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ACTIVE POWER MEASUREMENT IN ENERGY METERING

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ABSTRACT

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The monitoring and measuring of harmonics in electrical networks are becoming important with the increase of distributed generation, non-linear devices like converters and developing electricity markets. Measuring voltage and current harmonics will help us mitigate the adverse effects they can cause in the electrical networks. In this thesis measurements of a pilot building are utilized to analyse the effects of active power distortion by monitoring the active power and harmonic behaviour of the pilot building. Active power distortion can cause error in billing and there is a need to quantify harmonic active power.

Over the years various power definitions have been developed to include the effect of harmonic distortion in the metering. There are many studies available that include the effect of harmonic reactive power, but very limited data is available that describes the effect of harmonic active power on electrical energy. This thesis discusses smart meters and their advantages, some of the functionalities of modern smart meters and a standard is discussed which is relevant for measuring fundamental frequency and harmonic frequencies power.

The analysis of this thesis is focuses on the difference between total and fundamental frequency active powers and the sources of the harmonics that cause this difference of power in a pilot building. The difference is analysed in 1-second and 1-minute time intervals for different loads of the building to see the behaviour of the loads. The effect of this difference is utilized to find the energy difference it causes on each phase on the main distribution boards. The energy difference at two main distribution board shows that difference can be negative or positive that means some of the loads produce harmonics and some loads absorb harmonics. The difference of magnitude was less than 1% at both the distribution board of the pilot building. It was observed that non-linear loads generate more difference in energy. This difference of result can cause an effect on billing of active power if the effect of harmonic active power is not considered.

Keywords: active power, harmonic active power, measurements, power definitions, power quality,

The originality of this thesis has been checked using the Turnitin Originality Check service.

PREFACE

I would like to thank D.Sc. Pertti Pakonen for helping and guiding me in choosing this thesis topic and helping me throughout my work on this thesis by providing me his expert opinions and co-operation. I also want to thank Antti Hildén for providing me the necessary data for the implementation of this thesis and guiding me during this data analysis.

In the end I want to thank my parents and Tampere University for supporting me throughout my master studies.

Tampere, 19 October 2020

Syed Ali Hassan Naqvi

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating current
AMI	Advanced metering interface
AMR	Automated meter reading
API	Application programming interface
BC	Blockchain
BREEAM	Building Research Establishment's Environmental Assessment Method
CHP	Combined heat and power
CIGRE	Conseil International des Grands Réseaux Électriques
CO_2	Carbon dioxide
DC	Direct current
DER	Distributed energy resources
DFT	Discrete Fourier transform
DR	Demand response
DSO	Distribution system operator
EN	European standard
EU	European union
FACTS	Flexible alternating current transmission system
FFT	Fast Fourier transform
HIP	Harmonic Impact Project
ICT	Information and communications technology
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IT	Information technology
IoT	Internet of Things
JWG	Joint working group
LED	Light emitting diode
LV	Low voltage
LV3	Laatuvahti 3 meter
MV	Medium voltage
PCC	Point of common coupling
PM3255	Power meter PM3255
PM820	Power meter PM820MG
ProCem	Prosumer Centric Energy Ecosystem
PV	Photovoltaic
SFS	Suomen Standardisoimisliitto
V2G	Vehicle-to-grid technology
a_n	Fourier series coefficient
a_0	Mean value of periodic signal in Fourier series
A_n	Magnitude of harmonic frequency
b_n	Fourier series coefficient
D_I	Distortion power caused by distortion current
D_V	Distortion power caused by distortion voltage
D_H	Harmonic distortion power
DPF	Displacement power factor
I	Peak current
i	Instantaneous current
I_h	Harmonic current
I_n	Magnitude of harmonic frequency current
I_1	Magnitude of fundamental frequency current
n	Number of harmonic orders
N	Maximum number of harmonic components
P	Total active power
P_1	Fundamental frequency active power
P_H	Harmonic active power

p_q	Instantaneous active power
p_a	Instantaneous reactive power
PF	Power factor
Q	Total reactive power
Q_1	Fundamental frequency reactive power
S	Total apparent power
S_1	Fundamental frequency apparent power
S_H	Harmonic apparent power
t	Time instant in periodic signal of Fourier series
T	Length of time period in Fourier series
TDI	Total distortion of current
TDU	Total distortion of voltage
TDD	Total demand distortion
THD	Total harmonic distortion
TEHD	Total even harmonic distortion
TOHD	Total odd harmonic distortion
V	Peak voltage
V_h	Harmonic voltage
v	Instantaneous voltage
$x(t)$	Instant value of periodic signal in Fourier series
θ_1	Phase difference between fundamental frequency voltage and current
θ_h	Phase difference between harmonic voltage and current
Φ_n	Phase of harmonic frequency

1. INTRODUCTION

In the last few years with the increase of distributed energy systems importance of power quality has increased. Distributed energy systems like solar and wind are one of the causes of harmonic distortions in the modern power system affecting the power quality as the power converters that are used with these systems are non-linear devices. As with the use of switched-mode converters harmonics in the power system cause distortions in both active power and reactive power. This causes problems both for the customers and the utility grids and needs to be addressed like incorrect billing if the effect of distortion is not included in the energy billing. The need to study the power flow measurements in distribution network both in frequency and time domain has increased [47]. There is a need to quantify fundamental frequency power and total power consumed by the load.

In electrical systems power is divided into apparent power which consists of active and reactive. To calculate these powers there are different standards that are available, and the use of these standards depends on the application for which the smart meters are used [21]. Over the years there was great importance was given to quantify harmonic reactive power, but little information is available for quantifying of harmonic active power. For an energy meter the is being used for tariff and load control the standard of this meter will be different from the meter which is used for local data exchange [20]. One of the main driving forces in the increase of distributed energy resources (DER) is to reduce the carbon footprint and CO_2 emissions. But at the same time modern loads and distributed energy resources like power converters, PV systems, wind farms affect the power quality [47].

In this thesis practical measurements are used to analyze the active power in respect with viewpoint of power quality, from new university building of **Tampere University (Hervanta campus)** named Kampusareena. This building is also a power platform for various studies and a some of the companies have their research center and offices there. Kampusareena also has a modern power generation system like PV plant and modern loads like ventilation system. On the parking area there is an electric car charging station. To collect the measurements building has a monitoring system that continuously collects data from several sources. Data is then stored in database and can be delivered for required applications. The data is sourced from electrical energy systems such as weather station, solar inverters, and forecasting system. Time resolution of 1 second was used to analyze concurrent measurements from diverse loads of the building. The goal of this thesis is to utilize these measurements for data analysis to examine the difference between fundamental frequency active power and total active power and how this difference is creating the energy difference at each phase over a day at the main distribution boards of the building. At the same time, the data can also be utilized to find the sources of current distortion and the effect that distributed energy generation creates in the building's electrical network.

The thesis begins by looking into smart meter standards and applications of smart energy meters in modern distribution networks. Chapter 3 explains briefly about electrical power and harmonics, measurement practices for electrical power and harmonics. Chapter 4 discusses the pilot building, electrical network, and data system. After that, the analysis of measured data of building loads is performed. The difference in total active power and fundamental frequency active power also analyzed in two different time intervals. The measurement data was also used to find the sources of distortion. In last the energy difference caused by the power difference at each phase of the two main distribution board is calculated. Finally, in Chapter 5 conclusion is provided based on what was done and analyzed during this thesis.

2. SMART ENERGY METERS

Modern Energy meters are different from analog meters that used to have electromechanical dials whereas smart meters include a microcontroller and calculation hardware for sophisticated measurement, a software which is used for calibration and communication capabilities [22, 38]. These are termed as smart to indicate storage and data processing capabilities as required by the needs of utilities or customers along with providing automated meter readings (AMR). The smart meter's functionalities depend in addition to smart meter, project for which it is designed, stake holder's interests, and economic benefits. They have changed the operation of power grids by performing not only traditional energy metering functions like measuring electricity parameters (voltage, current, kilowatt hour energy) but also working as sensors for the entire distribution system, providing services like emergency notifications to distribution companies to operate grid safely and reliably, and daily hour reads on demand [32]. In advanced metering infrastructure (AMI) smart meters perform measurements at certain intervals and at the same time record power usage [38, 40]. Using communication channels this data can be send to central command system. This information allows utilities to perform load forecasting, enhancing energy knowledge and performing the demand response.

2.1 Smart meter standards

Smart meters are designed with certain standards to have an interoperability with grid infrastructure. The use of different standards that are available depend on the application and requirements.

The definitions used until 10 years ago of active, reactive, and apparent power were developed on the knowledge available in 1940s [21]. These definitions were very effective for the industry and power system if the system is sinusoidal and balanced but during the last 5 decades a lot of changes has occurred in generation, transmission, and distribution side due to the following facts [8].

1. With the integration of non-linear loads such as AC/DC converters disturbances like harmonics currents and voltages has increased that are creating problems and losses for utilities.
2. Due to the non-sinusoidal flow of electricity caused by harmonics in voltages and currents, new power definitions have been discussed in the last few decades [21].

3. Advancements in technology like microcontrollers and processors enable manufacturers to construct accurate and versatile measuring equipments with multiple functionalities.
4. To have a fair distribution of financial burden distortions must be quantified accurately for good electric quality

Definitions presented in IEEE Std 1459-2010 give guidelines with respect to measured quantities or monitoring related to revenue, economic decisions and to identify the components causing major harmonic problems.

2.2 IEEE Std 1459-2010

This standard provides power definitions for active, reactive and apparent power in the cases when voltage is not sinusoidal, load is unbalanced, voltages are not symmetrical, and there is a zero sequence current in neutral path that causes energy dissipation resulting in losses in the electrical network [21]. Mathematical expressions defined by this standard for measurements are given below.

2.2.1 Power equations in sinusoidal condition

For active power

Equations for sinusoidal voltage and currents are

$$v = \sqrt{2}V \sin wt \qquad (2.1)$$

$$i = \sqrt{2}I \sin wt \qquad (2.2)$$

v	instantaneous voltage
i	instantaneous current
V	peak voltage
I	peak current
w	angular frequency
t	time

Active power is calculated by taking the average of instantaneous power measured over an interval τ to τ+kT

Instantaneous power is given by

$$p = iv \qquad (2.3)$$

$$p = p_a + p_q \qquad (2.4)$$

where is p_a instantaneous active power and p_q is instantaneous reactive power

$T = \frac{1}{f}$	is the cycle time in seconds
k	positive integer number

τ starting time (when measurement is started)

$$P = \frac{1}{kT}\int_{\tau}^{\tau+kT} pdt \quad (2.5)$$

$$P = \frac{V}{I}\cos\theta \quad (2.6)$$

Where P is the average active power over an interval

For reactive power

As the magnitude of average reactive power over an interval is 0, Q is calculated by calculating the amplitude of oscillations of instantaneous reactive power

$$Q = VI\sin\theta \quad (2.7)$$

$$Q = \frac{\omega}{kT}\int_{\tau}^{\tau+kT} i[\int vdt]dt \quad (2.8)$$

It is to be remembered that if Q < 0 we have ha capacitive load and if it's Q > 0 then it will be inductive.

For apparent power

In an ideal condition apparent power is the maximum power that can be transmitted through the line if rms voltage V is constant and power loss of supplying line is constant.

$$S = VI \quad (2.9)$$

Or

$$S = \sqrt{P^2 + Q^2} \quad (2.10)$$

Where power factor is

$$PF = \frac{P}{S} \quad (2.11)$$

And complex power is given by

$$S = P + jQ = \boldsymbol{VI}^* \quad (2.12)$$

2.2.2 Power in non-sinusoidal condition

As the major focus of this thesis is active power measurement so we will only investigate the non-sinusoidal active power equations.

$$P = P_1 + P_{\mathrm{H}} \quad (2.13)$$

Where P_1 and P_{H} are fundamental frequency active power and harmonic active power respectively and they are given by

$$P_1 = V_1 I_1 \cos\theta \quad (2.14)$$

$$P_H = V_0 I_0 + \sum_{h\neq 1} V_h I_{\mathrm{h}} \cos\theta_{\mathrm{h}} \quad (2.15)$$

P_1 fundamental frequency active power

P_{H} harmonic active power

V_h	harmonic voltage
I_h	harmonic current
θ_h	phase difference between harmonic voltage and current

It is very important to note that harmonic active power is not useful power, and it should be separated from fundamental frequency active power. Also, h is also not an integer in case of inter-harmonics which are included in P_H.

2.3 Applications of energy meters

Smart meters have numerous applications both at the utility side and on the customer side. Following are some applications in which smart meters are utilized [16, 29].

2.3.1 Billing

Smart Meter provides accurate data in real time thus eliminating the need for estimation for correct settlement and billing. This reduces the cost of additional settlements for distribution system operators (DSOs). For metering point of view, measured data can be requested any time helping the regulators read data remotely that reduces the cost for DSOs. This also enhances the possibility of billing customers based on actual consumption data. In this thesis the we will look into the effect of total and fundamental frequency active power on energy consumption of the building and the impact it will have on billing if the effect of harmonic power is not quantified for billing purposes.

2.3.2 State estimation

In this technique smart meters and their measurements in a network are combined with a physical network model and its load [1, 2]. This helps in calculation of unknown variables and to identify measurements that are unreliable and other model input data that may not be true. A data of small-time intervals (2 or 5 minutes) may be used for state estimation. This method helps in monitoring the losses and loading more accurately and preventing overloading of components and improving the power quality.

2.3.3 Power quality monitoring

Power Quality involves the monitoring of voltage and current quality that is the voltage supplied by the network and currents of the loads [46]. Voltage quality monitoring means that the voltage does not deviate from a specified limits from the standard value and it should be sinusoidal with constant amplitude and frequency and for 3-phase systems it must be symmetrical with a certain phase difference. EN 50160 is one of the standard used in Europe to specify voltage quality whereas IEEE 1564 provides guidance for voltage sag indices and IEEE 1453 discusses voltage flickering in public alternating current (AC) networks [25, 35]. Monitoring of voltage quality parameters like voltage sag and power interruptions will help distribution companies to plan and invest in areas where improvement is required. In this thesis we will look that measurement systems installed in the pilot building measures the total current and voltage distortion which helps us to monitor power quality and to find the sources of distortion in building's network.

2.3.4 Load forecasting and modeling

Smart meters data of load consumption of a house (heating, electricity, air conditioning) or a large-scale industrial sector can be used for load analysis and load forecasting. Load data from a single-family house or an industrial sector combining it with the other environmental factors like outdoor weather can be modelled. This will help us give the load profile, peak demands, total energy usage and time variations [26]. This information is very helpful for retail suppliers, DSOs, and customers. Customers can be asked to get involved in energy saving activity during the peak demand hours in order the reduce the burden of load on distribution network. The measurement system installed in the building gives us the idea of how the loads and PV generation behaves on different days. For example, on sunny day PV generation was high whereas on cloudy day it was small. Similarly, cooling units were running for longer period on hot sunny day as compared to cloudy day. This gives us the idea of how we can forecast load in different environmental conditions.

2.3.5 Demand response

Demand response gives consumer the capability to reduce or shift their electricity consumption during peak hours in response to some financial incentives or time of day tariffs. It covers both direct load control and price control. Direct load control means that certain loads in the network can be turned on and off when depending upon the network situation by sending a signal. Price control means that there are variable time prices for the customers. Price control tariffs can be time of use tariffs, real time tariffs and critical peak tariffs [26].

Distributed generation is increasing with time, storing electricity is expensive and power losses in storing are more it is necessary that consumption and generation are in balance. To achieve the balance of consumption and generation real time tariffs are utilized in modern distribution systems which requires metering data in real time. Smart meters provide real time data which can be used to adjust the tariffs so that there remains a balance between consumption and generation. Peak power generation is an expensive process, and it is very expensive and difficult to use nuclear and combined heat and power (CHP) plants for peak power generations.

2.3.6 Energy saving

One main advantage of using smart meters is their contribution in energy saving which is very necessary environmentally. Customers get information about their energy consumption, allowing them to control the way they use electricity [3]. Smart meters will also tell the customers if there is an abnormality in their network such as if there is a malfunctioning equipment and consuming more energy or if there is a heating problem, which will allow customers to rectify this problem [31].

On the network side data from smart meters will allow DSOs or utilities to install products and equipment’s that are more environment friendly and energy saving products. For example, if the transformer on distribution side is old and causing more power losses than it will give information to DSO to replace it with new one. Energy saving products can be based on smart meter’s core functions that are maybe related to price tariffs (time of use, spot price etc.) or maybe related to remote load monitoring function that can allow DSOs to remotely control customers load.

3. POWER IN LOW VOLTAGE NETWORKS

In chapter 3 we will investigate power definitions and power quality issues like harmonic distortion in currents and voltages, their causes and how they can be measured. The world is moving towards green energy and environment friendly solutions so the concept of smart grids is becoming more important and in fact a reality now as the penetration of distributed energy sources like photo voltaic (PV) has increased a lot [3]. This has created problems with respect to power quality. Poor power quality maybe due to distortion voltages in the network and distortion in the load current [5]. Power electronics devices used in DER like wind and PV are one of the sources of poor power quality [28]. Poor power quality and inaccurate measurements cause economic losses for network utilities and customers as poor power quality can cause frequent interruptions and blackouts.

The focus of this chapter is to discuss the effect of voltage and current distortion on active power in a low voltage network. Power quality is related to distortion in voltage and current and their measurements. The chapter will also discuss the importance of measuring power quality related measurements like harmonic voltage and current [43].

3.1 Power types

Distribution network uses alternating current (AC) electrical power which is divided into three types, active, reactive, and apparent powers. Active power is the real power used by the loads that the power that is dissipated by the resistance of in a network and it depends on the load resistance. Reactive power is because of inductive and capacitive components in the network and load and it represents the exchange of energy between the source and load's reactive part. Apparent power is the magnitude of complex component in the network and can be found by the taking the product of rms phasor voltage and complex conjugate of rms phasor current. While designing and operating a network apparent power must be taken into account, since current of reactive power does not produce any real power but it must be supplied by the source and the network must be able to carry the whole current not just the current which produces real power. This thesis considers power in low voltage (LV) network in frequency domain and will consider the power definitions that are used for measuring LV network power in frequency domain [21].

Reactive power is an important component with respect to power quality. If there is an excess of reactive power in the network, the reactive current will be more in the network resulting in poor power factor and high losses. To reduce these losses power factor correction methods are used by the utilities to minimize these losses.

3.2 Power quality

Poor power quality is causing problems for utilities, distribution system operator (DSO's), and customers and it is very important to address this issue [15]. Also, the measurement of power should be accurate in non-sinusoidal conditions as with the development of active power tariffs.

Issues related to power quality are voltage imbalance, poor power factor, harmonic distortions, and load current imbalance. Many countries and academics are discussing the issue of power quality and the causes of poor power quality. Introduction of power electronics devices in PVs, electric vehicle charging, wind farms, micro grids and non-linear loads are the examples of sources of voltage and current distortion [7, 39]. Power electronics devices create harmonics in the system, and the modern distribution networks will have functionalities considering the effects of harmonics in the system.

Due to the reasons discussed above several electric power definitions have been discussed in the last few decades and there is still not a single definition which is fit for all the measurement purposes. One of the standards which is used for measuring harmonic active and reactive power is IEEE Std 1459 and is discussed above in chapter 2 [21]. Power quality is a diverse and complex topic, and the focus of this thesis is to study current and voltage distortion that are responsible for the production of harmonic active power at harmonic frequencies. In the section below we will review distortion and total harmonic distortion THD and their usage in the analysis of this thesis [33, 45].

