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Impact of Voltage Variation on Domestic and Commercial Loads

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Abstract

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This Thesis studies the impact of variations in supply voltage on various loads representing different types of loads. The scope of Thesis is analysis of active and reactive power used by appliances at different supply voltages varying from 90% up to 110% of rated value, as well as other factors that these variations influence. Previous studies showed that power consumption of certain device varies with changing of supply voltage, but most of them were dealing with 120V networks, and the other ones are outdated. This study provides ZIP models (polynomial of 2^{nd} power with coefficients Z, I and P standing for constant impedance, current and power correspondingly) for typical house appliances, also results of induction motor heating test and analysis of typical household appliances mix. Results show, which of appliances can withstand voltage variations better, as well as give an idea what is power-voltage curve of the household and what is the percentage of economical losses. Also studies show that almost every device is able to maintain its operation during critical voltage deviations of ±10% Using that data, it is possible to optimize energy usage and decrease losses. The results encourage continuing further investigation of devices with higher power and show the necessity of dynamic seasonal household model.

Keywords: Active power, Voltage variation, Measurement, ZIP model, Life expectancy, Temperature, Appliances

Table of contents

List of figures

List of tables

Symbols and abbreviations

Symbols:

D – Power frequency damping factor

LE_{pu} – Life expectancy in per unit

P – Active power consumption

P_r – Rated power of the appliance (from nameplate)

Q – Reactive power consumption

V_0 – Network rated voltage

V_1 – Supplied voltage

Δf – Supply voltage frequency deviation

α_f – Exponential model frequency coefficient for active power

β_f – Exponential model frequency coefficient for reactive power

α_v – Exponential model voltage coefficient for active power

β_v – Exponential model voltage coefficient for reactive power

Abbreviations:

AC – Alternating current

CFL – Compact fluorescent lamp

CPU – Central processor unit

DC – Direct current

EM - Electromagnetic

FL – Fluorescent lamp

HDD – Hard disc drive

HID – High-intensity discharge

LCD – Liquid crystal display

LED – Light-emitting diode

PC – Personal computer

RMS – Root mean square

RMSE – Root mean square error

1 INTRODUCTION

As electronic devices are improved and new technologies are used for illumination purposes it is necessary to have the data about their energy consumption at different voltage levels. Voltage quality events, in particular voltage sags, have adverse effects on the electrical equipment and in industrial manufacturing processes. These events and the impacts of voltage quality events are not into scope of this thesis, however detailed information can be found at [20]-[32].

Modern electricity supply standards allow ten percent voltage variation under normal operation, which means that in Finland, supply voltage can be varied between 207V and 253V as it's not considered as fault [1]. Almost every modern device is designed for operation at that voltage band, but manufacturers don't provide any information of how voltage variations influence the performance of the device. For some of them voltage variation has almost no effect, but for others it can cause increased power consumption, negatively affect the performance and shorten the life expectancy.

A common approach in absence of accurate data on load characteristics is assuming pessimistic representation of the load, providing safety margin. A good example is the Tokyo system collapse in 1987 happened due to underestimation of characteristics of AC reactive power consumption. [2]

Only few studies were performed before in order to investigate the behavior of different appliances at varying voltage, and most of them are outdated, thus it is necessary to update the information to make it possible to model economical losses due to voltage variations. That way proper modeling of electrical loads will benefit in increasing of power transfer limits in case of overly-pessimistic results, or preventing the system emergencies in case of overly-optimistic results.

The obtained power-voltage curves will help to classify loads and will also be useful in estimation of economical losses due to voltage variations, as well as in modeling of load groups.

1.1 Target of study

The aim of thesis is to investigate influence of 10% voltage variation on different house and commercial appliances and provide data for estimation of economical losses due to that.

1.2 Scope of study

During the period of study different house and office appliances were tested, their power-voltage curves and ZIP models were obtained. Also dependence of life expectancy on voltage variations was estimated for some of loads.

1.3 Structure of the thesis

The rest of the thesis is structured the following way: in *Chapter 2* the existing modeling techniques are introduced. Exponential and polynomial ZIP models are described and difference between them is explained. *Chapter 3* introduces the laboratory test installation and describes its operation in details. In *Chapter 4* the results of measurements, consisting of power-voltage curves and short comments are presented for each load. Also the table with ZIP coefficients is presented in the end of the chapter. In chapter 5 the response of typical household and office to voltage variations is investigated. Chapter 6 presents the results of fan thermal measurements and its life expectancy model. In addition, the influence of voltage variation on other loads is investigated.

