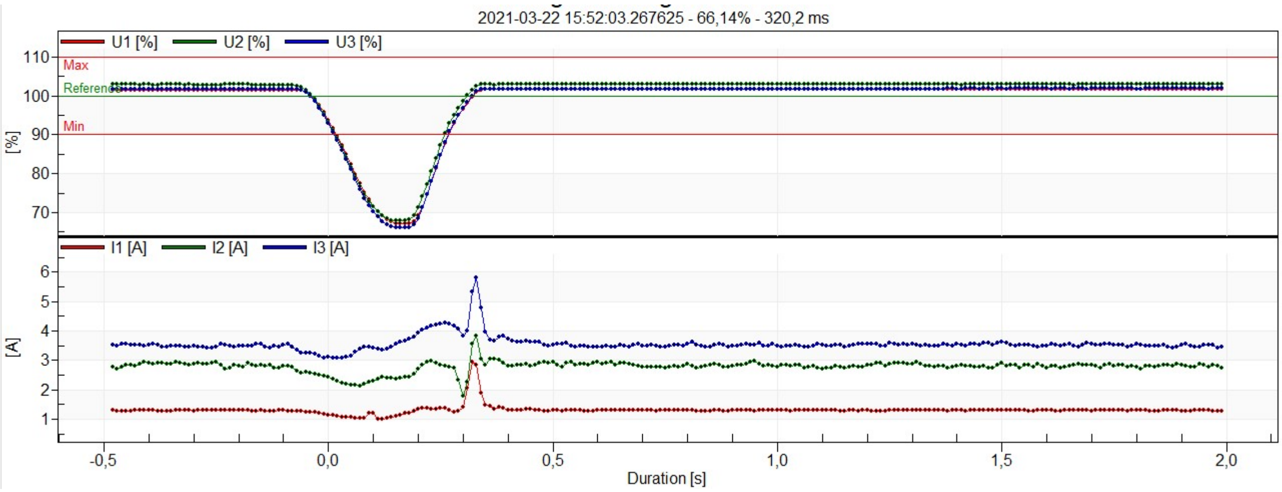


Figure 7.3: 33.86% induced voltage sag. Voltage above, Current below. Red = Phase 1, Green = Phase 2, Blue = Phase 3

After each voltage sag the machine was inspected in order to verify whether the sag had an effect or not on the machine. In each case there were no interruptions or malfunctions registered by the internal computer in the EBM machine. This will be discussed further in the designated chapter 9 discussions.

8

Fourth Measurement Sequence: High Voltage Supply

In this measurement sequence the Unilyzer 900 was connected directly to the HV supply to test its PQ. By checking for harmonics and see how the load is distributed over the different phases. The HV supply measured on was the one installed in M1. As mentioned earlier the machine M1 is not a fully functioning machine but has most vital parts that we are interested in for PQ.

8.1 HV Supply Measurement Preparation

The HV supply is connected with a 3phase connector. By connecting the BC between 3-phase supply in the EBM machine and the HV supply we were able to isolate the PQ for the HV supply and only check the different voltages and currents downstream and upstream from the supply.

8.2 HV Supply Measurements

There were two HV supply measurements completed. The two different measurements will be described here. The total amount of time measured with HV supply was about 1hour over 2 measurements.

8.2.1 First Measurement

The first measurement was setup with 1 minute storage intervals and was measure over 38 minutes. The first measurement registered the starting of the HV supply and some use short use of the electron beam to try out the load created from the HV supply.

8.2.2 Second Measurement

The second measurement was setup with 1 minute storage intervals and was measured over 20 minutes. First part of the measurement was to test and figure out the settings for creating a sweep of current in through the cathode of the electron beam. During the second part of measurement the HV supply went through 3 different programs using the electron beam to heat up a metal plate. During these three different programs different currents for the electron beam were set. By setting different currents we were able to check the different load caused by the HV supply. The different currents used during this test were:

1. Cathode current = 10mA
2. Cathode current = 15mA
3. Cathode current = 20mA

8.3 HV Supply Data Assessment & Result

In this section the data which was measured for the HV supply will be analyzed and assessed. In table 8.1, a summary of the measured data can be seen. The data in the table is an average over the time measured.