3.2.1 Harmonic distortion

In power system harmonic distortion means the voltage and current deviation from sinusoidal waveform at fundamental frequency. The deviation can take place at integer multiple of fundamental frequency called harmonic distortion or at the non-integer multiple of fundamental frequency called inter-harmonic distortion. All over the world, distortion is increasing as the use of non-linear loads and power electronic devices is increasing. To separate harmonic and inter-harmonic distortions from fundamental frequency measurements smart meters employ power definitions one of which IEEE 1459 is discussed in the chapter 2 [21]. The bandwidth of meters that are used during the implementation of this thesis to measure harmonics and inter-harmonics is up to 2 kHz. The harmonics above this frequency are called super-harmonics and they range from 2 kHz to 150 kHz.

Modern micro processing technology has enabled engineers to develop smart energy meters that allow us to quantify the distortions. To divide a periodical waveform like sinusoid to fundamental frequency components, multiple of fundamental frequency component and DC components, Fourier series is utilized. This helps us to separate harmonic components from fundamental frequency components [4].

$$f(x) = a_0 + \sum_{n=1}^{\infty} \left(a_n \cos\frac{2n\pi t}{T} + b_n \sin\frac{2n\pi t}{T}\right) \quad (3.1)$$

a_0 Mean value of periodic signal in Fourier series

n order of harmonics & n=1 fundamental frequency

T Time Period

t Instant time

a_n & b_n magnitude of coefficients at instant time

To calculate total magnitude and phase angle at that instant time 't' following equations are used

$$A_n = \sqrt{a_n^2 + b_n^2} \quad (3.2)$$

$$\emptyset_n = \tan^{-1}\frac{b_n}{a_n} \quad (3.3)$$

Modern smart meters use Fourier Transforms like DFT (Discreet Fourier Transform) or FFT (Fast Fourier Transform) as it converts the time domain of voltage and current values into frequency domain [4]. This simplifies and reduces the time required for measurement and is more efficient.

Generally, there are two types of harmonics even and odd. In most cases, odd harmonics are measured and filter out in AC power systems [33]. On low voltage side harmonics can cause significant losses as compared to transmission side so their effects must be quantified to improve the power quality. Even harmonics can cause unequal positive and negative peak voltages and a dc component which is not desired [33]. The phenomenon of unequal peak values is called waveform asymmetry. Some standards suggest (IEEE Standard 519-1992, IEC Standard 61000-2-2) strict limits to consider the adverse effect of waveform asymmetry [12, 13, 22].

Harmonics in power system also includes inter-harmonics, which are the harmonics between two adjacent integer values. For example, harmonics between 5^{th} harmonics and 6^{th} harmonics are called inter-harmonics. IEC 61000-4-7 standard defines these harmonics and subgroups of harmonics [12, 13, 14].

Non-linear devices that are responsible for distortion in current includes, saturating transformers, arcing devices and power electronics converters which include switched-mode converters and rectifying devices. There are different techniques available for finding voltage distortion source as it is hard to find voltage distortion source, one of which is using machine learning [18]. Voltage distortion maybe due to distortion current which is caused by non-linear loads. It is to be noted that voltage distortion caused by non-linear loads is more significant than caused by loads such as synchronous machines. Distortion in voltage by loads also creates harmonics on customer side and this makes it very difficult for the utilities to find the exact source of voltage distortions. It is to be noted that current distortion can be analyzed at PCC (Point of Common Coupling) in terms of summation of load currents. Each harmonic component has a magnitude value and phase value, and summation depends on phase values of harmonics currents. In case of two harmonic sources, cancellation will occur if phases are 180 degree apart and superposition will occur if they have equal phase angles. If we install a huge number of lamps in the same feeder harmonic currents of lamps cancels each other greatly as this thing is reported by a publication on power quality monitoring publication [42].

In power quality studies the study of harmonic distortion includes a certain bandwidth that calculates magnitudes of harmonic distortion within that bandwidth, which means measurement of harmonic distortion is limited. Normally it is restricted to 2.5 kHz because the standards that we are using have little information about harmonics above these frequencies, and this thesis only considers total value of distortions which will be discussed in this chapter later [22, 44].

3.2.2 Total harmonic distortion

Total harmonic distortion (THD) considers ratio of sums of powers all harmonic distortion present in the current or voltage to the power of fundamental frequency of voltage or current [45]. It is a relative measure to fundamental frequency that how much distortion in the current or voltage signal caused by the harmonics present in the system. In this section we will look in to how THD is calculated. Now a days, many standards suggest including even harmonics when calculating THD to minimize the adverse effects of harmonic distortion in the network. In IEEE Std 519 standard individual even, harmonics are limited as one quarter of the limit of these individual odd harmonics [22, 33]. To minimize effect of waveform asymmetry and dc component Total Even Harmonic Distortion (TEHD) should be included along with Total Odd Harmonic Distortion (TOHD) in THD [33]. The bandwidth for THD measurements at 50 Hz is either 0–2 kHz or 0–2.5 kHz and for phase to neutral measurements [12, 13]. Phase (L1) measurements and bandwidth of the measurements is 2 kHz are utilized, that meets with the standards of IEC 61000-4-30 and SFS-EN 50160 [12, 13, 35].

$$TEHD = \frac{\sqrt{\sum_{n\geq 1}^{N} I_{2n}^2}}{I_0} \quad (3.4)$$

$$TOHD = \frac{\sqrt{\sum_{n\gneqq 1}^{N} I_{2n-1}^2}}{I_0} \quad (3.5)$$

THD is calculated

$$THD = \sqrt{TEHD^2 + TOHD^2} \quad (3.6)$$

In the equation above n denotes the harmonic order, I_0 denotes rms value of current at fundamental frequency 50 Hz or 60 Hz and N denotes the last harmonic order included in THD calculation. The same equation is applying for calculating voltage distortion except that current will be replaced by voltage.

There is another method to measure distortion used by power engineers known as Total Demand Distortion (TDD). It is calculated by measuring harmonic current distortion against the demand level of electrical system at full load TDD(I)=THD(I). The reference current in this calculation is not fundamental frequency current but the rated or maximum value of current of the load or power generation.

$$TDD = \frac{\sqrt{\sum_{n=2}^{N} I_n^2}}{I_R} \quad (3.7)$$

TDD is not much have relevance for voltage as voltage remains almost constant when calculating THD but as the fundamental frequency current is always changing and does not remain constant, it is very important to choose correct I_R value while TDD calculation. IEEE Std 519 provides guidance for I_R selection [22].

Harmonics measurement is an important aspects of power quality measurement along with voltage sags and swells. And due to frequent complaints from customers it has become important for DSO’s to measure harmonics to improve power quality. With the advancements in the technology power quality measurements future is promising as we now have more cheap and accurate devices to measure power quality parameters. This thesis analyzes the active power measurements with respect to power quality by utilizing advanced and diverse power quality meters by continuously monitoring a pilot building. IEC 61000-4-30 and IEEE Std 1159 standards have been updated recently for power quality measurements [12, 13, 29]. Limits for voltage distribution network are provided in standard SFS-EN 50160 and standards IEEE Std 519 and IEC 61000-4-7 provides information concerning with distortion in the network [12, 14, 22, 35].

3.2.3 Distortion sources and consequences

Distortion is caused by the non-linear behavior of voltage and current waveform which means that if an ideal sine wave is applied into a system it starts producing non-sinusoidal waveform. The main sources of voltage and current distortions are non-linear devices like transformers, switch mode converters, flexible alternating current transmission systems (FACTS) devices, arcing devices etc. [7, 39]. Kalair review describes causes of distortion and distortion waveforms [27]. As we have discussed earlier in the chapter voltage distortion maybe because of distortion in current, but it is difficult to find voltage distortion's source as compared to current distortion's source.

Poor power quality may result in power outages which can have adverse effects for DSO's and customers financially. If harmonic effects are not kept into account, billing will be inaccurate, and this will cause a financial loss for both the customers and DSO's. If the distortion in the electrical network is high this will reduce the life of transformers and capacitor banks and will also increase power losses. Distortion can also cause resonant condition in the network between inductive and capacitive banks which can cause huge overvoltage and overcurrent. Resonance occurs at harmonic frequencies which means overvoltage and overcurrent is harmonic. If there is an accumulation of distortion current in neutral wire of 3-phase system, neutral wire may experience over loading and overheating.

On customer side can also cause flickering lamps and LEDs, vibrations in motors due to unwanted torque and create power losses which results in various problems for customers in consumer appliances [7, 39]. Flickering can be caused by PV power plant because it generates inter-harmonics beneath the fundamental frequency [41].

There are also solutions available to minimize the effect of voltage and current distortions by performing harmonic assessment to detect current and voltage distortion and if necessary, passive or active filter depending on the requirement can be used to filter out these harmonics. A device should be well implemented for it to work within the specified voltage distortion limits of standard and complying with current distortion emission regulations at the same time [17, 22]. Unified power theory and design principles are promoted for power measurements [37].

To include the effect of harmonics in meter readings IEEE Std 1459 definition is used in a harmonic impact project in Canada as it provides power definitions at harmonic frequencies [5, 21]. This project was proposed in Canada to show that present smart meters technology can be used to implement these definitions. This project also showed that metering inequities exists, and they have a significant impact on both the utilities and customer side. In this thesis we utilize the concept of this project in analysis of measured data in the pilot building.

3.3 Power definitions

With advancements in distribution networks, and advent of modern smart grid systems, it is important to discuss these evolving power definitions. There is no fit for all definitions, and each is utilized with respect to the application for which smart meter is in use [20, 23]. The standard for load control equipment and tariff is different as compared to standard that specifies requirement for time switches and ripple control receivers. We have discussed IEEE 1459 standard in the previous chapter and saw how fundamental frequency power and harmonic power are measured using this standard [21]. In this thesis, we will discuss power in low voltage network in frequency domain to consider the effects of distortion powers. It is to be noted that due to measurement devices constraint the bandwidth is limited to 2 kHz.

The product of phase voltage and current gives single phase apparent power and it is the maximum power that can be delivered if power factor is one that means phase shift between voltage and current is zero and no reactive power is flowing in the network.

$U = rms\ voltage$

$I = rms\ current$

$$S = UI \tag{3.7}$$

Emmanuel's and IEEE Std 1459 power equations are defined to calculate fundamental power and total harmonic power [7, 20]. There are other power definitions that are available also. The main idea of discussing this is to give an idea of how harmonic effect can be included in smart meter measurements. In IEEE Std 1459 P_1, Q_1 and S_1 represents fundamental frequency active power, reactive power, apparent power, respectively. According to the standard fundamental frequency active power can be called real power and it is the average of instantaneous active power samples [21].

$$S_1 = \sqrt{P_1^2 + Q_1^2} \quad (3.8)$$

Total apparent Power according to IEEE Std 1459 is given by

$$S = \sqrt{S_1^2 + S_N^2} = \sqrt{(P_1^2 + Q_1^2) + (D_I^2 + D_V^2 + S_H^2)} \quad (3.9)$$

P_1	Fundamental frequency active power
Q_1	Fundamental frequency reactive power
D_I	Distortion power caused by distortion current
D_V	Distortion power caused by distortion voltage
D_H	Harmonic distortion power
S_1	Fundamental frequency apparent power
S_N	Non-fundamental apparent power
S_H	Harmonic apparent power

The equation above gives the apparent power is non-sinusoidal conditions. Power in non-sinusoidal condition consists of harmonic distortion power due to voltage and current distortion. D_I, D_V and S_H represents distortion powers.

IEEE 1459 also defines power factor calculation both at fundamental frequency harmonics and at harmonic frequency. Ratio of active power and apparent power is called power factor. Power factors in IEEE Std 1459 standard are called displacement power factor (DPF) and power factor (PF).

$$DPF = \cos\theta_1 = \frac{P_1}{S_1} \quad (3.10)$$

$$PF = \frac{P}{S} \quad (3.11)$$

Where θ_1 is the phase difference between fundamental frequency voltage and current. PF calculates the power factor by considering the overall distortion in the network. DPF and PF help us calculate the concentration of overall active power and fundamental frequency active power helping us understanding the power network and compensation it needs to filter out the harmonic losses improving the overall power factor.

Fundamental frequency active power is the net power that contributes to actual work in the system. In most cases, e.g. motors, harmonic active power does not contribute to electric torque in the motor whereas harmonic reactive power only causes losses in the network and does not perform any work. In most countries nowadays billing usually involves total active power and fundamental frequency reactive power [8, 10]. This gives us the idea that even though harmonic active power is wasted, customer is still paying for it. That is why it is necessary to quantify harmonic active power [8, 21].

3.4 Power measurement

The measurement parameters that are in use in most of the meters are more or less the same that were in use for electromechanical meters but in future smart grid system with more non-linear devices, DERs and bidirectional current flow future meters should have power quality metering capabilities. In case of severe distortions, the differences can be up to 3% of active energy as it is observed in theoretical and laboratory studies [5]. By implementing the smart meter definitions that have been studied above like IEEE Std 1459 we can separate filter out fundamental frequency power P_1 with the total power [5, 21]. For apparent power in cases of severe distortion difference between fundamental frequency S_1 power and total apparent power S is up to 15% [5]. These factors make it necessary to measure both S and S_1 for equipment capacity requirement and the other for billing objective.

Smart meter of today uses multiple microprocessors that can perform metering, communication and functions related to data and communication security. Several manufacturers use 71M65xx family of chips and the DSP in these can be reprogrammed to implement different measurement definitions based on the requirements for which smart meter is needed [5]. In the figure below the architecture of Vision Smart meter is shown which is used for Harmonic Impact Project in Canada that implements IEEE Std 1459 definitions of electrical power measurement to measure fundamental frequency power and total power [5, 21].

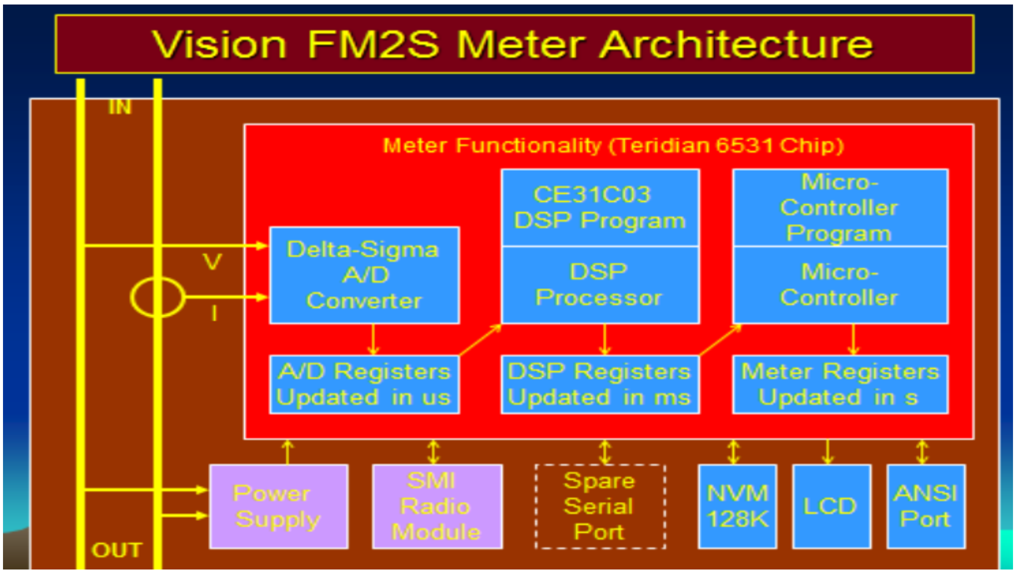

Figure 1. *Vision smart meter's architecture [5].*

To minimize adverse effects of poor power quality modern smart meters also monitor power quality parameters. In the last few decades improvement in standards have taken place for example, to define accuracy test for static meters when harmonics are present IEC 62053-21 is utilized. If designed well, static meters perform metering accurately and there are now standards available for accurate measurements, for energy meters like 62052-11, 62053-21 and 62053-23 [9, 10, 11].

4. ANALYSIS OF MEASURED DATA

In this chapter we will investigate the data we collected from smart meter installed in a building. We will analyze how harmonics have an impact on the total active power versus fundamental frequency active power. First, we will investigate the selected building dynamics, which means how many loads and consumer building has, DER systems it employs and the measurement and data collection techniques it uses.

The building that was considered for to analyze the difference between the fundamental frequency active power and total active power is known as Kampusareena. Kampusareena is a newly constructed building in 2015 at the premises of Tampere University (Hervanta campus), a multi-storey building with diverse loads, educational and official facilities. The building was also a part of the project Prosumer Centric Energy Ecosystem (ProCem) [30, 42]. In ProCem building served as a model for future smart buildings, as measurement and data collection system were designed and implemented during this project. In this thesis we will focus on the active power measurements at fundamental and harmonic frequencies provided by the ProCem which is monitoring the measurements of electrical system in the building [18, 30, 42].

4.1 Pilot building

The front view of Kampusareena is shown in Fig. 2. As it was told earlier the building provides educational and research facilities along with the offices for many multinational organizations. The construction of building was completed in 2015 and the building serves a very good model for environmentally friendly buildings as it has achieved an energy rating of ‘Very Good’ by Building Research Establishment’s Environmental Assessment Method (BREEAM) [18]. The building has a good heating and cooling system to maintain the inside temperature of the building both in summer and winters. Hundreds of people visit the premises of building every year and dozens of people work inside that building as building have facilities such as restaurants, student affairs office, IT service help desk and library services [18]. On darker colored walls PV panels are installed.

Figure 2. *Front view of Kampusareena.*

4.2 Electrical network of the building

To monitor the diverse loads, measurement devices along with the ICT system are installed for communication and storing data in the building. Building has its own DER in the form of a PV power plant and the major loads of the building includes ventilation system, cooling units and elevators. There Kampusareena has a 20 kV access point, main distribution boards, loads and power generation. Radial electrical systems were used for network operation, and though Kampusareena has a PV generation as DER but it cannot be considered as microgrid because it does not fit in microgrid definition. The definitions of microgrid can be found in the publication of JWG C6.22 of CIGRE [34].

At Tampere University (Hervanta campus) Kampusareena has its own access point to (MV) medium voltage network. Fig. 3 shows main electricity distribution of the building. Two main distribution boards that form the network are named service electricity and tenants' electricity. Service electricity distribution board provides electricity to ventilation units, cooling units and elevators. Tenant's electricity distribution board feeds the appliances of the tenants that includes lighting and has numerous smaller loads mixed in groups. To get more information about building's network Antti Hilden's thesis provides the data in detail [18].