2 SELECTION OF THE APPROACH

2.1 Modeling techniques

Any load can be represented by different types of static models: polynomial (also known as ZIP model) and exponential ones. Each model represents variation of active and reactive power with change of supply voltage.

ZIP model is based on fact that every load can be represented as constant current, power, impedance load, or composition of them represented by the polynomial expression of the nth, usually 2nd order, that looks as follows:

$$P = P_0 \left[a_1 + a_2 \left(\frac{V}{V_0} \right) + a_3 \left(\frac{V}{V_0} \right)^2 \right]$$

$$Q = Q_0 \left[a_4 + a_5 \left(\frac{V}{V_0} \right) + a_6 \left(\frac{V}{V_0} \right)^2 \right]$$

where $a_1 \ldots a_6$ are ZIP coefficients, $a_1+a_2+a_3= a_4+a_5+a_6=1$

V_0 is the rated voltage of the network,

P_0, Q_0 is active and reactive power at V_0;

In order to include the influence of frequency variation the expressions above can be multiplied by frequency correction factor:

$$P = P_0 \left[a_1 + a_2 \left(\frac{V}{V_0} \right) + a_3 \left(\frac{V}{V_0} \right)^2 \right] [1 + D\Delta f]$$

where D is power frequency damping coefficient

Δf is frequency deviation

Exponential model is represented by the following equations

$$P = P_0 \left[\frac{V}{V_0} \right]^{\alpha_v} \left[\frac{f}{f_0} \right]^{\alpha_f}$$

$$Q = Q_0 \left[\frac{V}{V_0} \right]^{\beta_v} \left[\frac{f}{f_0} \right]^{\beta_f}$$

Both models work well for voltages close to rated, however the accuracy of exponential form deteriorates rapidly when voltage significantly exceeds rated value, whereas the accuracy of ZIP model deteriorates when voltage falls significantly below its rated value [3] [4].

Both models possess high accuracy at voltages close to nominal, but since during the literature review most of the data was represented in ZIP form, in order to simplify comparison of results polynomial form was selected for load modeling.

Influence of frequency variation on consumed power is neglected because if the voltage is in the band of ±10%, the change in frequency will be negligibly small [3]

Table 1 – Zip coefficients 2007 [5]

Appliance	S0	PF	Vmin	ZP	IP	PP	ZQ	IQ	PQ
Pump	1424.9	0.99	0.63	5.51	-11.3	6.82	11.77	-24.28	13.51
Fan	210.45	0.69	0.5	0.61	0.42	-0.04	0.83	0.17	0
Elevator	1976.4	0.51	0.85	-2.33	4.95	-1.62	2.50	-3.69	2.18
Escalator	715.2	0.29	0.75	12.58	-26.3	14.67	8.51	-14.21	6.7
Halogen	75.7	1	0.83	0.48	0.57	-0.05	-3.57	0.69	0
Incandescent	60	1	0.87	0.43	0.64	-0.08	0	0	1
Resistive	60	1	0.75	1	0	0	0	0	1
TV, printer	360	1	0.83	1	0	0	0	0	1
Computer	132.5	0.98	0.5	0.27	-0.61	1.34	-0.11	0.02	1.08
Microwave	1309.5	0.99	0.75	0.55	1.86	-1.4	19.74	-31.30	12.56
UPS	6430	0.76	0.77	0.13	-0.14	1.01	-0.62	1.84	-0.22
Magnetic Fluorescent	94.8	0.99	0.76	-5.24	10.71	-4.47	-5.68	12.27	-5.59
Electronic Fluorescent	77.7	0.99	0.5	-7.42	13.97	-5.55	7.42	-10.59	4.18

If scrutinize the literature about ZIP coefficients one can see that they can differ a lot depending on source. For example, in [6] dated 1995 and loads are represented by polynomials, but the sum of coefficients is not equal to unity, so it is unreasonable to compare this model to the latter ones. It is also quite hard to compare coefficients from [5] and [7] (both for 120V rated voltage) because devices with different rated power were tested, although one can see that coefficients differ a lot.