Table 8.1: Summary of measured data

Measurement#:	1:	2:
THDFU1:	2.14%	4.6%
THDFU2:	1.96%	4.4%
THDFU3:	1.97%	4.4%
THDFI1:	17.4%	66.6%
THDFI2:	59.6%	96.1%
THDFI3:	61.3%	101.6%
PFtot:	0.14	0.249
#Sags/Swells:	0/0	0/0
#Transients:	0	0
Hours.Minutes:	0.38	0.20

8.3.1 First Measurement

During the start of the HV supply there was an inrush current of 30.83A on I2, 25.63A on I1 and 19.49A on I3. The HV supply had an idle current of about 0.9A split on all three phases. Once a current was applied to the beam we were able to see the different load applied on the phases. During lower currents I1 had a lower current compared to I2 and I3. As can be seen in figure 8.1.

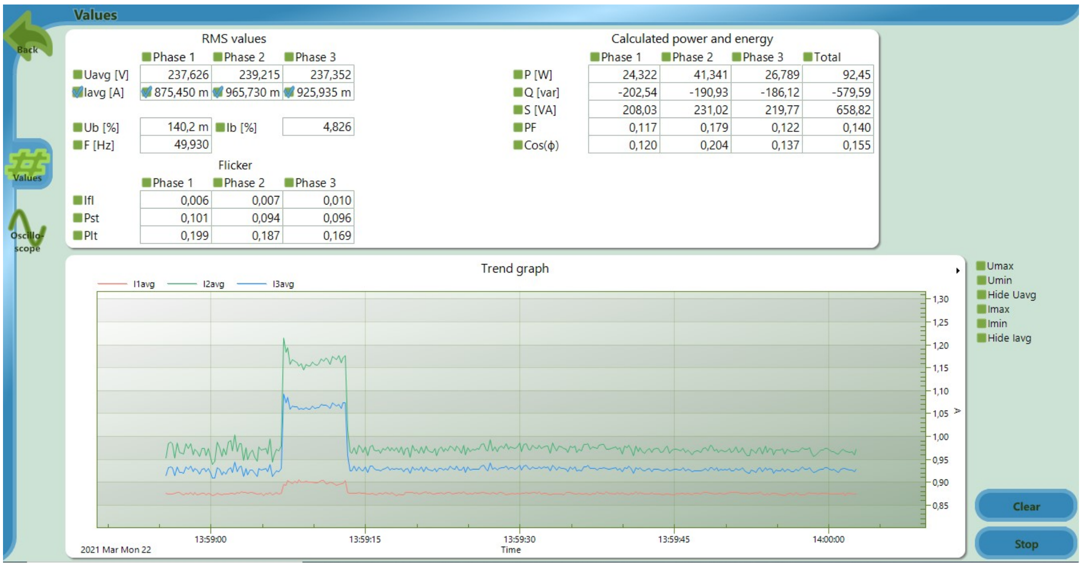


Figure 8.1: Live currents from HV supply in PQ Online.

The PF for the three phases was very low during idle, around 0.1 and 0.2. But as the current increased from the HV supply the PF increased as well. The total average active power consumed during the measurement was 93.46W while the total average reactive power produced was 586.18VAr, this due to the poor PF. The THD for the phases increased as the current increased in the HV supply. THDI3 and THDI2 was severely higher than THDI1 as seen below:

- THDI1 = 68.83 %
- THDI2 = 64.55 %
- THDI3 = 17.58 %

The highest individual harmonics can be seen in the list below:

1. HI2-05(250Hz) = 25.7 %
2. HI3-03(150Hz) = 21.40 %
3. HI3-11(550Hz) = 21.39 %
4. HI2-11(550Hz) = 21.11 %
5. HI3-09(450Hz) = 19.99 %

8.3.2 Second Measurement

Looking at the first part of the measurement, before 14.50 as seen in figure 8.2, we can see that the currents drawn from the different phases are a little unbalanced. With I1 around 2.5A, I2 around 3.46A and I3 around 3.69A. As the current in the cathode increased the gap between the phases decreased, as seen in the following current peaks.