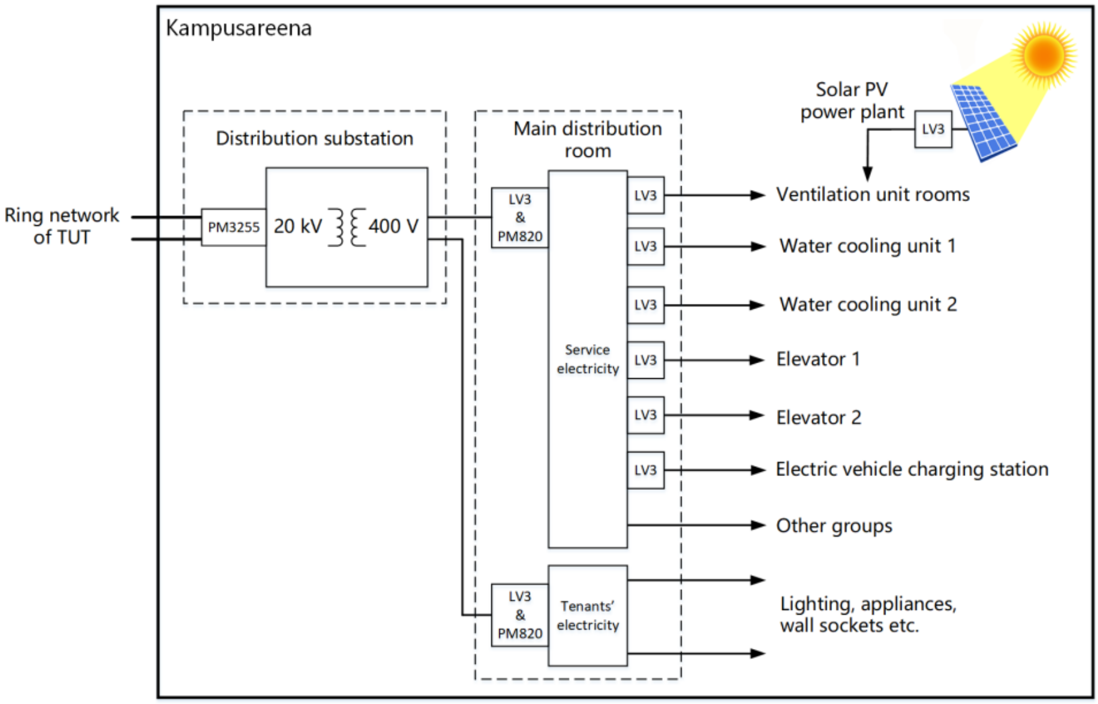

***Figure 3.** Kampusareena's main distribution board of electricity [18].*

Laatuvahti 3 and Schneider PM820 and PM3255 are measurement devices that are denoted at the measurement locations. Figure 3 shows measurement locations and loads that are utilized for analysis in this thesis. As we can see in the figure PV generation supplies power to ventilation units in parallel with the main distribution board [18].

4.2.1 Building electrical loads

Building has a many small and large loads that consume electrical power and not all the appliances are considered in this thesis. Following are the major loads of the building.

- Cooling unit 1
- Cooling unit 2
- Ventilation units
- Elevator 1
- Elevator 2
- Tenants
- Electric vehicle (EV) charging station

Figure 4. *Darker walls that are facing south-east, west and south-west shows solar panels on the building [18].*

Service electricity distribution board provides power to cooling units, ventilation units and elevators. At distribution network's access point and at main distribution board load parameters are measured. To get more information about the above-mentioned building's loads Antti Hilden thesis provides more information [18]. The solar panels are installed on the darker walls of the building as shown in Fig. 4[18].

4.3 ICT system of the building

The pilot project in the building involved the design and implementation of the ICT system. The main purpose of this is to collect the data parameters of all the building loads and PV generator and store it in a place where it is readily accessible. As this involves monitoring and control features, fast and accurate communication between various building loads is very important. To perform data analysis and develop applications, data and ICT system were made available for users. Figure 5 illustrates architecture of ICT system presenting the data and information flows. ICT system will help in gathering the data of the building comprehensively into a single place [18].

Fig. 5 shows the architecture which consists of two virtual platforms of Linux and internet of things (IoT) implementation. To get more information about the data sources, data provider, connection and communication protocol, and building's ICT system thesis by Antti Hilden can be studied where more information is given in detail [18].

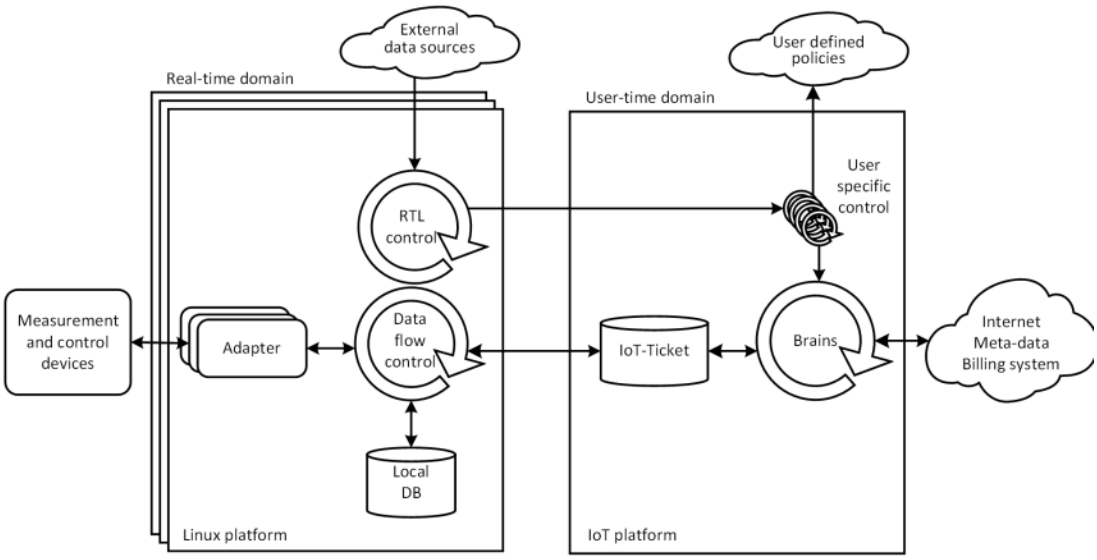

Figure 5. *Design of ICT system's architecture in ProCem project [18].*

4.4 Behavior of electrical network of the building

In this section we will investigate the data that was gathered from electrical network of the building. But before we go further, it is to be noted here that environmental and other factors can also alter the electrical behavior of the building. These factors may affect hourly, daily, or yearly. On weekdays building is more congested than on weekends which means more CO_2 content in weekdays. In summer due to summer holidays it is less crowded but is hotter than winters. In summer PV power production is higher because sun is significantly higher than in winters. These conditions influence the electrical parameters of the building. While during the analysis, both internal and external conditions that influence electrical parameters of the building are neglected, but the effect of solar irradiance on PV power generation is included. The ICT system of the building includes data of several days but only the data of two days are used in this analysis. The measurement data includes active power, current and voltage obtained as 1 second rms from Laatuvahti 3 meters. Laatuvahti 3 meters have bandwidth of 2 kHz. These measurements of different electrical parameters are limited to single phase to explicitly study the power flows in single phase because in three phase study behavior relating to individual phase may be concealed.

The measurements of Laatuvahti 3 meters consists of: total active power (PL), fundamental frequency active power (PL1), phase voltage (UL), fundamental frequency phase voltage (UL1), current (IL), fundamental frequency current (IL1), total distortion voltage (TDUL), total distortion current (TDIL).

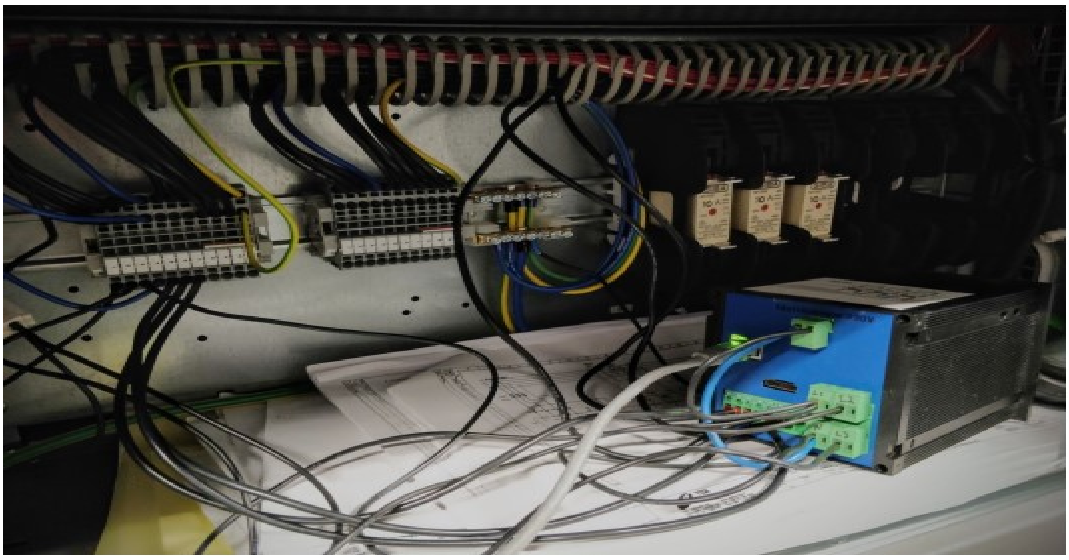

Figure 6. *Laatuvahti 3 installed in the main distribution room at pilot building [18].*

4.4.1 Service electricity

As discussed earlier there are two main distribution boards with service electricity being one that provides power to numerous loads in the building which include cooling units, ventilation, and elevators where these loads are aggregated. There is also a connection of service distribution board with PV generating plant via ventilation feeder. Service electricity's maximum power generation (three phase) is 150 kW. PV power generation have a profound effect on active power consumption of service electricity.

In the Fig. 7 and Fig 8. two different days are represented, one of the days was cloudy and the other day was sunny to examine the behavior of service electricity. PV generation's effect is visible on service electricity parameters in these figures. On cloudy day there were repetitive peaks in active power and distortion current. The reason is because the compressors of the cooling units in the building were restarting continuously throughout the day which we later see in electrical parameters graphs of cooling units. Ventilation has significant effect on active power and total distortion current that is visible in Fig. 9 and 10. Total distortion current varies around 50% even at high loading of the service electricity. Voltage distortion remains within the limits as defined by the standard SFS-EN 50160 [35].

Figure 10 gives details about the power variations because of solar power plant by measuring the parameters at the main distribution board. For PV power plants the reactive power is drawn from main distribution panel and it provides active power to the ventilation units. Total distortion of current is high and goes to maximum 80% at almost noon which maybe a cause of high voltage distortion. The effect of solar power generation is visible in the measurement of active power on August 8th caused by solar power generation as compared to July 3rd measurements. It was observed by looking at the pattern of day to day data that if no solar power is generated, power behavior of the ventilation units remains same. Solar inverters usually do not have compensation mechanism for distortion

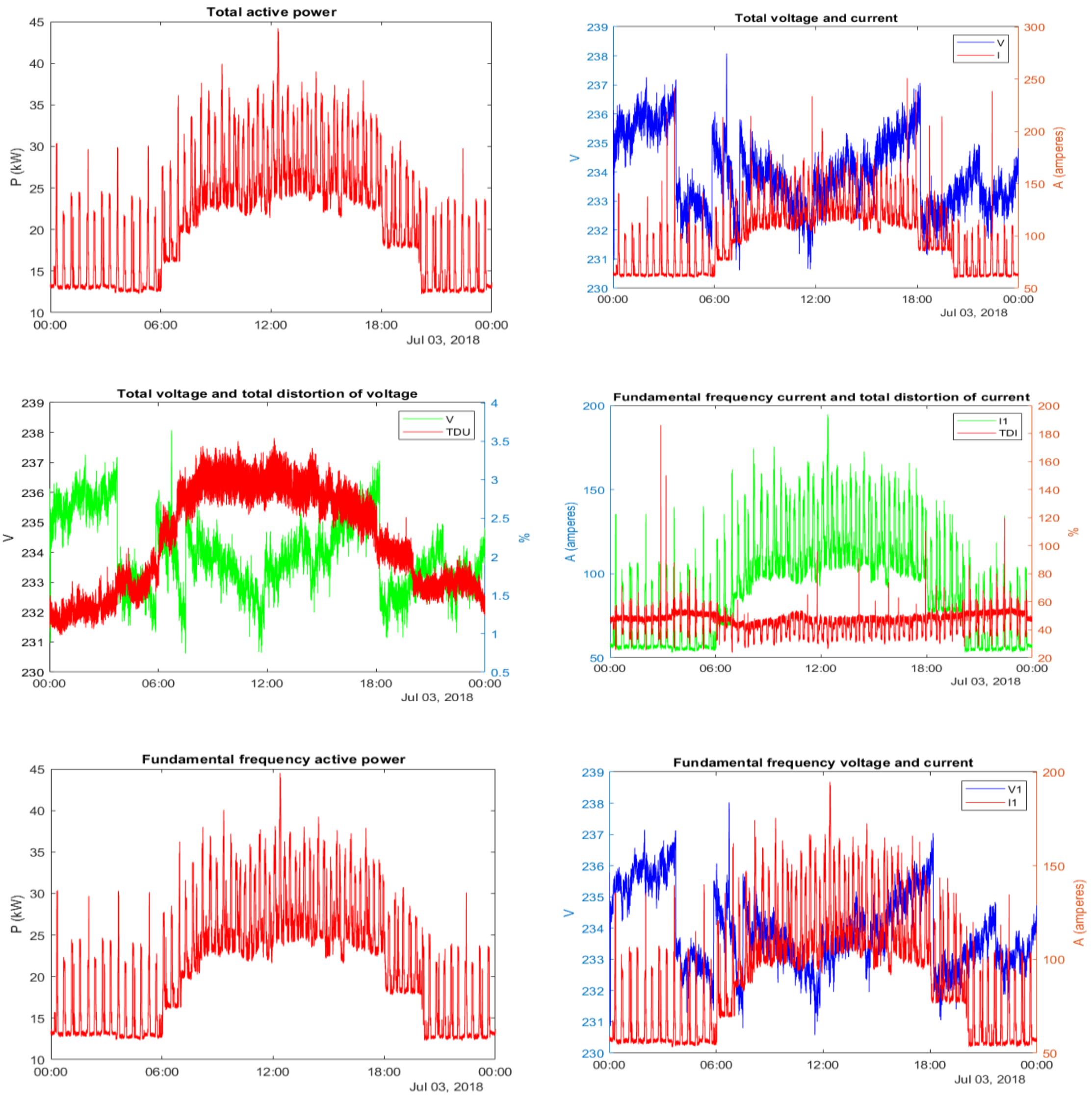

Figure 7. Service electricity parameters overview on July 3rd, 2018, *Top left: total active power (P), Top right: total voltage (V) and current (I) of L1, Middle Left: total distortion of voltage (TDU) and total voltage at L1, Middle right: total distortion of current (TDI) and fundamental frequency current (I) at L1, Bottom left: fundamental frequency active power (P_1) at L1, Bottom Right: fundamental frequency voltage (V_1) and current (I_1) at L1.*

current but advancement in control system has allowed the generation of desired distortion current. Power behavior shown by ventilation units is because reactive power produce by solar power plant is almost negligible and it is mostly drawn from the main distribution board.

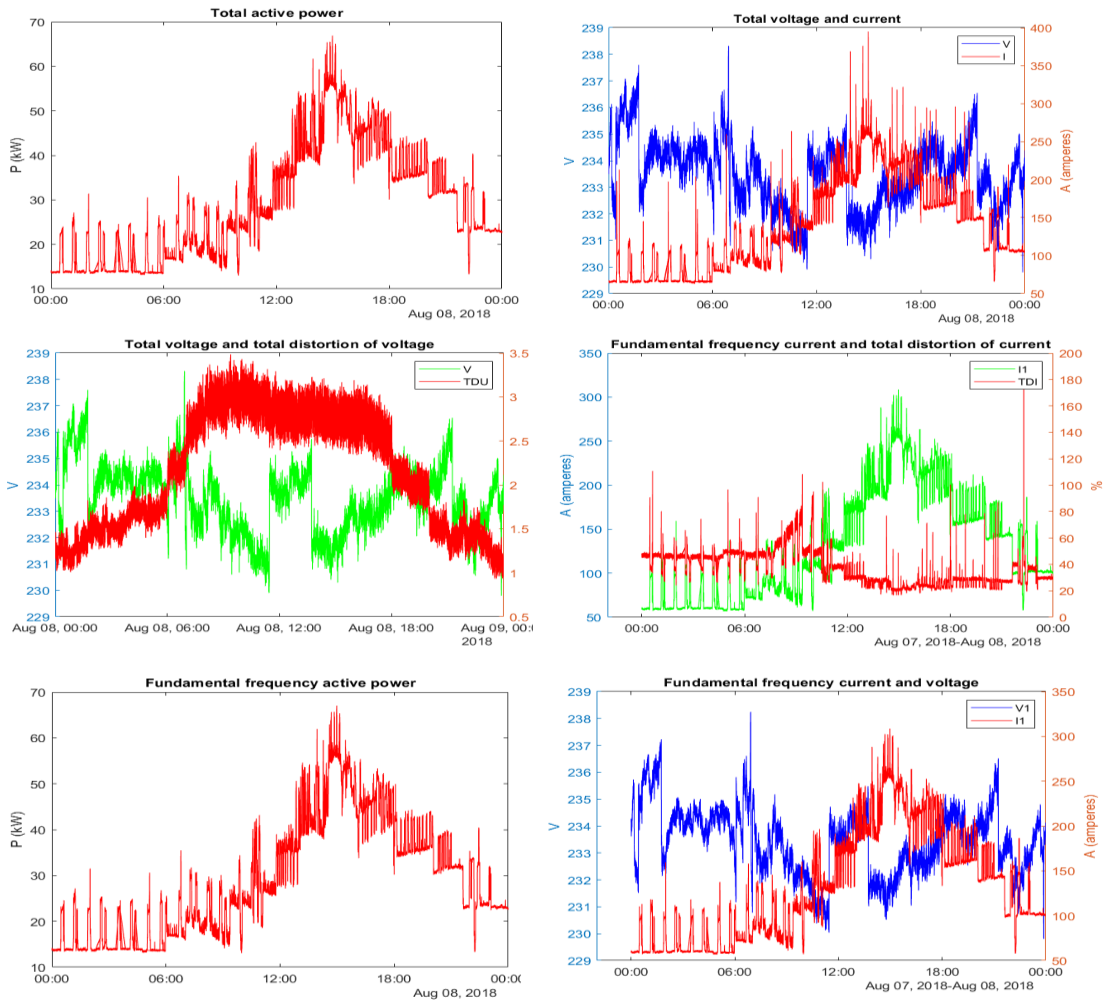

Figure 8. *Service electricity parameters overview on August 8th, 2018, Top left: total active power (P), Top right: total voltage (V) and current (I) of L1, Middle Left: total distortion of voltage (TDU) and total voltage at L1, Middle right: total distortion of current (TDI) and fundamental frequency current (I) at L1, Bottom left: fundamental frequency active power (P_1) at L1, Bottom Right: fundamental frequency active voltage (V_1) and current (I_1) at L1.*

August 8th, 2018 was a sunny day which results in higher irradiance received by PV plant generating more electrical power. As this sunny day was hot more cooling was required inside the building and this causes the active power curve to differ greatly from the cloudy day. The number compressors running continuously on that day were more, so the power peaks are few when compared with the cloudy day.

4.4.2 Ventilation

Ventilation units are run by the power electronics devices such frequency converters for air ventilation inside the building. Solar power plant also supply power to one of the ventilation rooms. Ventilation unit's maximum three phase power can be 100kW or above.