Here follows an example of comparison models for fan from [5] (2007) and [7] (2014)

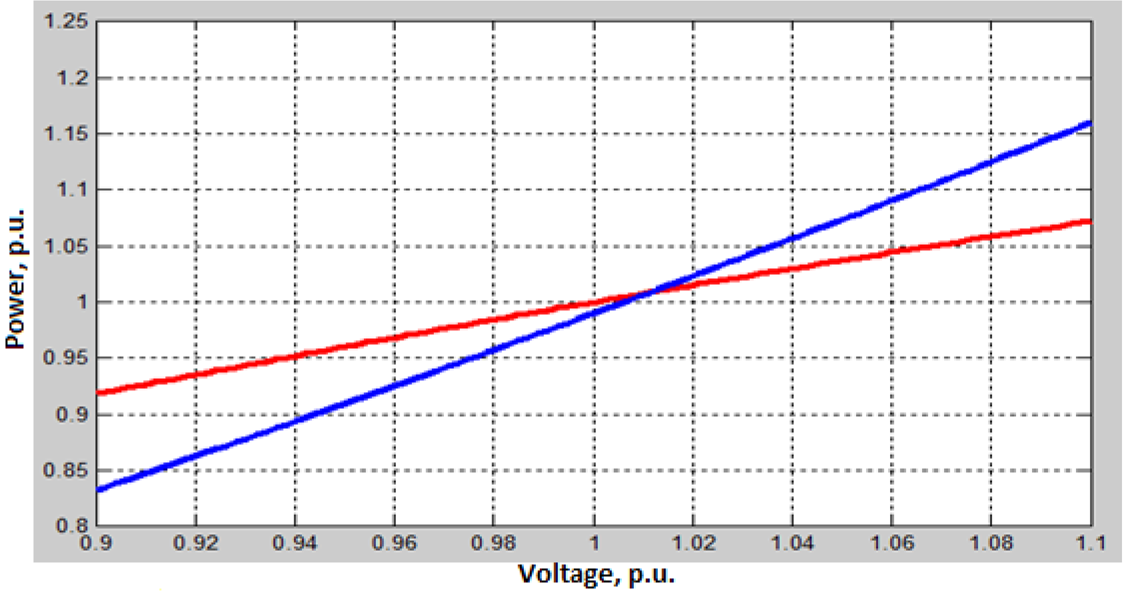


Figure 2.1 - Comparison of fan ZIP models from [5] (red) and [7] (blue)

The figure shows that these two models are very different. Further investigation of coefficients from [8] (1998) showed even more diversity in results.

Unfortunately, the fact that there are not that many models for 220-240V 50Hz systems, proves the necessity of developing one. Also rapid development and integration of electronic devices such as CFLs, LCD TVs, computers and laptops made huge changes to how load behaves now if compare to 10-15 years ago. Moreover, nowadays renewable energy sources are rapidly integrated into grids changing conditions for transmission and distribution networks as well as making difficulties for electricity generation companies to match demand and supply. Creation of refreshed static load models will help to take into account load response while planning smart systems.

2.2 Experimental part

In order to create reasonable model it's necessary to collect the initial data. It is possible to simulate individual appliances, using software, but when it comes to complex devices such as PC, it's much more convenient and simpler to perform tests, measuring dependence of devices' consumed active and reactive power on input (supply) voltage. Hereby a set of points can be obtained and these points can be used for curve fitting in order to obtain empirical formulae describing load's behavior.

In order to create the testing procedure it is necessary to select objects to be tested. List of most common house appliances was created based on easily accessibility and it looks as follows:

- Resistive space heater
- Fan
- Microwave oven
- PC CPU
- PC display
- TV
- Directly supplied induction drive
- Halogen lamp
- Incandescent lamp
- CFL (electronic ballast)
- Fluorescent lamb (EM ballast)
- LED
- HID lamp (metal halide/high pressure sodium/low pressure sodium/mercury vapor)

All the appliances were tested with TOPAZ FLUKE P/Q measurement unit. Advantages of that unit are transportability, internal memory and high sensitivity to transients (even though it's not required during that particular experiment). The major disadvantage is software that doesn't have suitable mechanism for data transfer, has low reliability and periodically returns errors. The procedure is to be described below.

Measurements are to be taken for the voltage range 230V±10% i.e. 207÷253V, the measurement points are 207, 210, 214, 218, 224, 230, 236, 242, 246, 250, 253. Therefore, 11 points will have been obtained, that is sufficient to receive high accuracy during curve fitting.

The measurement is to be performed with FLUKE TOPAS 1760TR measuring unit, where RMS values of active and reactive power are to be taken every 15 seconds during period of 150 seconds for each voltage level. That allows avoiding incorrect measurements during transients and is necessary to obtain higher accuracy of received results. The supply voltage can be taken from the grid that will allow testing the equipment in real life conditions. In that case output voltage can be varied using simple autotransformer.

The next step is the processing of measurement results. ZIP coefficients for different loads will be obtained by fitting 2nd degree polynomial into measured points.