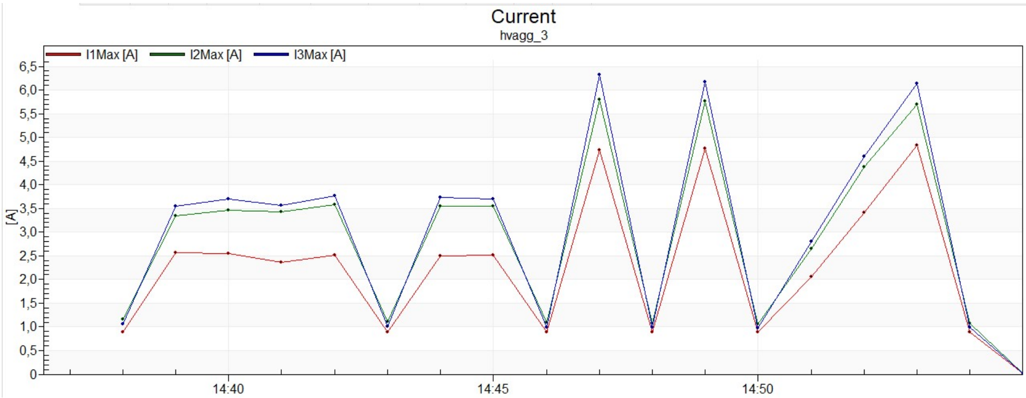


Figure 8.2: Graph of currents from PQ Secure.

After 14.50 the machine was programmed to run three different currents through the cathode heating up a metal plate. As seen in figure 8.2, the current increased every minute from 14.50 to 14.53 where the last peak is. The currents drawn from the different phases are also closer together and more balanced the higher the current in the cathode was. The different set currents which was discussed in chapter 8.2.2, can be seen in figure 8.3, where the first heating program was 10mA, second 15mA and third 20mA.

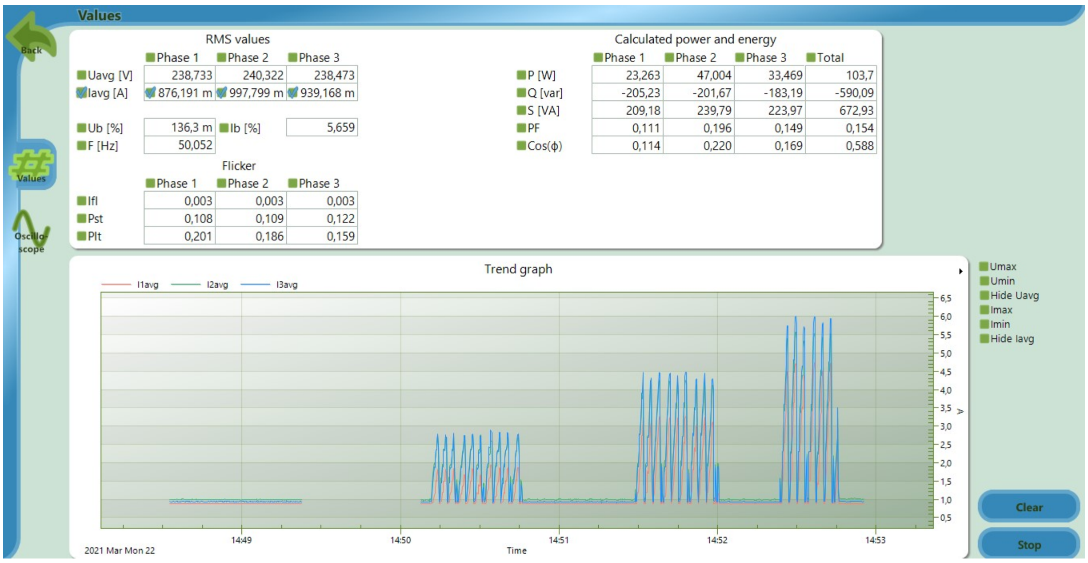


Figure 8.3: Live currents seen in PQ online.