Figure 9 shows total active power, current, voltage and total distortion in voltage and current of the ventilation units on July 03, 2018 that was a cloudy day whereas Fig. 9 shows the behavior for a sunny day on August 8th, 2018. From the graphs it can be observed that ventilation behavior is affected by the solar power plant. At noon when solar power production is high the distortion in current is low as seen in Fig. 9. Active power consumption in morning and evening is almost same and distortion in voltage and current is significantly higher in the morning when power consumption is low. It can be observed from the graphs that in the morning when power consumption and fundamental frequency current is low total current distortion is significantly high, but amplitude of distortion current is low. In the middle of the day when fundamental frequency current increases distortion current also increases but total current distortion is less as compared to in the morning. On the other hand, fundamental frequency voltage is low at the middle of the day when power consumption is high as compared to total voltage resulting in high voltage distortion as can be seen in Fig. 9. This may be caused by changes in network. It is observed in the pilot and while browsing data that ventilation behavior remains the same in terms of power if no solar power is generated.

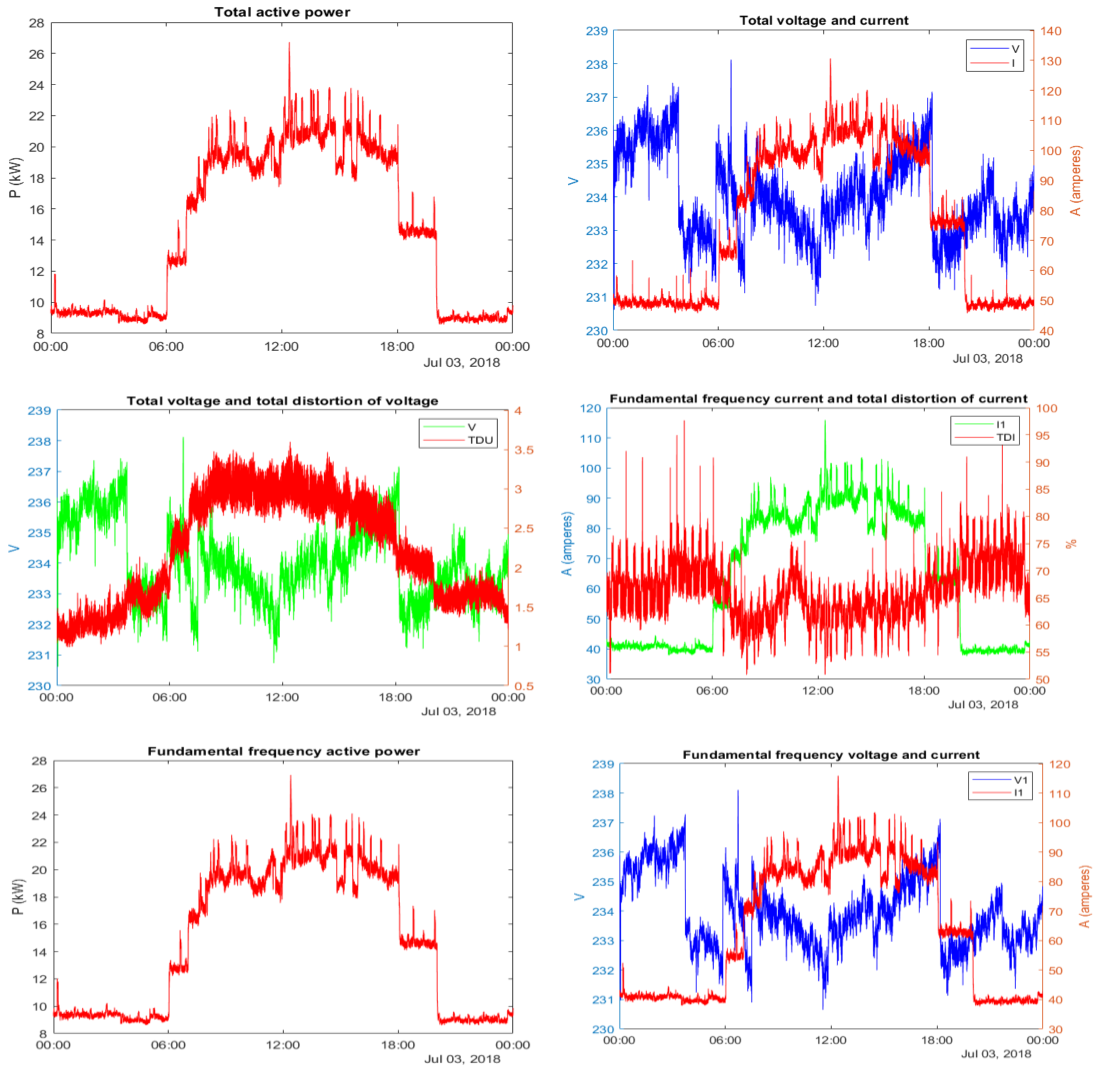

Figure 9. *Electrical ventilation parameters overview on July 3rd, 2018, Top left: total active power (P), Top right: total voltage (V) and current (I) of L1, Middle left: total distortion of voltage (TDU) and total voltage at L1, Middle right: total distortion of current (TDI) and fundamental frequency current (I) at L1, Bottom left: fundamental frequency active power (P_1) at L1, Bottom Right: fundamental frequency active voltage (V_1) and current (I_1) at L1.*

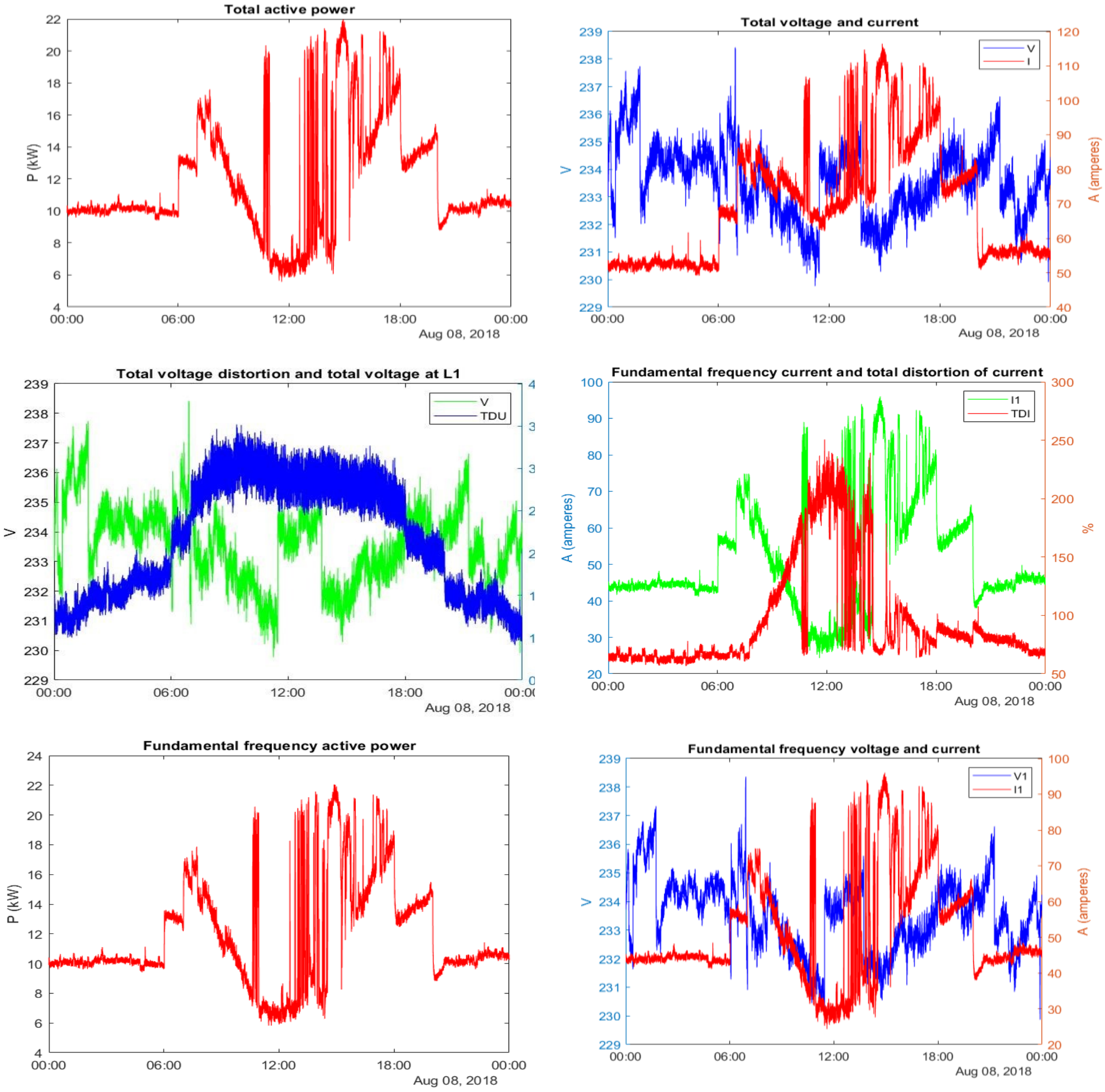

Figure 10. *Electrical ventilation parameters overview on 8th August 2018, Top left: total active power (P), Top right: total voltage and current at L1, Middle left: total distortion of voltage (TDU) and voltage (V) at L1, Middle right: fundamental frequency current (I_1) and total distortion of current (TDI), Bottom left: fundamental frequency power (P_1), Bottom right: fundamental frequency voltage (V_1) and current (I_1) at L1.*

4.4.3 Elevators

Service electricity supplies power to two passenger elevators in the building. Elevators are located next to each other and they are mostly used in daytime to transfer people between eight floors of the building. For one elevator the maximum 3-phase active power measured is 7 kW and they are driven by 3-phase frequency converters. The behavior of both elevators when measured has identical electrical behavior over a day. Fig 11 gives electrical parameters of elevator 1 and by examining it we can see the variations in active power because of frequent operation of lifts during the day. As compared to other loads of service electricity e.g. ventilation, power consumption of elevators is small, which results in less influence on overall power consumption of service electricity.

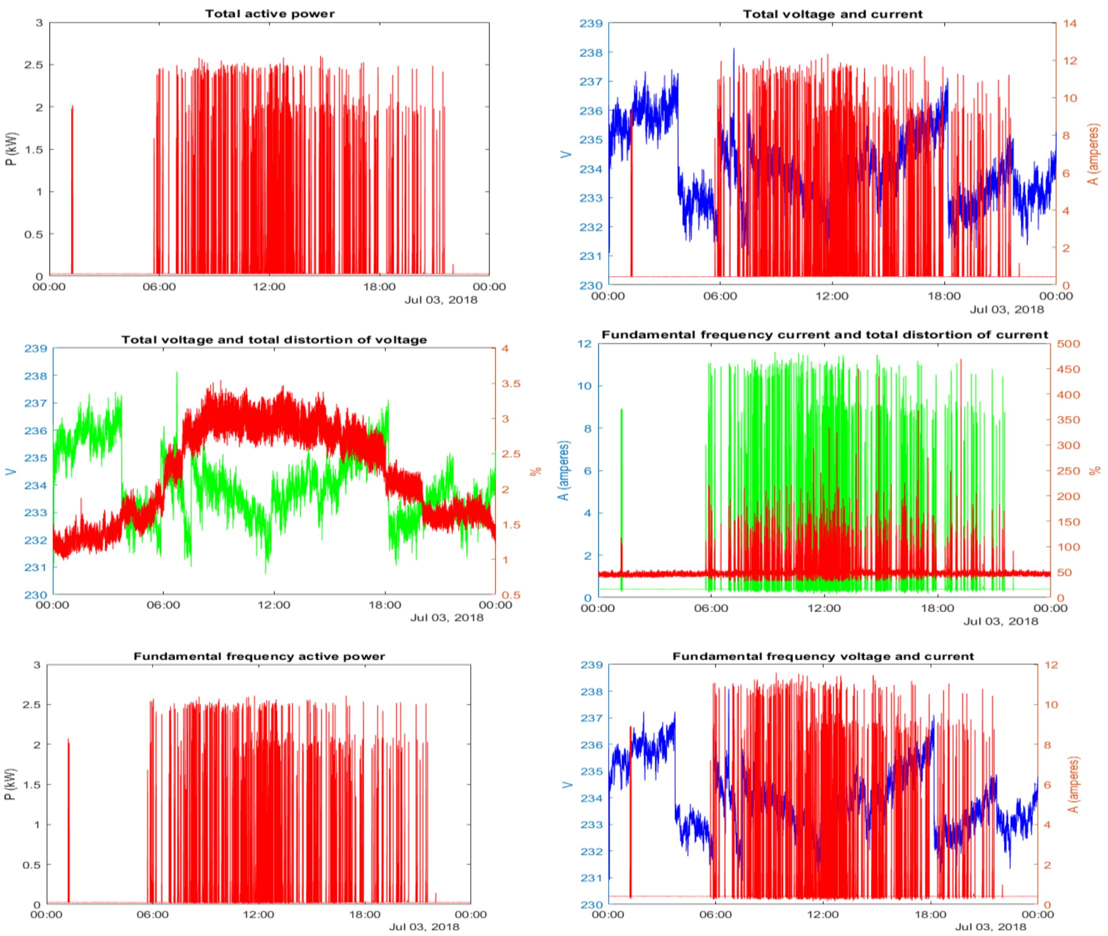

Figure 11. *Elevator 1 electrical parameters overview on 3rd July 2018, Top left: total active power (P), Top right: total voltage and current at L1, Middle left: total distortion of voltage (TDU) and total voltage (V) at L1, Middle right: fundamental frequency current (I_1) and total distortion of current (TDI), Bottom left: fundamental frequency power (P_1), Bottom right: fundamental frequency voltage (V_1) and current (I_1) at L1.*

There is a difference in up and down movement of lifts in electrical terms which means that active power consumption is high when lift is going down and is minimal when moving upward. The distortion in current during the operation is due to the presence of power electronic devices in elevators. Also, there are peaks in active power during the operation before it settles down. The peaks are visible because the time resolution of measurements is 1s. Fig. 12 represents the behavior of elevator 2 that is almost like elevator 1 except that on July 3rd, 2018 the usage of elevator 2 was less than elevator 1. One reason for this may be due to the coordinated operation between the two elevators.

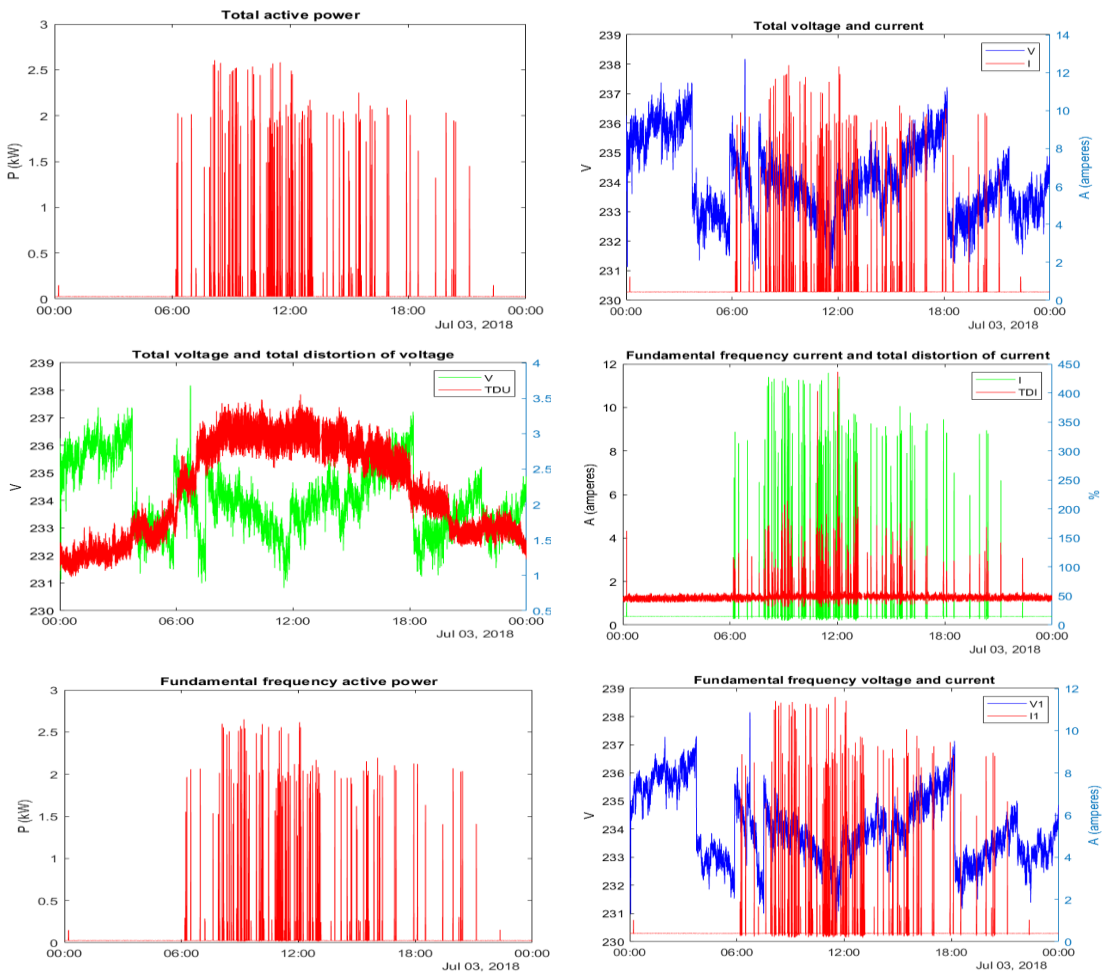

Figure 12. *Elevator 2 electrical parameters overview on 3rd July 2018, Elevator 2 electrical parameters overview on 3rd July 2018. Top left: total active power (P), Top right: total voltage and current at L1, Middle left: total distortion of voltage (TDU) and voltage (V) at L1, Middle right: fundamental frequency current (I_1) and total distortion of current (TDI), Bottom left: fundamental frequency power (P_1), Bottom right: fundamental frequency voltage (V_1) and current (I_1) at L1*

4.4.4 Cooling units

The building has two cooling units that are powered by the main distribution board of service electricity. Their job is to maintain the temperature of the coolant to set point so that indoor building's temperature can be maintained with respect to outside environment. For cooling process many parallel compressors are used and highest three phase active powers for cooling unit 1 is 70 kW and for cooling unit 2 is 80 kW. Electrical parameters for both cooling units are presented both for a cloudy day July 3rd and for a sunny hot day August 8th in Fig. 13, 14, 15 and 16. Fig.13 shows cooling unit 1 behavior that tells us that there are repetitive peaks in active power and distortion current. The reason behind these repetitive peaks is that the compressors of cooling units continuously on and off with respect to outside temperature which in turn affecting the indoor the indoor temperature of the building.