During estimation of actual economical losses that occur due to voltage variations a lot of problems are to be solved

For example, lowering power in heater leads to slower wearing, but also main function of device is not working properly, causing discomfort. On the other hand electronic devices are not that sensitive, current is usually kept more or less within limits, so devices work perfectly at any voltage level, but losses are caused by increased reactive power consumption. That leads to other challenge: evaluation of reactive power cost.

According to HELEN, domestic customers pay only for active power, but industrial ones pay for both: active and reactive [9]. In this Thesis only commercial and domestic loads are investigated, thus reactive power variations are not taken into account as economical losses, but during following years distribution companies may start gathering data about reactive power consumption, because a lot of power electronic devices with low power factor are used.

3 TEST INSTALLATION

3.1 Description of experimental process

The measurement was performed as was planned, although for some devices additional tuning was required.

The measurement circuit looks as follows: The network voltage V_1 is changed using autotransformer (Variac), then the readings of voltage V and consumed current I are taken via FLUKE probes, connected to socket converter and recorded in FLUKE's memory.

The settings file with following configuration was created for the measurement: read 20ms (one period) RMS values every 20 seconds for 3 seconds.

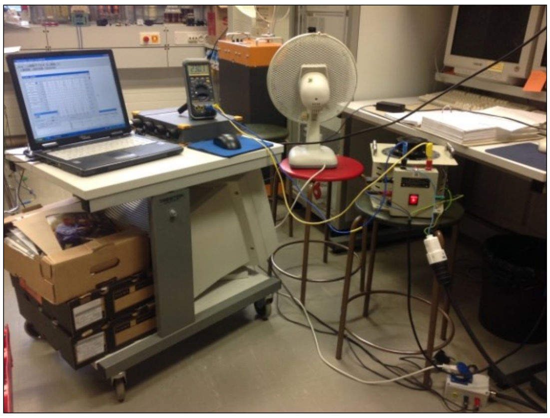


Figure 3.1 – Test installation

For some loads (e.g. microwave) it was necessary to use continuous measurement of RMS values, because only that way it was possible to observe specific operation cycle and obtain reasonable results.

Each voltage level was tested for 5 minutes, which results in around 6.7k values and provides necessary amount of data to reliably take an average for the following curve fitting.

For some devices though it was necessary to enable continuous measurement, because of specific power cycle of device, for example microwave oven.

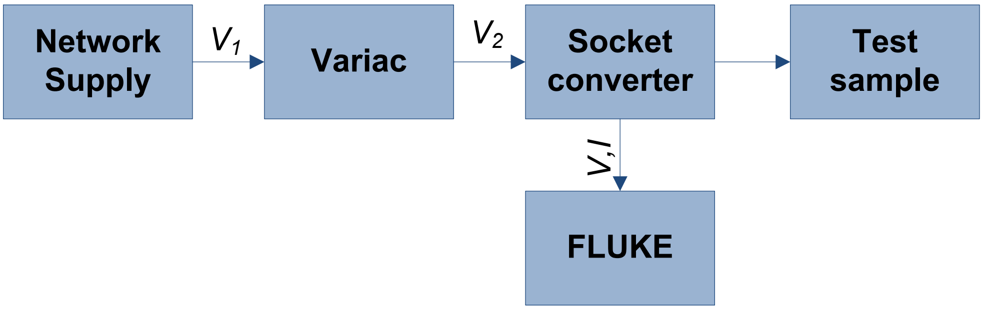


Figure 3.2 – Block diagram of the test installation

The processing of measurement results was performed in MatLab R2015a, using built in curve fitting tool and other functions. The settings for curve fitting tool were set as follows: polynomial of 2nd power curve fitting. Sometimes bisquare method showed slightly better results so in these cases it was preferred. RMS error was used as curve fitting quality indicator. As a result set of figures as well as ZIP coefficients were obtained.

Loads can be subdivided for four groups according to device's nature:

- Illumination loads
- Power electronics loads
- Resistive loads
- Motor loads

This classification is not perfect though, because nowadays power electronic devices are used in combination with illumination devices and motors.

4 EXPERIMENTAL RESULTS

4.1 Illumination devices

Illumination devices are widely used by domestic, commercial and industrial customers. There's wide selection of lamp's types, as well as manufacturers. As incandescent lamps were replaced by halogen ones, incandescent lamps haven't been tested, but the other widely used types of lamps such as CFL, fluorescent lamp, halogen lamp, high intensity discharge lamp and LED were investigated.