Important to notice in this figure 8.3 is that the current is only on for about 20-30 seconds which will affect the average value of power consumed. The active and reactive power consumed is an average value calculated over 1 minute therefor has to be multiplied by 2 or 3 depending on how long the beam was on. For example if the electron beam was on for 30 seconds then the average value calculated by PQ secure would be 30second/60seconds = 0.5 of the real value, therefore you would have to multiply this by 2 to calculate the real value.

The current drawn from the three different phases can be seen in the table below for different cathode current values:

Table 8.2: Current drawn from phases.

Cathode	Phase 1:	Phase 2:	Phase 3:
10mA	2.05A	2.65A	2.80A
15mA	3.40A	4.38A	4.59A
20mA	4.82A	5.70A	6.13A

The highest individual harmonics are listed below:

1. HI3-05(250Hz) = 45.74 %
2. HI2-05(250Hz) = 45.38 %
3. HI3-07(350Hz) = 41.94 %
4. HI3-11(550Hz) = 37.98 %
5. HI2-11(550Hz) = 36.30 %

It is worth noting that the value of the individual harmonics increased considerably when there is a current in the cathode, compared to when there is no current running through it. E.g. when there is 20 mA in the cathode the HI3-05(250Hz) is at 76 %, compared to 17.9 % when there is no current in the cathode.

During the whole measurement the reactive power remains steady around -0.59kVAr with and without load. The maximum total active power drawn was 0.95kW. Both when heating up the metal plate the active power consumed increased from 0.27kW, 0.38kW and 0.42kW.

As before, the more current induced in the cathode from the HV supply the higher the PF. During the heating of the metal plate the PF changed:

- current = 10 mA → PF = 0.32
- current = 15 mA → PF = 0.35
- current = 20 mA → PF = 0.38

The average THDI for the three phases can be seen in the list below:

- THDI1 = 66.69 %
- THDI2 = 96.07 %
- THDI3 = 101.62 %

Following the individual harmonics the THDI also increased for higher currents in the cathode of the beam, E.g the THDI1 during 20mA of current was 112.42 % while during no current the THDI1 was 16.78 %. All the results will be discussed further in the upcoming chapter.

9

Conclusion and discussion

In this chapter we will discuss and present conclusions for the power quality in the EBM machines. We will also further discuss the outcomes of measured data. There will be additional discussion regarding ethics and sustainable development. Closing the chapter will present discussion regarding future studies and continued work. The problem description described in chapter 1.4 can be seen below. These are the problems that will be answered in this chaper.

- What does the EBM machine send out on the grid?
- How does the EBM machine affect the PQ?
- Unbalanced load?
- What currents and voltages are sent into the machine?
- How is an EBM machine affected by different kinds of disturbances?
- Analysis of the HV-supply

9.1 Power quality in the EBM machine

In this section the conclusions drawn from the gathered data in the earlier chapters will be presented and discussed. First the overall power quality in the EBM machine will be presented and discussed. Then second the tolerance against different disturbances measured and lastly the analysis of the HV supply will be discussed.

9.1.1 Overall Power Quality

According to the EN50160 standard, which is the PQ requirements in Europe and Sweden, the EBM machine has not failed a single PQ report out of the total 13 measurements completed. The overall PQ has been meeting the standard requirements meaning it passed all the disturbances listed below in table 9.1, except the 15th individual harmonic which we will discuss more:

Table 9.1: PQ Summary

Power Frequency	Passed
Unbalance	Passed
Voltage Variations	Passed
Flicker Severity	Passed
THD	Passed
Signalling Analysis	Passed
Individual Harmonics	Failed
Interuptions	Passed

The reason for the failure in the individual harmonics in table 9.1 was the 15th individual voltage harmonic. The 15th individual voltage harmonic was an under laying problem and was observed even without any load. Therefore the individual harmonic was neglected. A notation regarding the 15th individual harmonic is that the limit which is set to be 0.5 % is thought of being set too low according to our power quality experts at Unipower [1].