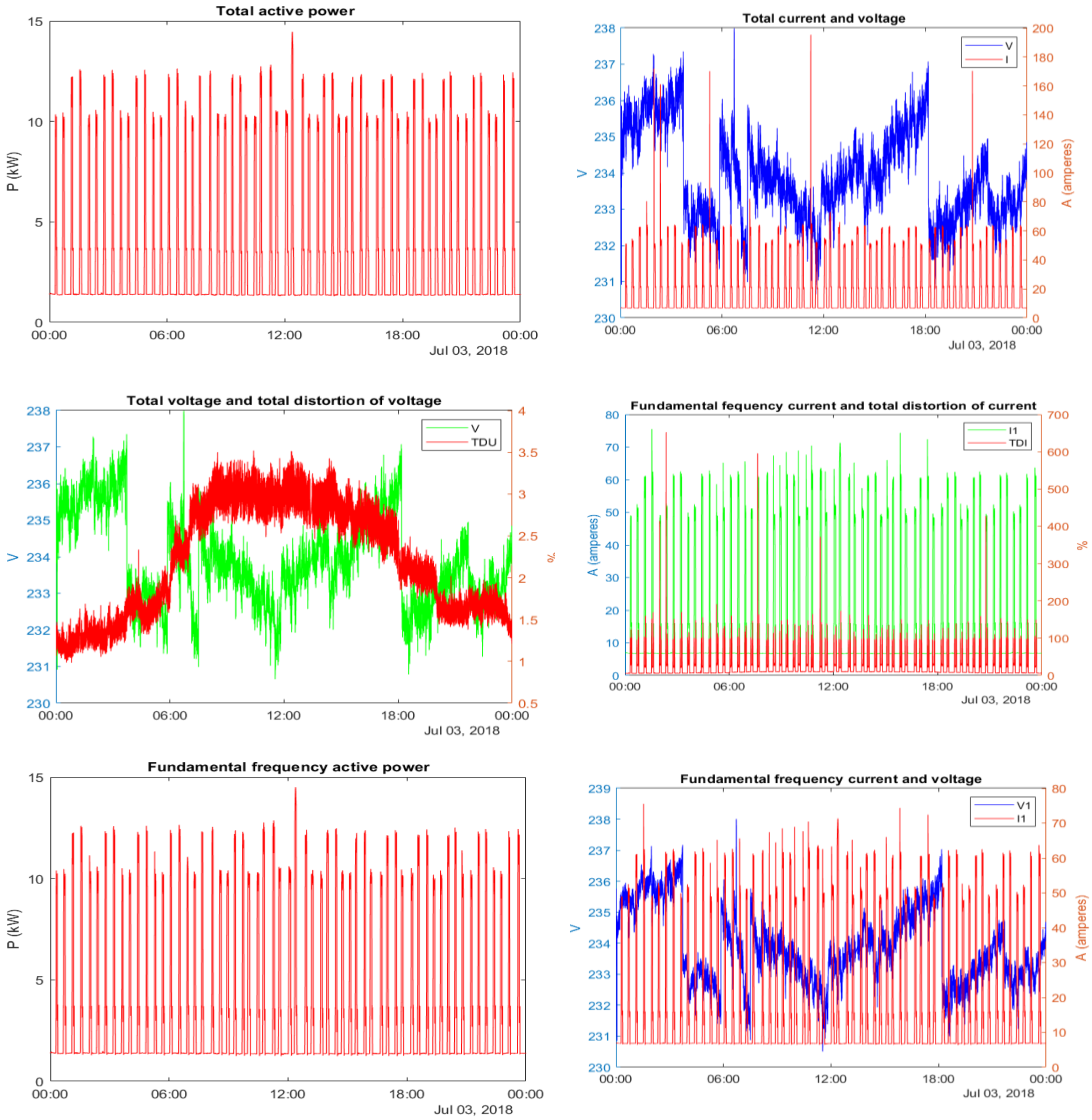

Figure 13. *Cooling Unit 1 electrical parameters overview on 3rd July 2018, Top left: total active power (P), Top right: total voltage and current at L1, Middle left: total distortion of voltage (TDU) and voltage (V) at L1, Middle right: fundamental frequency current (I_1) and total distortion of current (TDI), Bottom left: fundamental frequency power (P_1), Bottom right: fundamental frequency voltage (V_1) and current (I_1) at L1*

We can see from the Fig.13 that distortion current increases during the day but cooling unit 1 have no effect on voltage and on voltage distortion. It was observed that distortion current remains almost same during the whole operation of cooling unit except the transients that occur when turning on and turning off compressor. This behavior is because of directly coupled electric machine as compressor.

Fig. 14 represents cooling unit 2 behavior on 3rd July 2018. As it can be seen from the figure there were less peaks in active power as compared to unit 1 on the same day. Again, the peak power incidents are assumed to be caused by compressor and TDI (total current distortion) is affected by compressor operation that is also related with active power. Fig. 15 represents the cooling unit 1 electrical behavior on 8th August 2018 that was a sunny day. Hot temperature outside, increases building's internal temperature and

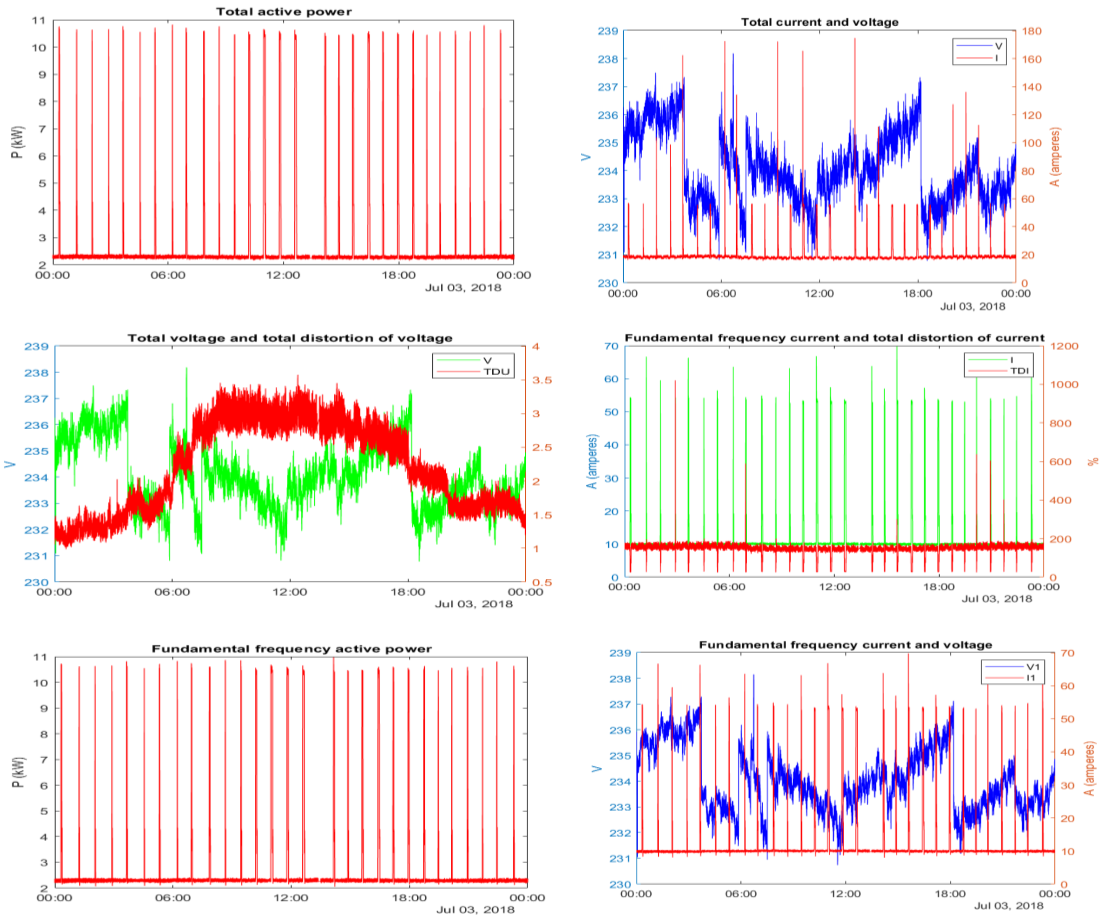

Figure 14. *Cooling Unit 2 electrical parameters overview on 3rd July 2018, Top left: total active power (P), Top right: total voltage and current at L1, Middle left: total distortion of voltage (TDU) and voltage (V) at L1, Middle right: fundamental frequency current (I_1) and total distortion of current (TDI), Bottom left: fundamental frequency power (P_1), Bottom right: fundamental frequency voltage (V_1) and current (I_1) at L1*

this results in greater demand for cooling. More compressors will be active now due to high cooling demand and they keep running for longer time periods, the effect of which can be seen in electrical parameters of cooling unit 1. More distortion current is induced repeatedly by cooling units, in building's electrical network on that day, as requirement for cooling has increased because of weather. Distortion current is considerably large during the starting and stopping operation of the compressors and it is visible in the graph of TDI (total distortion current).

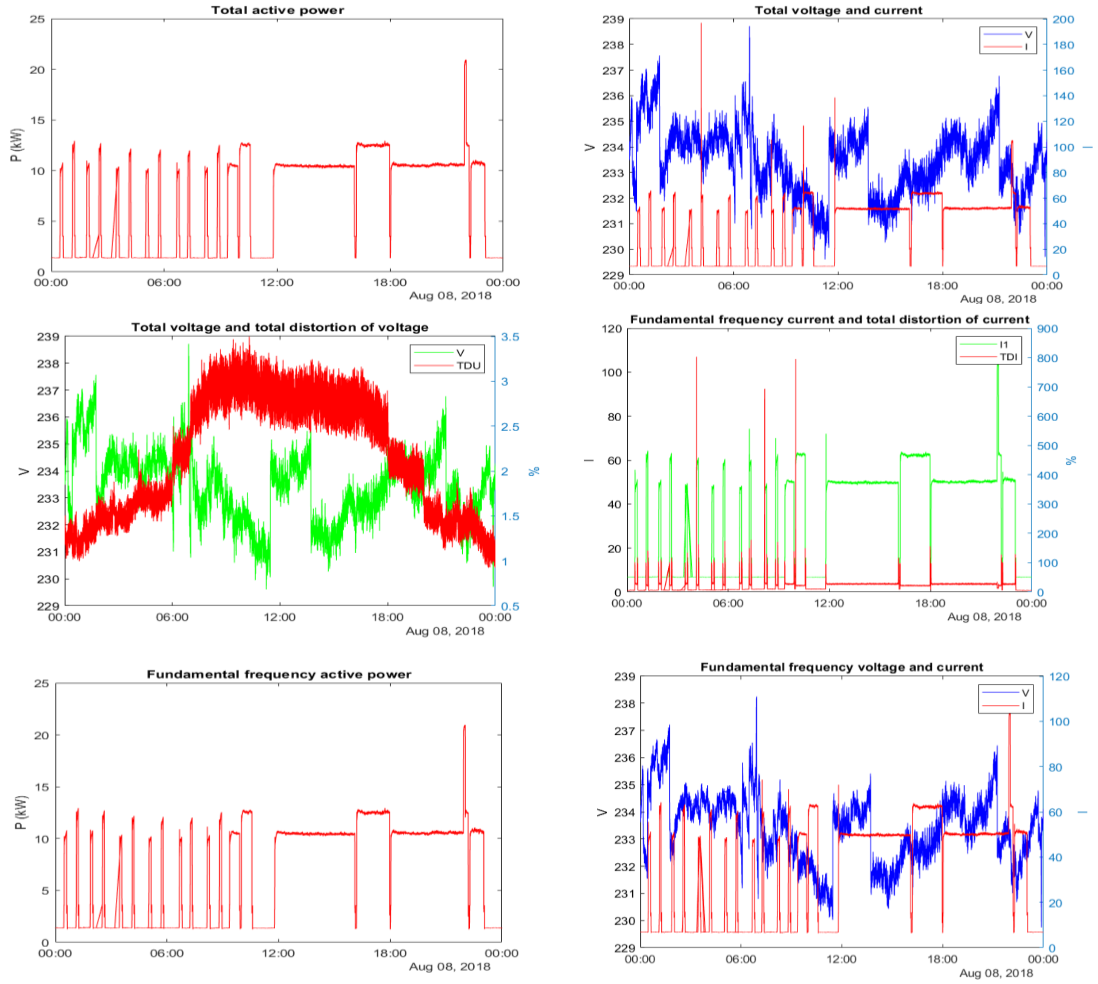

Figure 15. *Cooling Unit 1 electrical parameters overview on 8th August 2018, Top left: total active power (P), Top right: total voltage and current at L1, Middle left: total distortion of voltage (TDU) and voltage (V) at L1, Middle right: fundamental frequency current (I_1) and total distortion of current (TDI), Bottom left: fundamental frequency power (P_1), Bottom right: fundamental frequency voltage (V_1) and current (I_1) at L1*

4.4.5 Electric vehicle charging

Parking area in front of Kampusarrena is equipped with by five EV charging spots to charge electric vehicles. Main distribution board of service electricity supplies power to these charging spots. Electric cars being charged in these parking spots varies on daily basis and because of low usage it is the smallest load of service electricity. 22 kW was the largest 3-phase loading condition measured at EV charging station. On 3rd July 2018 there was no electric vehicle charging that took place. On August 8th, 2018 electric charging occur as shown in the Fig. 16. Charging behavior of charging station varies depending on the hybrid-electric and electric cars. They utilize either three phase or single-phase charging.

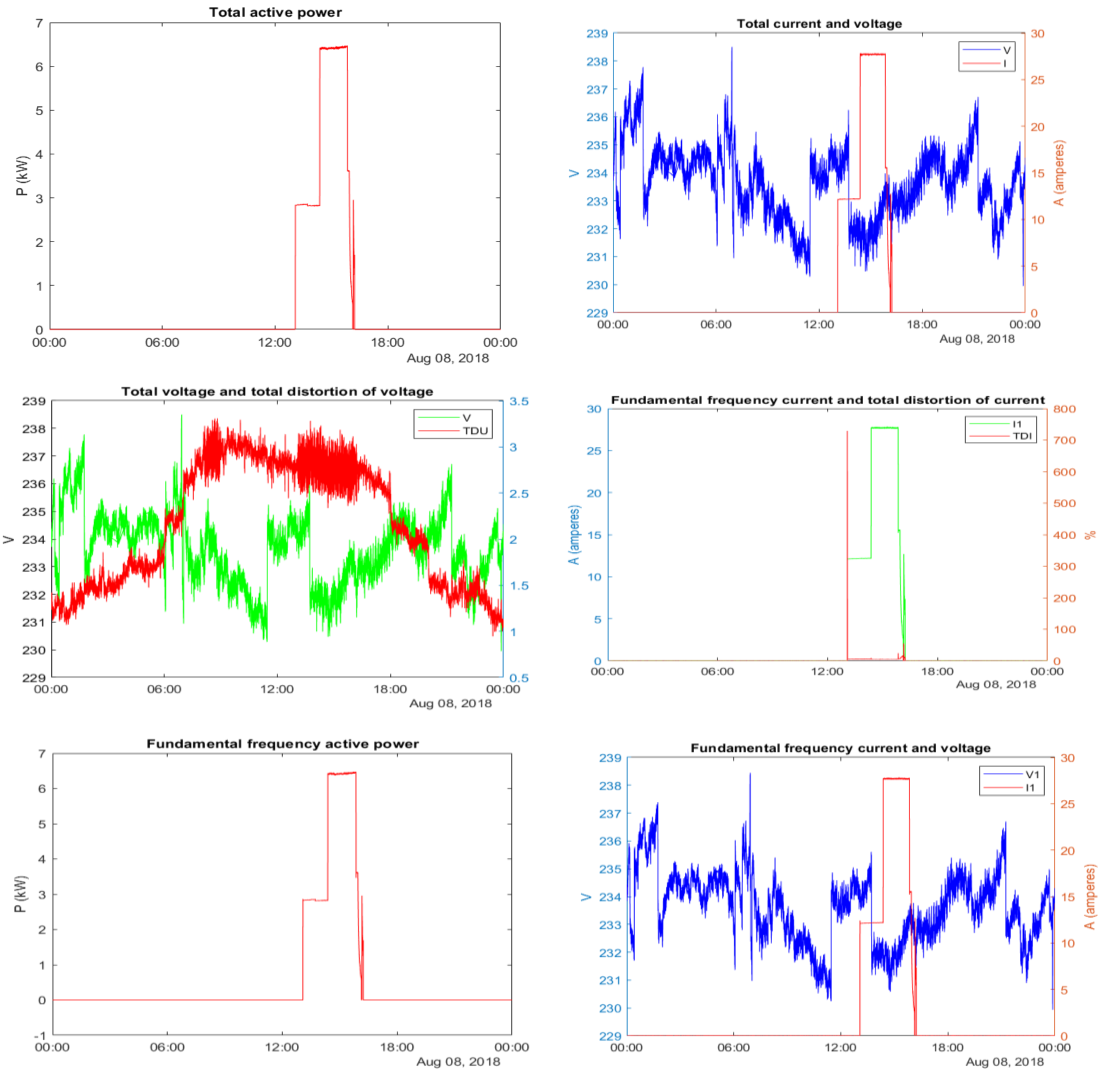

Figure 16. *Electric Vehicle electrical parameters overview on 8th August 2018, Top left: total active power (P), Top right: total voltage and current at L1, Middle left: total distortion of voltage (TDU) and voltage (V) at L1, Middle right: fundamental frequency current (I_1) and total distortion of current (TDI), Bottom left: fundamental frequency power (P_1), Bottom right: fundamental frequency voltage (V_1) and current (I_1) at L1*

Depending upon the battery system installed in the car magnitude and pattern of power charging varies for different cars. From Fig. 16 it can be observed that only L1 was involved for the first instance of charging and all three phases were involved for the later charging load. The second charging load was larger as shown in the figure compared to first one. There was a spike in TDI when the charging was started but as charging goes on TDI settles at 5% and TDU remains within limits of SFS-EN50160 [44].

4.4.6 Photovoltaic power plant

Figure 3 shows main electricity distribution of the building. PV power plant is primarily used for power generation for ventilation units. There is no battery storage system, so power generated by PV plant is fed directly to electrical system of the building [17]. The nominal power of the PV plant is 57 kW whereas the maximum measured power was 52 kW. When generating power close to nominal power PV plant provides power for the whole ventilation units and in some cases even for the whole service electricity. The point of common coupling (PCC) where three phase inverters of PV plant operate is located at the top of the building whereas the main distribution room is at the bottom floor [18]. The displacement power factors of the inverters are 1 p.u [18].

Fig. 17 and 18 represent the operation of PV plant on a cloudy and sunny day, respectively. The effect of PV generation was visible when ventilation parameters were analyzed in Fig. 10. From the figures we can see that active power flows towards the load i.e. ventilation units and even though the current is flowing towards the loads it is positive, whereas in conventional metering it would be negative.

It is visible in Fig. 17 that power generated on the cloudy day was less as PV generation depends on irradiance. Just hour before the noon the PV generation was maximum whereas until 6:00 AM it was 0 and it also stops generating after 21:00. During the midday, as power generation increases the magnitude of current increases which leads to mor distortion current but TDI decreases as it is visible in Fig. 17. Total distortion voltage is higher than 3.5 % during the middle of the day. In Finland as there are very few clear sunny days so the operation of PV generation is most of the time fluctuating as visible in Fig. 18, which shows the PV plant behavior on a sunny day, where there were numerous fluctuations in active power generation. The reason was because of the clouds that cover the sun occasionally during the day reducing the irradiance which in turn reduces power generation. It is visible that power generated can be dropped close to 0 within minutes and these fluctuations occurred more from noon to 18:00.

From Fig. 18 it is visible that TDI is minimum when PV plant is operating near nominal power, but magnitude of distortion current is higher as the magnitude of fundamental frequency current increases. There is a peak in TDI when PV plant starts generation and when it stops. Here again the voltage distortion TDU goes above 3.5%. Voltage distortion remains below 3.5% at main distribution board.

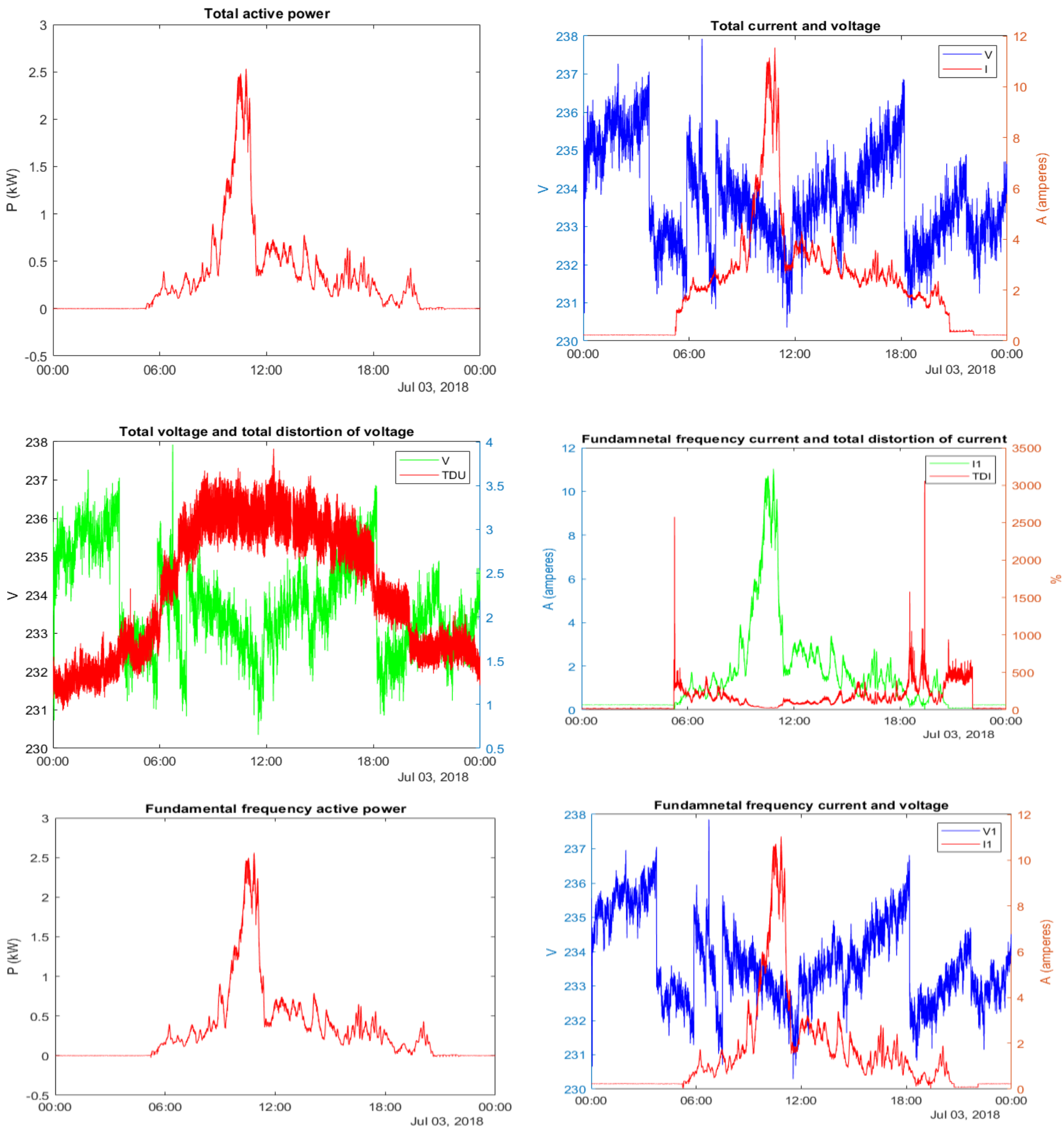

Figure 17. *PV plant parameters overview on 3rd July 2018, PV plant parameters overview on 3rd July 2018. Top left: total active power (P), Top right: total voltage and current at L1, Middle left: total distortion of voltage (TDU) and voltage (V) at L1, Middle right: fundamental frequency current (I_1) and total distortion of current (TDI), Bottom left: fundamental frequency power (P_1), Bottom right: fundamental frequency voltage (V_1) and current (I_1) at L1*

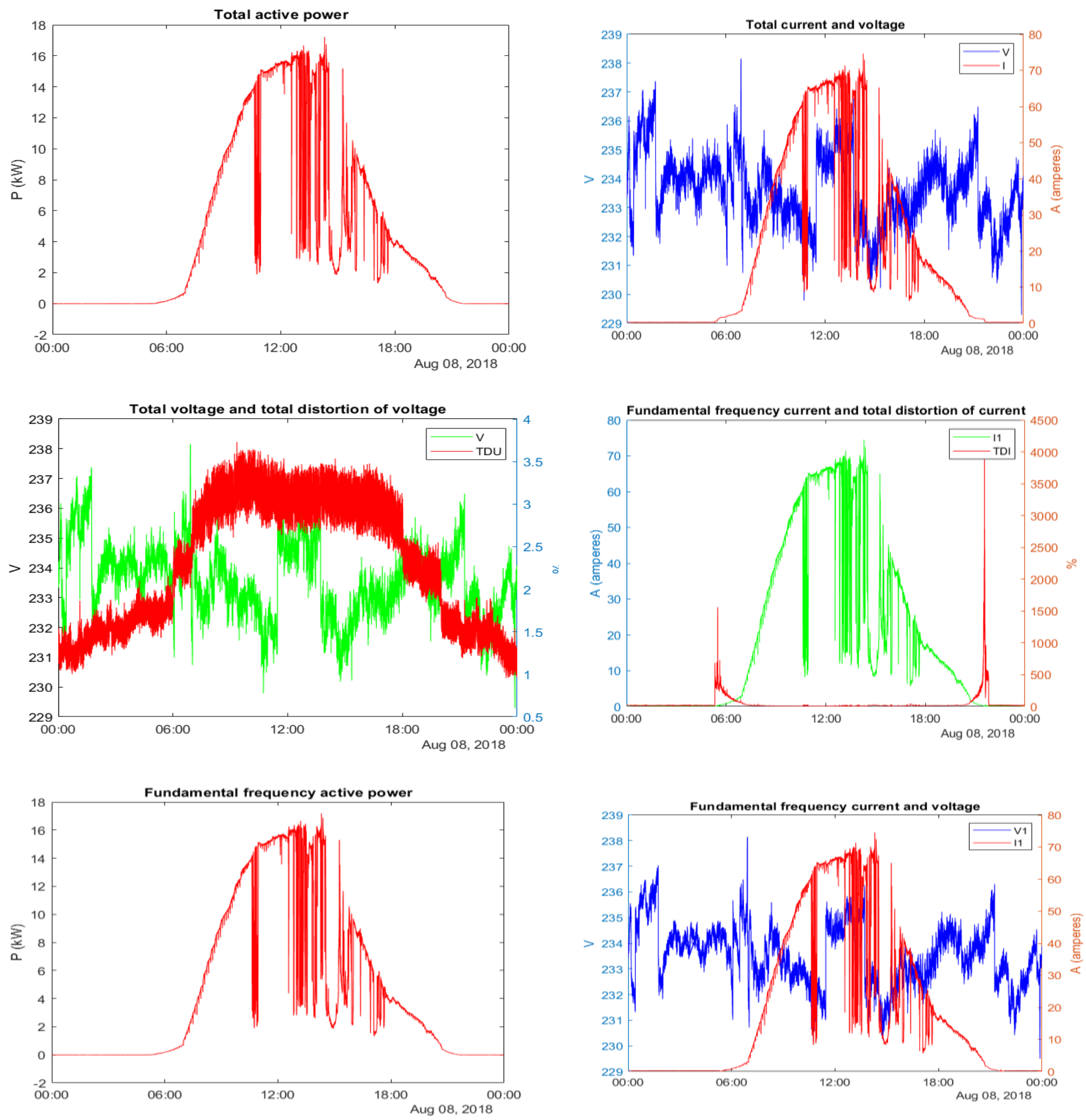

Figure 18. *PV plant electrical parameters overview on 8th August 2018, Top left: total active power (P), Top right: total voltage and current at L1, Middle left: total distortion of voltage (TDU) and voltage (V) at L1, Middle right: fundamental frequency current (I_1) and total distortion of current (TDI), Bottom left: fundamental frequency power (P_1), Bottom right: fundamental frequency voltage (V_1) and current (I_1) at L1*

4.4.7 Tenants' electricity

Tenants' electricity is the appliances and lightings of tenants in the building and is supplied by one of the two main distribution boards. In the pilot building there are offices of companies, restaurants and a library and they are included in tenants.

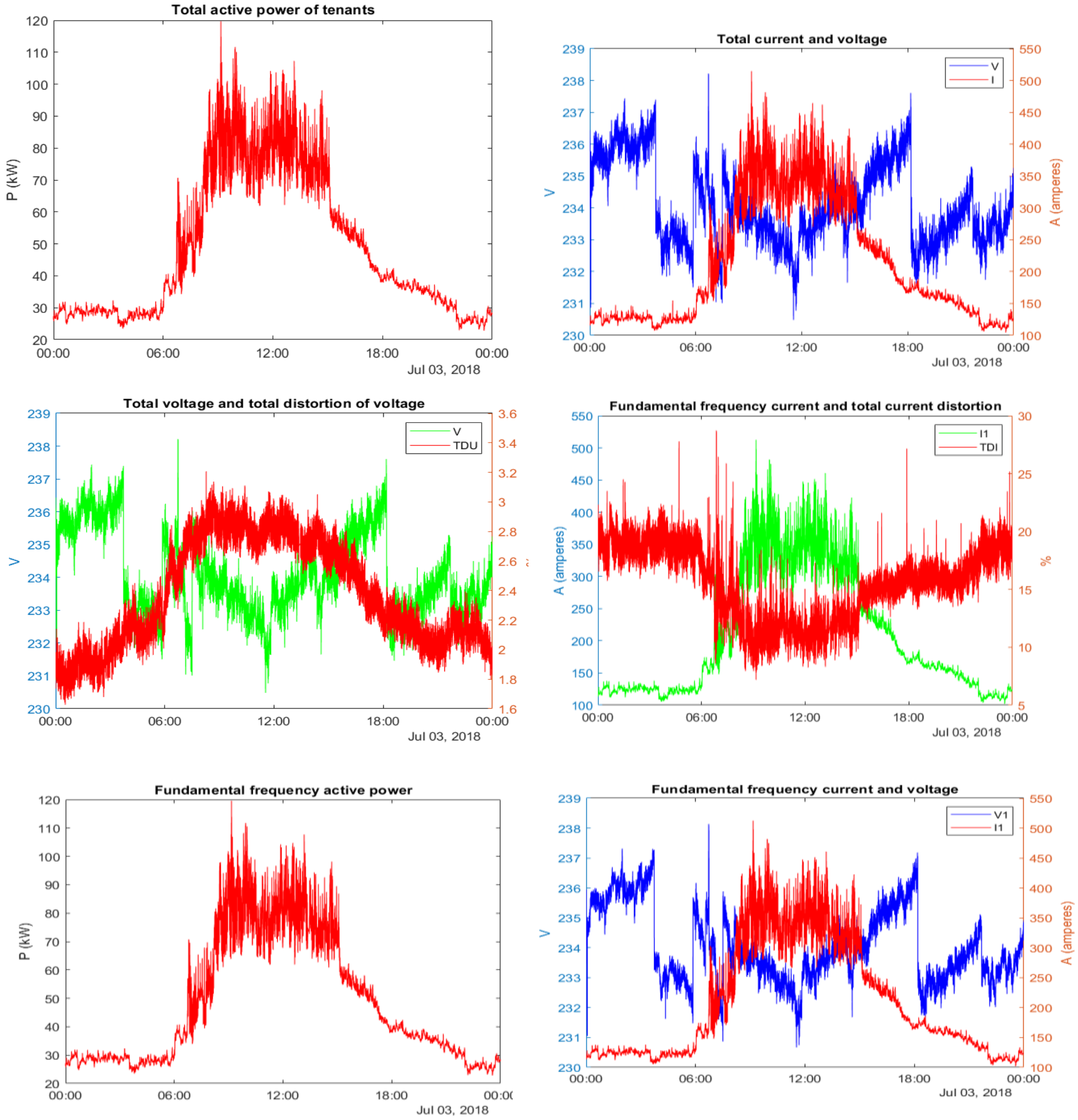

Figure 19. *Tenants electrical parameters overview on 3rd July 2018, Tenants' electrical parameters overview on 3rd July 2018. Top left: total active power (P), Top right: total voltage and current at L1, Middle left: total distortion voltage (TDU) and voltage (V) at L1, Middle right: fundamental frequency current (I_1) and total distortion current (TDI), Bottom left: fundamental frequency power (P_1), Bottom right: fundamental frequency voltage (V_1) and current (I_1) at L1.*

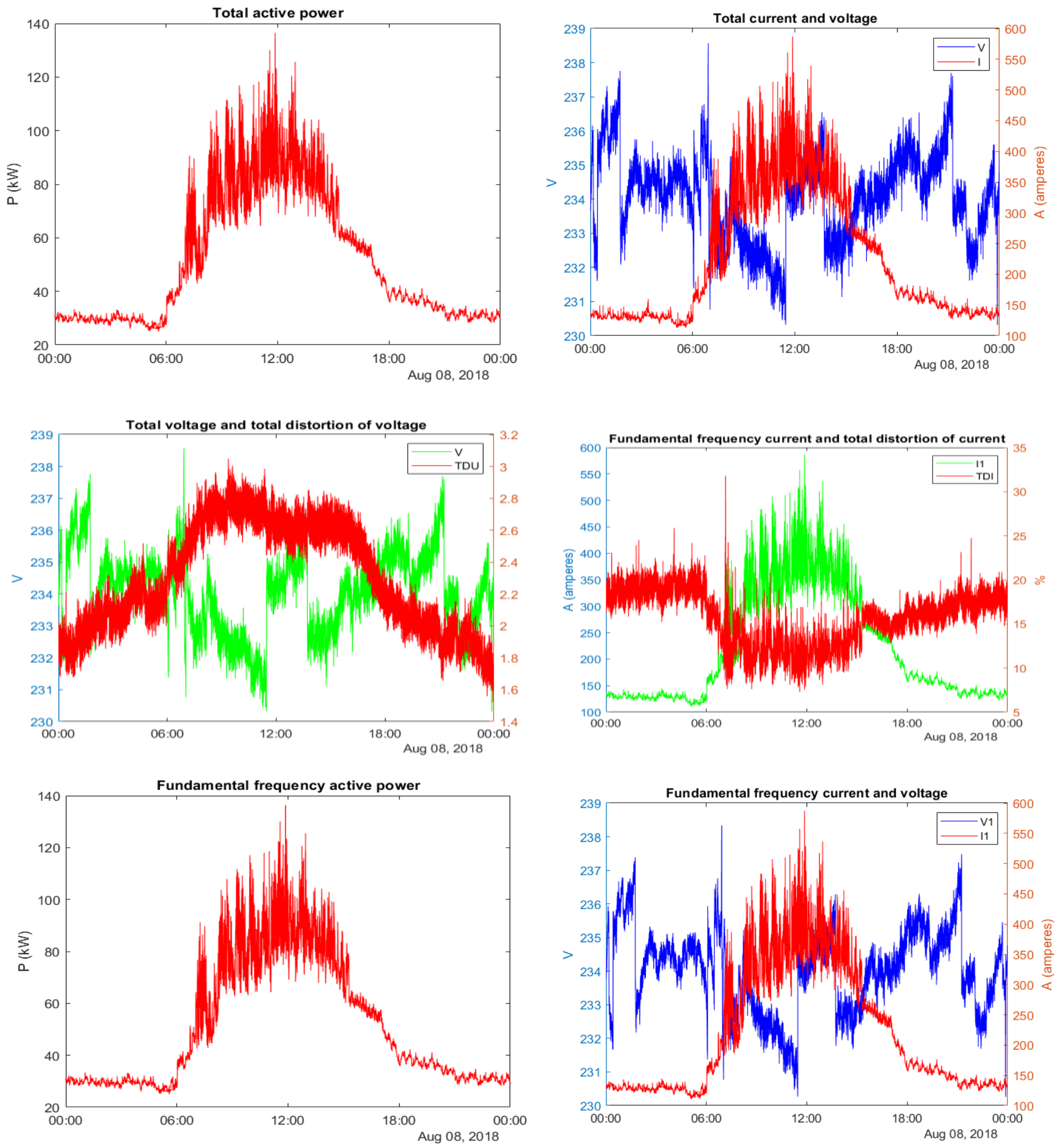

Figure 20. *Tenants electrical parameters overview on 8th August 2018, Top left: total active power (P), Top right: total voltage and current at L1, Middle left: total distortion of voltage (TDU) and voltage (V) at L1, Middle right: fundamental frequency current (I_1) and total distortion of current (TDI), Bottom left: fundamental frequency power (P_1), Bottom right: fundamental frequency voltage (V_1) and current (I_1) at L1.*

Fig. 19 represents the electrical behavior on July 3rd that was a cloudy day and Fig. 20 represents the behavior on July 25th that was a sunny day. Maximum active power at L1 goes to 140 kW. Majority of active power of the building is used by tenants. Fig. 19 shows electrical network behavior of tenants' electricity on a cloudy day. It shows that in the middle of the day when active power consumption is high percentage of distortion current and voltage is less, and we can see the variations in power created by larger appliances of tenants during daytime. The graph between total distortion of current and fundamental frequency current shows inverse behavior but it must be noted that absolute distortion current rises during the day. Voltage distortion remains within the limits of SFS-EN 50160 which is 8% [35]. It should be noted that there is only one measurement point with aggregation of different types of loads, so effects of individual loads on electrical network of pilot building is not clear.

There is no reactive power compensation installed in the main distribution board of the building and it is assumed that loads like lighting and individual loads like ovens and dishwashers effect network electrical behavior [18]. Fig. 20 shows network behavior on a sunny day. Power consumption is more on this day as peak power is higher on this day as compared to cloudy day. As power consumption is more on sunny day the percentage of distortion current is high, but voltage distortion remains within the limits.

4.5 Active power analysis

The use of power electronic devices in electrical power system is significantly increased in the past decade along with the concern related to power quality. In Finland, for small customers in LV network active power is only used for billing purposes and in power tariffs. As active power consists of fundamental frequency active power and active power at harmonic and inter-harmonic frequencies as defined in IEEE Std 1459 [21]. It must be noted that only active power at fundamental frequency performs the actual work as because the appliances used everywhere in the world operate at 50 Hz or 60 Hz frequency which is the value of fundamental frequency. But for billing purposes customer is paying the price of active power that was not even utilized [8 ,21].

Active power of the building network is majorly affected by PV plant, ventilation, and cooling units. Elevators are the most rapidly fluctuating in active power when in time domain. Fig. 21 and 22 shows the difference between total active power and fundamental frequency active power on a cloudy and sunny day, respectively in 1 second time interval. It can be observed that at some instances the difference is negative which means that total active power was less than fundamental frequency active power.

As total active power is used for billing purposes this means that utility was getting less money as compared to the active power it was giving to the customer. The negative and the positive difference at different intervals shows that loads absorbs power at some point and generate active power at other points and this phenomenon increases as power consumption increases.