The International Electrotechnical Commission is in charge of the PQ standard IEC61000-2-4. The commission is currently working on updating the limits for individual harmonic and in the new edition, (ed3) which has not yet been released, the limit for the 15th individual harmonic is suggested to be raised from 0.5 % to 1 %, as can be seen in appendix A. Considering this, the 15th individual harmonic measured in this report was normally around 0.9 % so this is why the 15th harmonic has been neglected in this report.

In Sweden, where the measurements have been performed, there is a very strong electrical grid [8], meaning that the grids are able to support the demands of the industries and customers. Therefore the currents consumed by the EBM machine did not affect the voltage magnitude. The voltages applied to the EBM machine have been stable and there has been no real disturbances from the voltages. For the voltage can be affected by the voltage drop or rise over the source impedance which is caused by the currents of our load. The electrical grid in Sweden can however be considered as strong, thus the influence of the currents on the voltages is relatively small.

During all the measured hours there was no voltage unbalance registered. Looking at the currents consumed by the machine the machine has no severe current unbalance but due to the PF on the different phases the currents might differ more if the PF is improved. The active and reactive power from the load have been analyzed through this report in chapter 6. The apparent power consumed by the machine is affected by the PF and the THD, lower PF and higher THD will consume more apparent power.

The active power is the power the machine needs during operation, this cannot be changed by PF and is the least amount of apparent power that needs to be consumed from the grid. The apparent power however is decided from the PF and the THD from the different phases. The reactive power needs to be produced from the grid by consuming higher current, but this is power that will not produce any real work. Therefore we want to limit the reactive power consumed from the grid to avoid unnecessary strain on the grid. In table 9.2, is the average of all the active power, reactive power and power factor of all measured data.

Table 9.2: Average power consumed from all measurements.

Phase[#]	Power Factor	Active Power [kW]	Reactive Power [kVAr]
Total Average			
1	0.67	0.84	-0.76
2	0.40	0.37	-0.53
3	0.76	0.81	-0.23
Total Average During Printing			
1	0.74	1.22	-0.89
2	0.58	0.71	-0.70
3	0.92	1.4	-0.21

Since the reactive power is a negative value and our choice of current reference direction the measured load has an capacitive characteristic [4]. As seen in table 9.2 the PF increases when the machine is the most active. This is during the printing phase where the machine is performing its largest work and therefore consuming the most active power. Due to the increase of PF in this phase the machine uses less reactive power and therefore also less current. The latter is a good result.

Looking back at figure 6.7, the current's demand on the three phases is about the same, but the active power consumed is different. This is due to the PF on the three phases and the THD. As mentioned before the active power cannot be changed since this is the work that needs to be performed. Looking at Phase 3 the PF is close to one, this means that most of the current consumed is resulted in active power, seen in figure 6.9. Looking at Phase 2, the active power is lower than Phase 3 but they almost consume the same amount of current. This is the result of lower PF and THD. By increasing the PF on phase 2 the current consumed could be reduced.

An important note is that although reactive power is not causing disturbances and therefore not a power quality problem, it is an important factor since the strain on the electrical grid will be increased due to higher currents consumed for the same amount of delivered active power.