If we look at service electricity in Fig. 21, we see repetitive negative and positive peaks. These peaks are because that the compressors of cooling units were continuously turning on and turning off on during that day. In Fig. 21 most of the time when power consumption was high the difference was negative which means that fundamental frequency power is high as compared to total active power. As the electricity bill of small customers depends on total active power shorter imbalance settlement period (ISP) and power tariffs will affect the cost of electricity both for customers and for utilities. For example, in power tariff if the consumption of fundamental frequency active power is less as compared total active power by a customer, the customer will be paying more than the actual active power he is consuming and if the opposite is taking place than utilities are getting less money than they are actually providing.

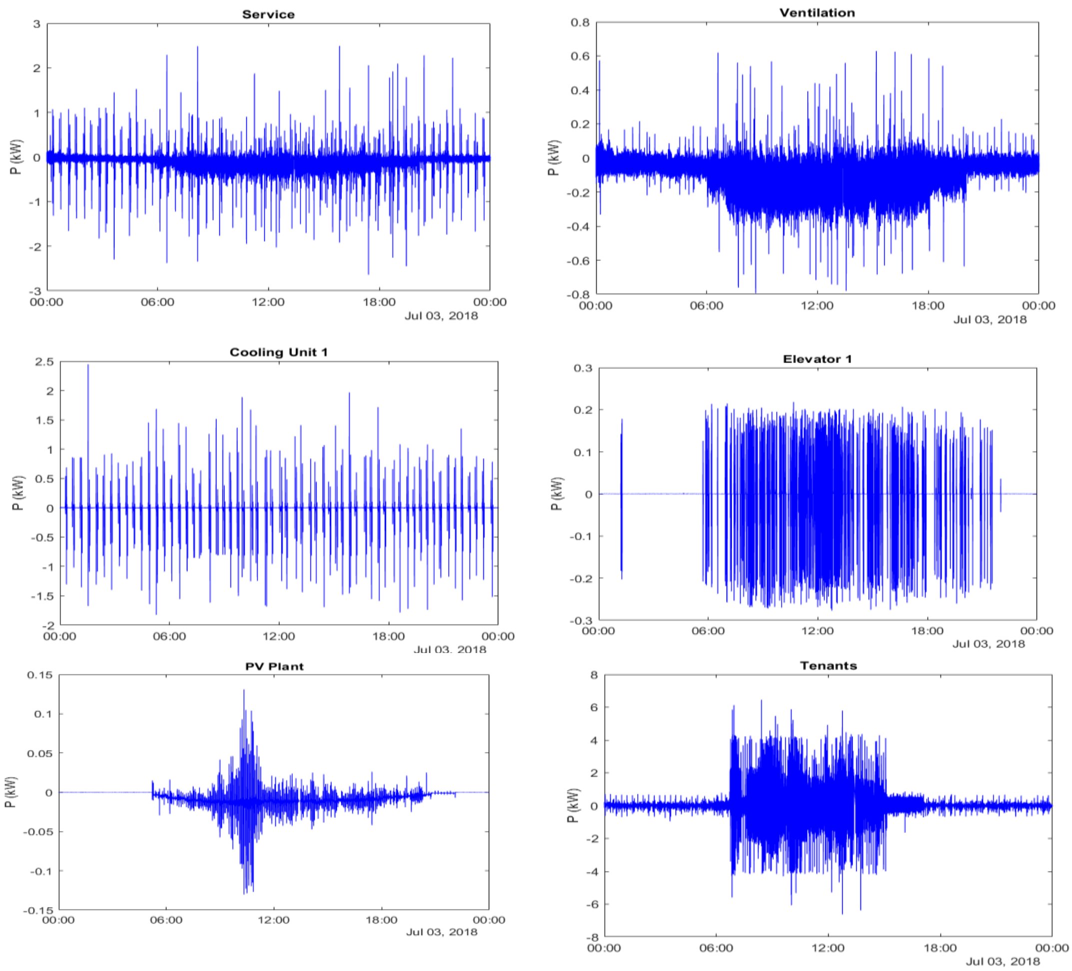

Figure 21. *Difference between fundamental frequency power and total active power of building loads on 3rd July 2018 in 1s time interval of phase L1.*

Fig. 22 shows the difference of fundamental frequency active power and total active power on a sunny day. The operation of solar power plant has great influence on the difference between fundamental and total active power as visible in the figure. If we compare the graphs of cooling units on sunny and cloudy day, we see a clear difference of how they behave as the environmental conditions change. On sunny day cooling units were in operation for majority of the day which means that compressors were running for major part of the day. There are less spikes on August 8th and for major part of the day the difference remains close to 0 as compared to July 3rd. On sunny day PV plant is generating more power and ventilation units are fed by the PV plants, the difference between the fundamental frequency active power and total active power is significantly higher as compared to July 3rd. One of the reasons for this behavior is maybe because the power generation of PV plant drops significantly as the irradiance decreases because of the clouds covering the sun during the day as this behavior is visible in Fig. 18. For PV plant as the irradiance changes frequently on August 8th the difference between fundamental frequency power and total active power is higher for majority of the day on August 8th compared to July 3rd. For elevators and tenants the behavior is almost similar on both days as visible in Fig. 21 and 22 but the difference between the fundamental frequency power and total active power is significantly higher on August 8th. This means the harmonic active power generated on Aug 8th is more as compared to July 3rd. The effect of solar power generation is visible on sunny day as it fluctuates because of changing irradiance creating more harmonics in the network. When we look in the graph of ventilation units on cloudy and sunny day, we find the difference is more on sunny day as compared to cloudy day thereby proving that the harmonics generated on sunny day are more.

Power consumption on sunny day was more as compared to cloudy day as we can see from Fig. 21 and Fig. 22 when power consumption increased difference between total active power and harmonic active power increased**.** Fig. 23 and 24 shows the difference of active power in phase L2 on sunny and cloudy day whereas Fig. 25 and 26 represents the difference of power on phase L3. If we analyze the difference between total active power and fundamental frequency active power, we see the same pattern in all phases, but the difference between the total active power and fundamental frequency active power is not same at each phase at a particular instant for most of the day. If we look at the difference of active power at each phase for ventilation, we see the difference clearly. For phase L2 the maximum difference between the fundamental active power and total active power was below 400 watts throughout the day whereas for phase L3 it goes above 400 watts. Similar behavior was observed for other loads. The reason is because a real network is in balanced condition rarely and the loading on each phase is different at the same time, which means the difference of active power will be different in each phase as observed in the figures.

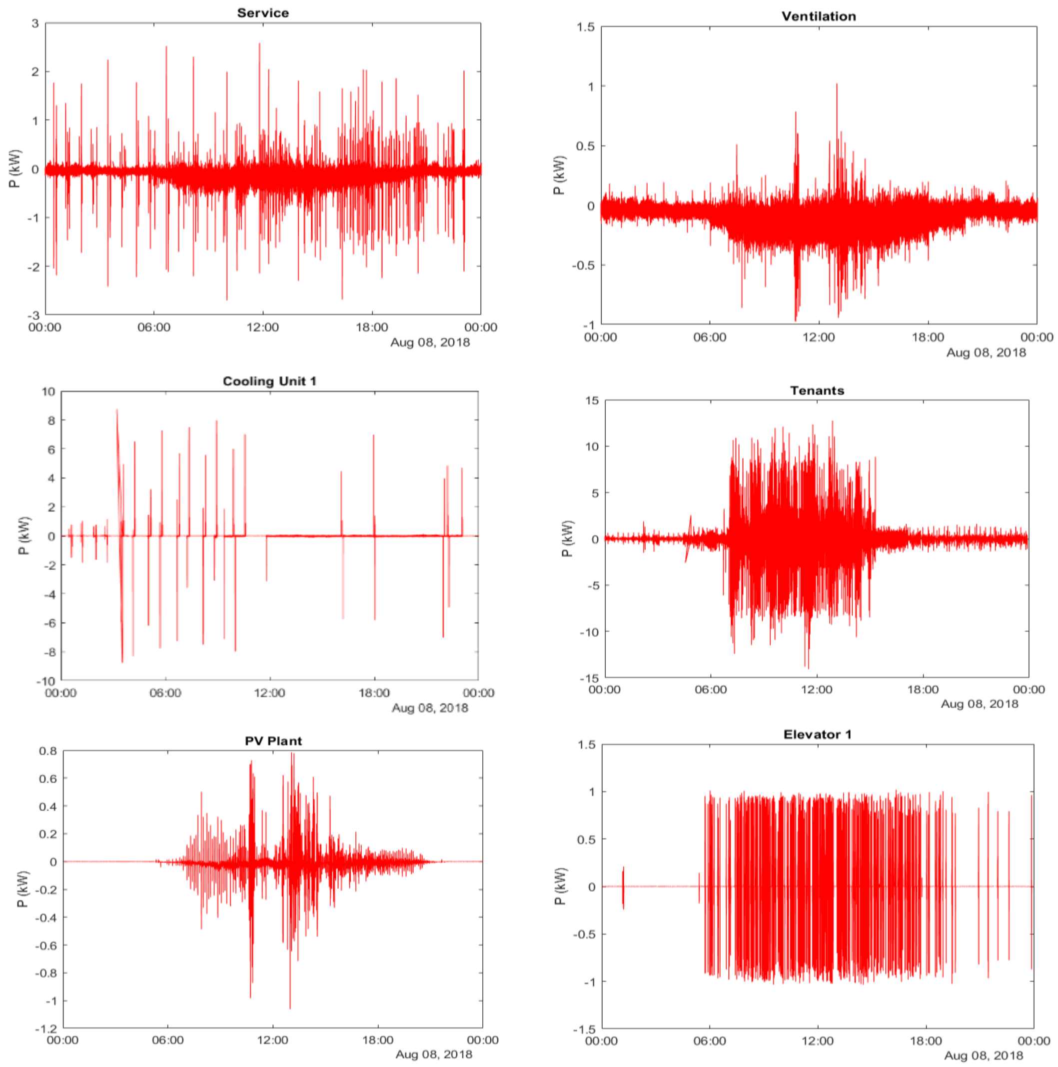

Figure 22. *Difference between fundamental frequency power and total active power of building loads on 8th August 2018 in 1s time interval of phase L1.*

Fig. 27 and 28 shows the difference between total active power and fundamental frequency active power in 1-minute time interval at phase 1. When comparing 1-second time interval with 1-minute time interval it is visible that if the time resolution is less, we can get more clear information about the difference in total active power and fundamental frequency active power. If we take a look in the difference of power in four big loads of the building's electrical network we find out that during 1 second time interval there are instances where the difference between the total active power and fundamental frequency active power becomes very large. If we look at the difference of power for tenants electricity on July 3rd both in 1-second and 1-minute time intervals we can see that there are instances in 1-second interval where the difference goes to above 6000 watts where as if we look in 1-minute time interval the maximum difference is slightly above 4000 watts. On August 8th if we again look at the difference of power in tenants in 1-second interval the power difference goes to around 12000 watts whereas maximum difference in 1-minute time interval at tenants is around 9000 watts. By looking power difference at different time intervals, we can get an idea that if time resolution is small, we can get clearer picture how much the harmonic power is present in the loads of the building. The main purpose to quantify the difference in total active power and fundamental frequency active power is that difference may yield a cost for network customers. If total active power is less as compared to fundamental frequency active power and customer is paying for total active power, this means the utility is billing the customer less for their energy use. This situation requires proper practices to look at the causes of this difference in power.

It is to be noted here that Laatuvahti 3 accuracy is class 1, for active energy so this means that in low load conditions and poor power factor there will be errors in the readings. There are noises at some instances that maybe caused by A/D converters or even changing behavior of loads.

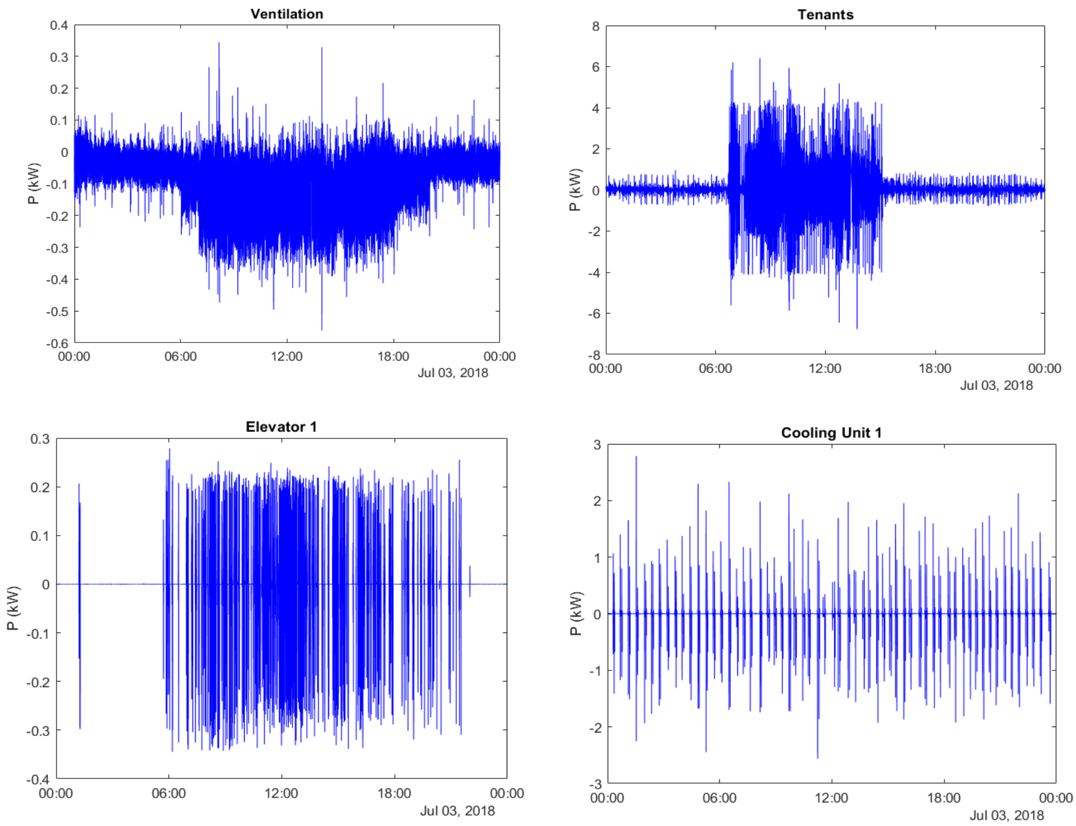

Figure 23. *Difference between fundamental frequency power and total active power of building loads on 3rd July 2018 in 1s time interval of phase L2.*

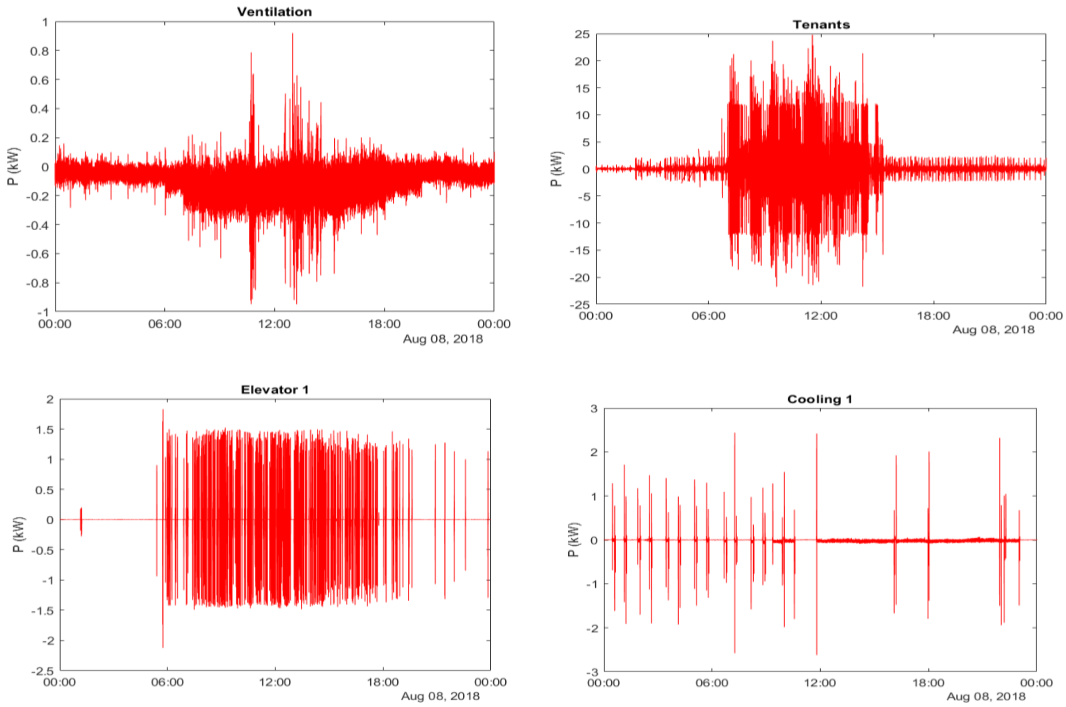

Figure 24. *Difference between fundamental frequency power and total active power of building loads on 8th August 2018 in 1s time interval of phase L2.*

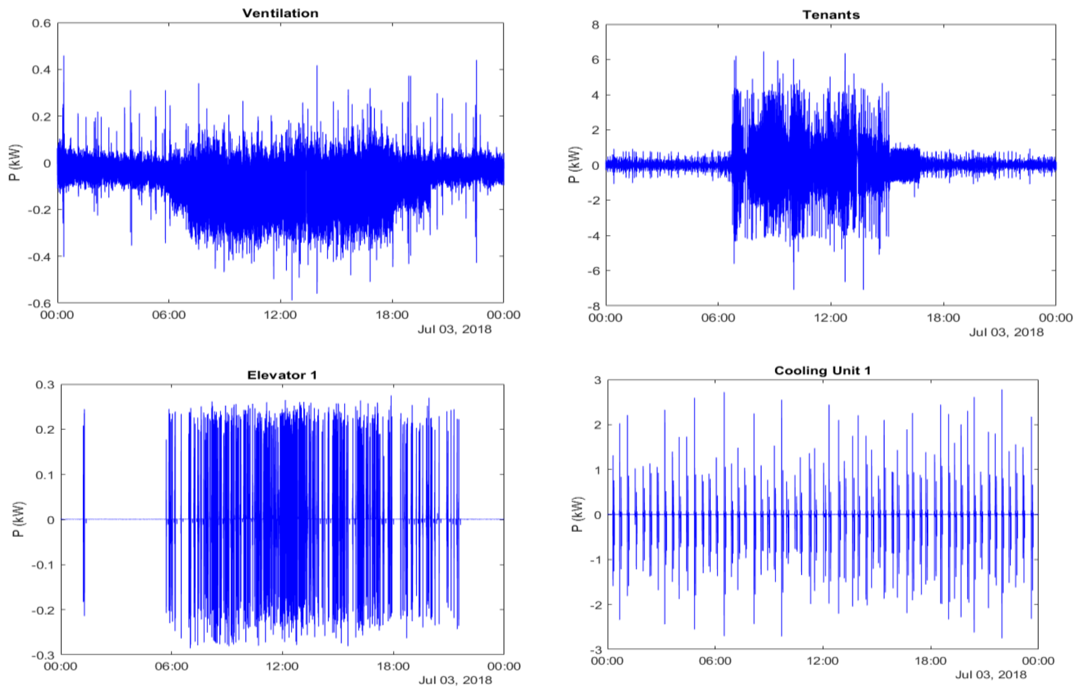

Figure 25. *Difference between fundamental frequency power and total active power of building loads on 3rd July 2018 in 1s time interval of phase L3.*