Looking at the harmonics, as we mentioned earlier in the report the THD increased during the printing time meaning that the individual current harmonic content increased. The top three largest individual current harmonic content during printing phase, can be seen in the list below:

1. I2-5(250Hz) = 57.31%
2. I2-7(350Hz) = 42.48%
3. I3-5(250Hz) = 37.44%

These three harmonics were the same top individual harmonics on all the measurements. Theoretically the reasons behind these individual harmonics are most probably due to a 3-phase rectifier, which seems reasonable. In a three phase rectifier all odd harmonics that are multiples of 3 are canceled out, so the main first individual harmonics are 5, 7, 11, 13 and so on. Therefore the registered individual harmonics of 5 and 7 are to be expected during the printing phase.[5, p. 106]

Looking at the full measurements, not only during the printing part of the measurements, the top three individual current harmonics differ from each measured data. The 5th and 7th individual current harmonics are usually in the top but the highest has been the 3rd individual harmonic. The individual harmonic changes from measurement to measurement depending on how the machine has been used and what different tasks it has performed. As mentioned before the triple-N harmonics have the property of summing their content in the neutral wire since the three phases end up in phase with each other. Looking at measurement 2 on M2 the largest individual harmonic was the 3rd current harmonic in phase 3 at 33%. This is something that could be investigated further to figure out the cause of this harmonic and how to reduce the harmonic.

Talking about Power Quality the focus is regarding the voltage disturbances, the voltage however is affected by the current consumed. By checking the power harmonics we could decide if the harmonics in the voltage are coming upstream or downstream [1]. Looking again at figure 6.8, there is a little peak in the beginning of the printing but during the rest of the print the power harmonics are very low, around 0-2W. The power harmonics are so low due to the fact that the voltage is not that disturbed and the voltage harmonics are very low.
Power[n] = Voltage[n] * Current[n], where n is the order harmonic, then since the voltage harmonic has such a small value the power harmonic is very small. If the voltage harmonics would have been larger then the result of the power harmonics would have shown more if the disturbance was coming from upstream or downstream.

The overall Power Quality in the EBM machine remains good and there was no real disturbances during the total measured time. The harmonic content could be studied further in future studies to determine how to lower certain aspects of it or if its even possible.

To determine the power quality through a series of measurements is very complex question. To analyze an electrical load on the grid multiple factors need to be considered, such as the ones we have brought up in this report. The PQ is determined by the strength of the electrical grid and how much the different currents affect the local grid. For example the grid in the United States might not be the same design as the Swedish grid. The important key notes to take away is that the electrical load should be able to sustain certain disturbances such as sags and transients, which according to the tests created in this report the EBM machine performed well. The other key note is that the electrical load should not affect other loads, such as EMI, EMC and harmonics. The EMI and EMC has not been researched in this report but the focus has been on the harmonics. The EBM machine seems to have some rise of harmonics during the printing phase, probably due to switching technology and non-linear loads. The harmonics have not affected the voltages in the measurements completed in this report.

9.1.2 Disturbance tolerance

During the measurements there was no natural disturbances registered, apart from the presence of the 15th harmonic which was ignored. Hence a series of artificially induced voltage dips was performed in order to see how an EBM machine is affected by this kind of disturbance.

The expected consequence of these voltage dips was that should be some sort of effect on the machine, more specifically that one or more internal components should fail to function or even turn off. In sensitive equipment, such as computers and other microprocessor systems like PLCs, it is common practice to include a protective system that turns off the system in order to protect it from the following current spikes created by the voltage dips. These current spikes may otherwise fry the sensitive electronic internals of the system. The indirect result of the voltage dips is then a long supply interruption, although it is technically not the the dip, but the protective system, that directly causes the interruption [9, p. 90].

As seen in picture 7.3 the voltage sag is followed by a current transient shortly thereafter. It is probable that if these transients had been higher, or if the increase in current had lasted for a longer period of time, either one or the other of the expected consequences had occurred. I.e. the protective system had been activated and the sensitive components had been shut down, or some of the internal electronics had been burned and damaged.

The only effect that was noticed was an audible lowering of the working frequency of the vacuum pumps. This could be explained by the lower voltages during the sag, which lead to a lower rotational frequency in the pump motor.

In conclusion, the EBM machines seem to be fairly tolerant towards voltage dips from what we were able to observe. However, since the tests were performed on the test prototype machine and no actual printing was taking place, not much can be said about how a voltage dip would affect the printing process or whether or not it would have an effect on the build quality of the printed object. This could be a subject for further studies on EBM machines.

9.1.3 HV Supply Power Quality

By connecting the Unilyzer 900 to the 3 phase HV supply we were able to analyze the character of the HV supply. As mentioned in the chapter before, the characteristics of a 3 phase rectifier has all odd multipes of 3 in the individual current harmonics removed. Looking at the harmonics in chapter 8.3.2, we notice that the key highest harmonics are 5, 7 and 11, which aligns with theory of a three phase rectifier. An important note during the measurements of the HV supply is that the electron beam was only on for about 5-20 seconds and the Unilyzer gathers data and stored it every 1 minute. This will result in an average current, harmonic and other data to be lowered by a factor of how long the electron beam was on, e.g. 20 seconds gives 60/20 = a factor 3.

We noticed that the PF was very low during low currents but as the current increased so did the PF. We were not able to increase the current too high due to the fact that the machine we measured on was only a test rig and the electron beam would melt the metal plate if the current was on too long. A future study could be to attach the Unilyzer to an operating machine and see how the HV performs during the printing time.

As seen in figure 8.3, the current in phase 1 is lagging behind the other currents during lower power consumption's, but the higher the power consumption, phase 1 gets closer to the other phases in current consumed. By noticing this we drew the conclusion that the HV supply performs better at higher loads, but it is only an assumption since we were not able to go to higher currents without a proper printout program.

The individual current harmonics that was listed in chapter 8.3, was 5, 7, 11 and 13. These are typical harmonics for a 3 phase rectifier which is what the HV supply is. This explains the individual harmonics during the printing operation of the machine.

9.2 Ethics and sustainability

Making sure that appliances and machines operate with high power quality is relevant for the environment and sustainability in many ways. First and foremost for the sake of energy efficiency. Since energy production is one of the most urgent issues in our society today, ensuring that the energy actually produced is made use of, and is not wasted, is of the utmost importance. Hence, making sure that an appliance has the highest PF, and produces as little low order harmonics, as possible can save immense amounts of energy. Simply looking at only one appliance the difference might seem insignificant, but from a societal standpoint, all appliances in our society combined will make an enormous difference. If the source of the energy is renewable or fossil is of course important as well. But whether the energy is renewable or not, there is no escaping the fact that even renewable energy costs resources and may have a negative effect on the environment. An example of this could be the extraction of rare minerals for the production batteries or disturbing habitats for wild life when building wind power plants at sea.

Furthermore, machines and appliances being exposed to low power quality may lead to them being damaged and breaking down, which is a waste. It would be better from an environmental perspective if their life could be maximized and last longer, that way we would not have to throw our appliance away and buy a new one as soon.

In addition, 3D-printing in general has great potential to contribute to a sustainable world since it allows us to easily create complex spare parts for broken products. And, additive EBM technology in particular since is keeps material loss at a minimum by permitting the re-use of unused printing material, since the unused printing powder is collected, filtered and re-used for the next print.

Another aspect of the importance of machines having good power quality is an ethical one. For example, when a machine or an appliance produces a lot of harmonics, the power grid is "polluted" with these. If the grid is not strong enough these harmonics will have a negative effect on the voltages used by other machines on the same power grid, which will lead to them too having lower efficiency as well as wear and tear on these machines.

9.3 Future studies

Future studies for which this report could serve as a foundation could be, for instance:

- How the currents could be lowered in order for the EBM machines to be under 16A instead of 32A.
- Improve PF and harmonics further.
- Balancing the loads in the EBM machines.
- Tolerance to voltage disturbances during printing.

The benefits of the first example would be economical, namely lighter cables and fuses could be used instead and thus, would be cheaper. Two standards that can be followed for the limits regarding maximum 16A per phase are:

- SS-EN 61000-3-3(Limit values - Limitation of voltage fluctuations and flicker in low voltage distribution systems caused by devices with rated current not exceeding 16 A per phase without special connection conditions)
- SS-EN IEC 61000-3-2(Limit values - Limits for harmonics caused by devices with a supply current not exceeding 16 A per phase)

The second example could improve the efficiency of the machines further, and energy could be saved while potentially emitting less harmonics to the power grid. Looking into power correction factors, if they will work and how to implement them.