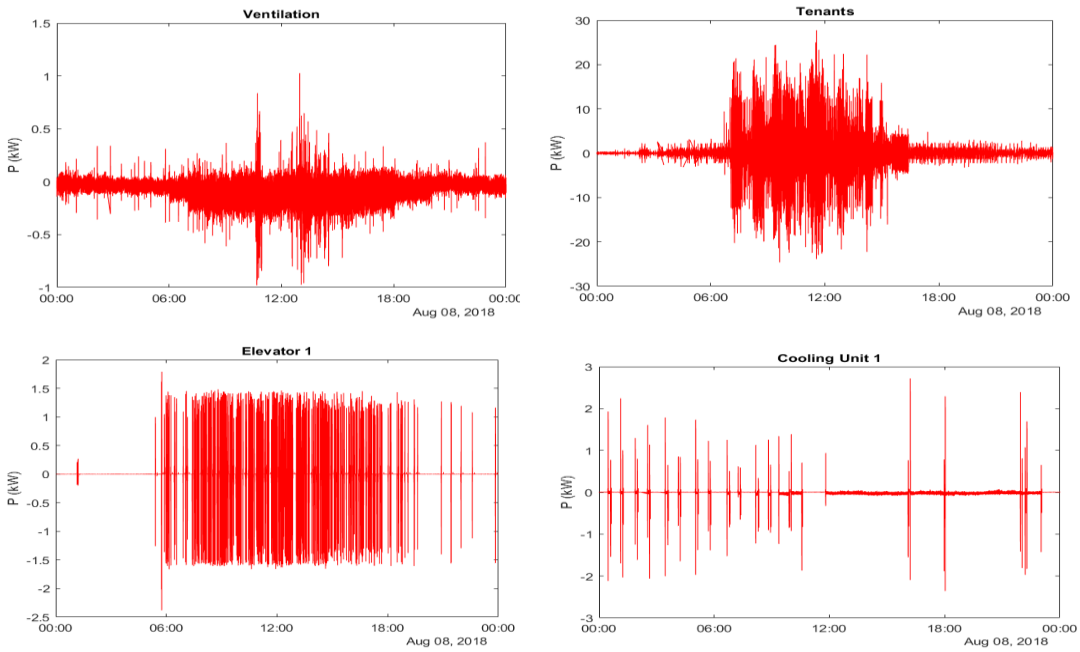

Figure 26. *Difference between fundamental frequency power and total active power of building loads on 8th August 2018 in 1s time interval of phase L3.*

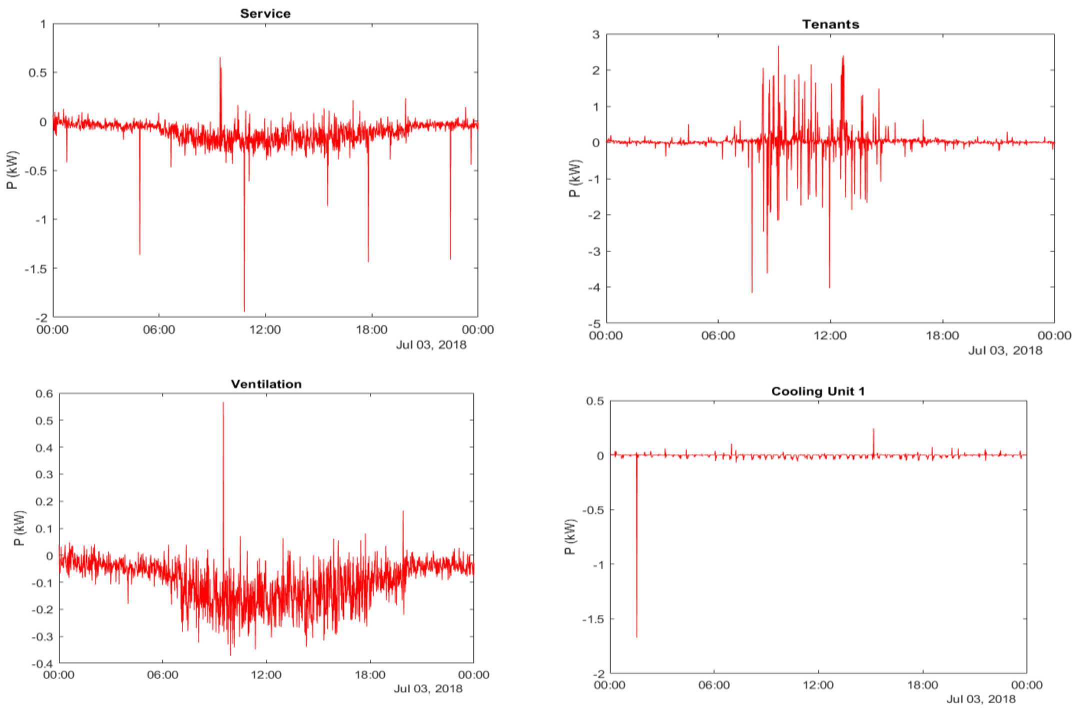

Figure 27. *Difference between fundamental frequency power and total active power of building loads on 3rd July 2018 in 1-minute time interval of phase L1.*

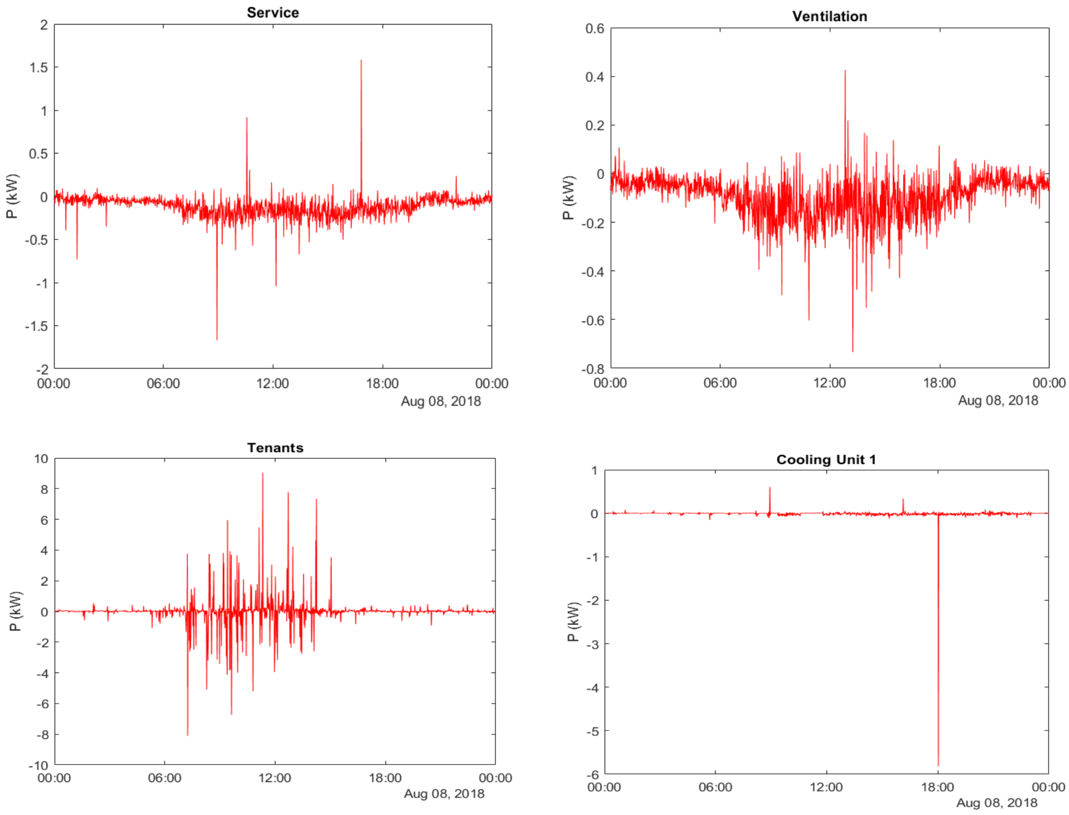

Figure 28. *Difference between fundamental frequency power and total active power of building loads on 8th August 2018 in 1-minute time interval of phase L1.*

4.6 Distortion current sources

In this section we will investigate distortion current measurements of building loads and find out the distortion current sources. In terms of power quality, the importance of looking into current distortion has increased and the measurement values are still valuated. It is hard to find voltage distortion source, but current distortion source can be measured easily. Distortion current can be measured easily of an appliance, but the source of voltage distortion is hard to locate. It may be caused by distortion in current at measurement point or maybe due to background distortion in distribution network. The background distortion voltage can increase the distortion current when it interacts with the dynamics of the appliance. In this section we will compare total distortion current of network loads and PV plant with each other.

Fig. 29 and 30 shows the distortion current and fundamental frequency current of building loads. The measurement data presented in the Fig. 29 and 30 are of 3rd July 2018 for tenants, elevators, ventilation. The distortion current of every building loads except tenants are aggregated at service electricity main distribution board. If we look in Fig. 29, we see that cooling units and elevators show high total distortion of current and ventilation unit has more total distortion of current than tenants. Distortion in ventilation may result from different power electronic converters used, for example for rectification purposes.

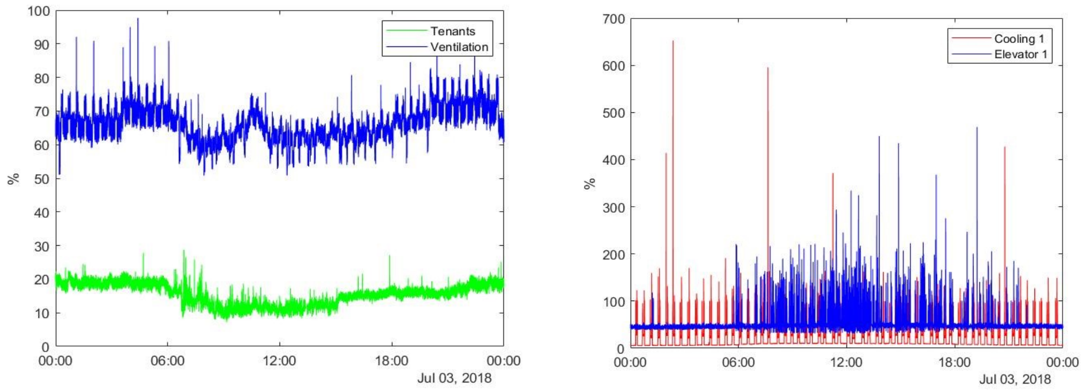

Figure 29. *Total distortion of current of loads of the building.*

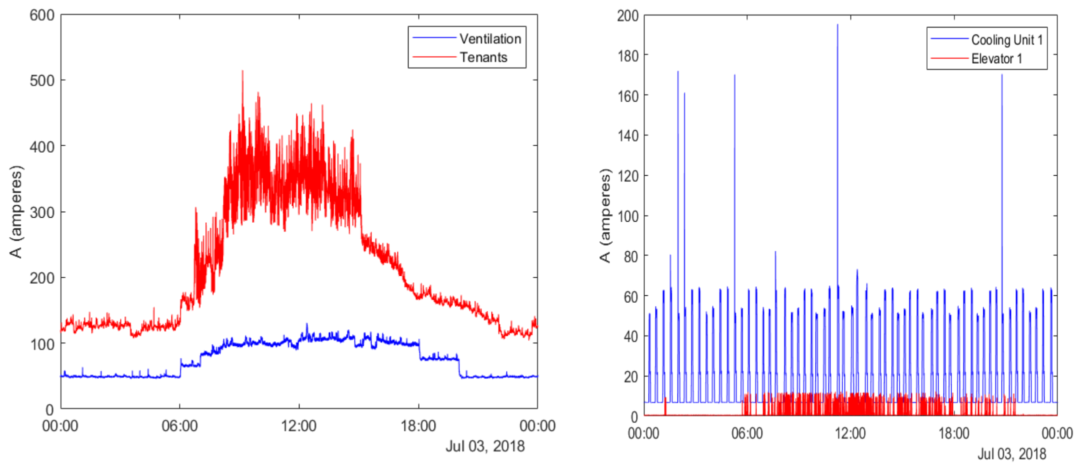

Figure 30. *Fundamental frequency current of the building loads.*

When we looked at the magnitude of distortion current it increases with the increase of fundamental frequency current. Fig. 30 shows fundamental frequency current that is responsible for providing actual energy. Tenants draw the most amount of current but when we compare Fig. 29 and 30, we see that total distortion of current in ventilation is high as compared to tenants.

Distortion current at service point of main distribution board greatly depends on the load conditions and the appliances installed. Also, cancelling of distortion currents may occur up to some extent as it is mentioned in Meyer studies for lighting devices [24]. The causes of voltage distortion are hard to find and certain methods are available to identify voltage distortion sources, however the focus of this thesis is to investigate the total active power and fundamental frequency active power.

In future the practices to measure power quality will greatly depend on standards, DSOs, legislation, and future development in measurement technology. The manufacturers use certain standards for quantification of electric power (active and reactive), for example, IEEE Std 1459 [21]. Even though after using these standards certain inaccuracies may occur while measurement from inaccurate current transformers or other instruments used in the measurements. These false measurements may affect the billing of critical loads of a building. The study done in this thesis may encourage for deeper look into theories of electrical power and their application with the advancement of modern distribution networks.

4.7 Energy difference

In this section we will see the effect of harmonic active power on total energy consumption of the building on both cloudy and sunny day. Table 3 and 4 shows the percentage difference of energy caused by the difference in fundamental active power and total active power at the two main distribution boards service, and tenants. The difference is calculated by first calculating the difference between two consecutive time intervals and multiplying it with the active power consumed during this time interval. This process was repeated for the whole day of 3rd July and 8th August for fundamental frequency power and total active power. After this the energy of the whole day was calculated by summing all the energy consumed in these time intervals. After getting the energy for the whole day by using fundamental frequency active power and total active power the percentage difference for each phase was found at two main distribution boards. This energy difference is the difference on energy caused by the difference of fundamental frequency active power and total active power.

From the table it is also visible that difference in each has different value because a real electrical network is always in an unbalanced state that means the loading on each phase is different. That is why the difference on each phase has different value. In case of tenants total active energy was more than fundamental frequency energy and the difference was very small but in case of service electricity the fundamental frequency active energy was more, and the difference was large as compared to tenants.

Table 1. *Percentage difference between total energy and fundamental frequency energy of tenants electricity*

Date	Phase	Difference (%)
3rd July 2018	1	-0.0376
3rd July 2018	2	-0.0675
3rd July 2018	3	-0.0633
8th Aug 2018	1	-0.0295
8th Aug 2018	2	-0.0496
8th Aug 2018	3	-0.0630

Table 2. *Percentage difference between total energy and fundamental frequency energy of service electricity*

Date	Phase	Difference (%)
3rd July 2018	1	0.5111
3rd July 2018	2	0.6261
3rd July 2018	3	0.4723
8th Aug 2018	1	0.3892
8th Aug 2018	2	0.4731
8th Aug 2018	3	0.3566

If only total active power is utilized for billing purposes than this means that tenants are paying more to utilities than the actual power they are consuming, and service is paying less than their actual energy usage. It must be noted inaccuracies in measuring devices can also cause this difference so in this studied case it can be neglected. The thesis was limited to building with diverse load. In case of large electrical networks such as an industrial load with high contents of harmonics the difference may become higher, and it will have a more economic effect both for the customer and utilities.

5. CONCLUSION

In this thesis the measurement data is collected by the ICT system of pilot building which is then being utilized to study building's behavior and to analyze the difference between total active power and fundamental frequency active power. The difference in power is then utilized to calculate the energy difference it has caused on the two main distribution boards of the building.

Power quality concerns have increased with the increase in voltage and current distortion as the use of non-linear devices, like power electronic devices has increased over the years due to increase in distributed energy generation and non-linear loads. With the introduction of demand response and evolving electricity markets and new energy tariffs the flow of power in electricity is quite different from conventional electrical networks. The distortion in the network can be measured which is then compared with the fundamental frequency component to get the idea about the power quality of a network. The voltage distortion source is difficult to find, especially on customer side due to the background voltage distortion and its interaction with the devices but finding the source of current distortion not that difficult.

Over the years many power standards have been developed to quantify the power distortion, IEEE Std 1459 being one [21]. The total active power and fundamental frequency active power can be quantified using this standard. With the advancement of the technology it has become easier to implement the standards like IEEE Std 1459, however the distorted conditions may result in varying measurements which may result in inaccurate billing. The measurement of electrical network of the building studied in this thesis consists of diverse loads at two main distribution boards, service, and tenants.

The behavior of electrical network of the building is studied using total active power and fundamental frequency active power, current and voltage in addition total distortion of voltage and current. Measurements of two different days are utilized to include the effect of the PV plant. Measurements are in 1-second time interval to include the effect of short time- period operation of cooling units and elevators. Due to electrical network stiffness voltage distortion was found similar across the measurement points but during working hours the voltage distortion increases.

The difference between the total and fundamental frequency active power was analyzed in 1-second and 1-minute time interval of each building load. It was observed that as the power consumption increases during the day the difference increases. As the power consumption by tenants was the highest, it has the highest difference between total and fundamental frequency active power. When the difference was observed in 1-minute time interval it was observed that the difference gets smaller. The reason for this was that during 1-minute time there were instances when the power difference was very large and those instances are obscured by the long averaging time in 1-minute data but we can clearly observe them in 1-second time interval data.

The source of distortion current can be found by looking into the values of total current distortion and it was observed that ventilation and tenants were the major sources of distortion. As the magnitude of fundamental frequency current increases the current distortion increases. Power electronics converters and rectifier diodes are the main reason for distortion current in ventilation. Tenants' devices include like lighting equipment and the appliances used by offices and restaurants, for example dishwashers, laptops. In this thesis analysis of single phase of data over a day was done.

As discussed earlier that for billing purposes total active power is used but if only fundamental active power is utilized for billing the customers who produce harmonics their billing will increase and for customers that absorb harmonics their billing will reduce as demonstrated in harmonic impact project (HIP) [5]. In this thesis the energy difference that was observed greatly depends on the type of load. In service electricity for example, ventilation utilize relatively high power non-linear devices which maybe the reason why the difference of energy is higher at distribution board of service electricity is higher than distribution board of tenants electricity. The value of energy difference in case of tenants is very small and it can be deduced by observing this that this difference maybe due to inaccuracies in measurement devices. It must be noted here that in this thesis the energy differences of a single building with diverse loads was observed. The results can be different for a large industrial load with high concentration of non-linear devices. The results also indicate that some loads are harmonic absorbers, and some are harmonic producers. To reduce the harmonics in the electrical network generated by customer loads, utilities may develop a program to provide incentives to those customers that are harmonic absorbers and can give penalty to those who produce high percentage of harmonics. This would be beneficial in improving the power quality of the electrical network.

The thesis promotes the idea to further research in relation to power quality measurements aspects and their analysis by also including environmental effects like weather conditions. In future the analysis of measured data may include measurements of 3-phases from pilot building over a year period. Measured quantities from the network may be utilized in future to calculate various other quantities like, finding voltage distortion origins. As the concept of smart grids is now becoming a realization the importance of quantifying the harmonics will increase further.

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