The third example, if the loads were more balanced and the effect drawn from the three phases were equal this too would result in a more efficient machine. As mentioned in the report too, the active power can not be changed but if the PF is corrected then the currents will look different and might need to be balanced.

The last example could be to further test the tolerance against the voltage disturbances. As mentioned earlier the induced sags was performed on a machine which is more of a laboratory machine. By actually testing sags on a machine while printing could show results in quality of print and how the machine performs while under full load.

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A

Appendix A

The compatibility levels for voltage distortion in differential mode above the 40th harmonic up to 9 kHz and from 9 kHz to 150 kHz are given in Table 4 and Table 5 respectively.

Table 1 – Compatibility levels for voltage tolerance, voltage unbalance and power-frequency variations

Disturbance		Class 1	Class 2a, Class 2b	Class 3
Voltage tolerance, relative to nominal voltage U_N:	$\Delta U/U_N$	±8 %	±10 % [a]	+10 % to –15 % [b]
Voltage unbalance	U_{neg}/U_{pos}	2 %	2 %	3 %
Power-frequency deviations [c]	Δf	±1 Hz	±1 Hz	±1 Hz

[a] Value not defined in IEC 61000-2-2.
[b] See 5.2
[c] ±2 Hz in case of isolated networks.

Table 2 – Compatibility levels for harmonics – Harmonic voltage components

Order *h*	Class 1 U_h %	Class 2a, Class 2b U_h %	Class 3 U_h %
2	2	2	3
3	3	5	6
4	1	1	3
5	3	6	8
6	1	1	3
7	3	5	7
8	1	1	3
9	1,5	1,5	3
10	1	1	3
11	3	3,5	5
12	1	1	3
13	3	3	4,5
14	1	1	4,4
15	1	1	4,2
16	1,4	1,4	4,1
17	2	2	4
18	1,4	1,4	3,75
19	1,8	1,8	3,5
20	1,4	1,4	3,3
21	1,4	1,4	3,1
22	1,4	1,4	3

B
Appendix B

UNIPOWER

Certificate of Calibration

Transducers for instrument: Unilyzer 900
Serial number: 27100532

Transducer	Serial No	Reference	Reading	Error
Voltage transducer 1000V	27110281	230,00V RMS	230,00	0,001
Voltage transducer 1000V	27110281	230,00V RMS	230,00	0,000
Voltage transducer 1000V	27110281	230,00V RMS	230,01	0,002
Current transducer 50A	27120805	20,000A RMS	20,000	0,001
Current transducer 50A	27120805	20,000A RMS	20,000	0,001
Current transducer 50A	27120805	20,000A RMS	20,000	-0,001
Current transducer 1000A	27120360	1000,0A RMS	999,99	-0,001
Current transducer 1000A	27120360	1000,0A RMS	1000,00	0,000
Current transducer 1000A	27120360	1000,0A RMS	999,99	-0,001

Calibrated reference instrument:
FLUKE 6100B Electrical power standard, Serial No: 386172266

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Date of issue: 2021-02-01

Calibration performed by: Pete And
Peter O Andersson

UNIPOWER

Certificate of Calibration

Calibrated Instrument: Unilyzer 900
Serial number: 27100532

Channel	Reference	Reading	Error
1	0,50000V RMS	0,50003	0,006
2	0,50000V RMS	0,50000	-0,001
3	0,50000V RMS	0,49995	-0,009
4	0,50000V RMS	0,49997	-0,005
5	0,50000V RMS	0,49999	-0,002
6	0,50000V RMS	0,50003	0,005
7	0,50000V RMS	0,50001	0,002
8	0,50000V RMS	0,50000	0,001

Calibrated reference instrument:
FLUKE 6100B Electrical power standard, Serial No: 386172266

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