4.1.1 Compact fluorescent lamp

Nowadays compact fluorescent lamps (CFL) are widely used by domestic and public sector customers. It possesses longer lifetime and consumes 4 times less electrical power if compared to analogue incandescent lamp [10] [11]. Electronic ballast is used in CFL, which also allows referring the lamp to power electronic devices. One lamp name was used as test specimen.

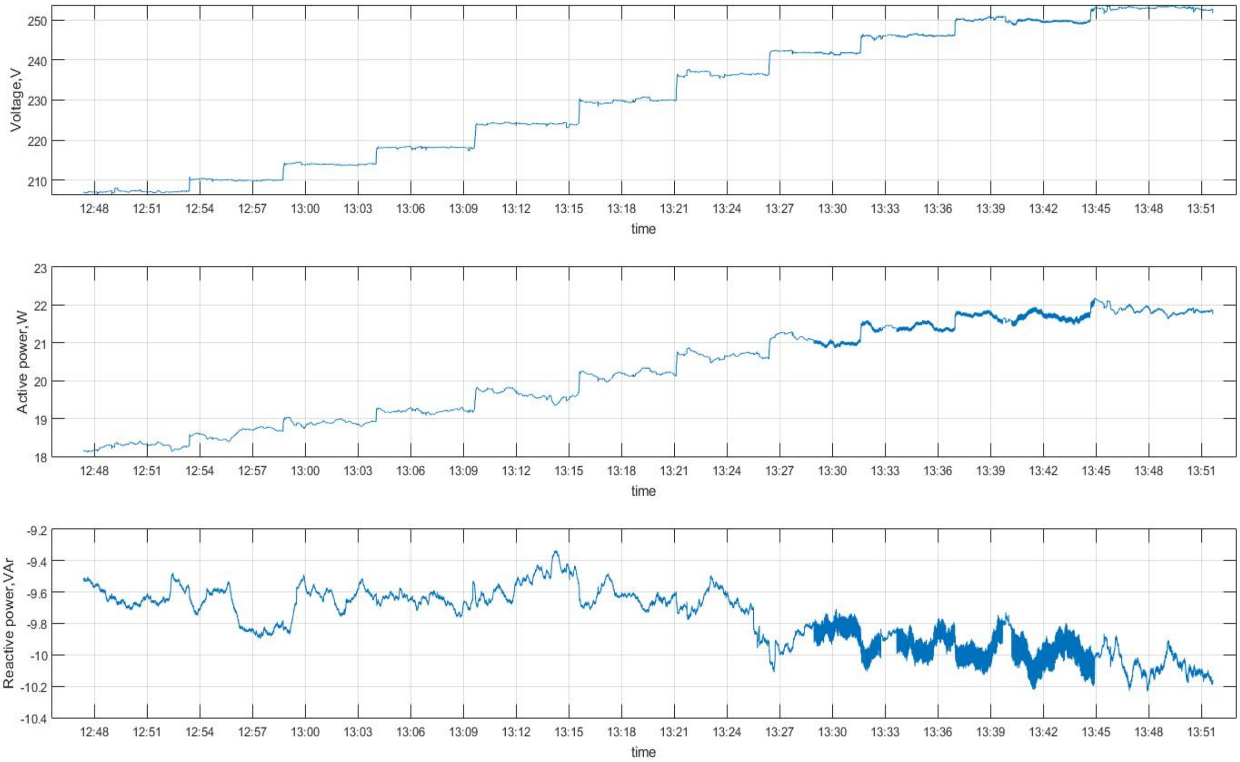


Figure 4.1 – Voltage, Active and Reactive power versus time for CFL

During the experiment the active power varied between 18.2W at $0.9V_0$ and 21.8W at $1.1V_0$. The lamp draws capacitive current with quite high reactive power quantities. Reactive power drawn varies between -9.3VAr and -10.2VAr, so CFL's reactive power consumption is not that sensitive to voltage. Active power consumption is almost proportional to voltage, that leads to conclusion that CFL can be referred to as a constant current load.

The ZIP coefficients as well as P and Q versus V curves were obtained and are represented below. The curve fitting quality parameter RMSE is 0.456% for active power and 0.98% for reactive one. It can also be observer that fitted reactive power curve doesn't exactly follow the experimentally received data at voltage lower than rated, but these small deviations may be neglected due to very small deviation value of around 0.01 or 0.98% as given in RMSE. The active power consumed varies between -9% and +8%; that shows that the CFL can stand 10% voltage variations very well thanks to electronic ballast.

Thus CFL can be referred to as constant current load, which is not influenced that much by voltage variations. The output light quality should be measured in order to obtain more data about harm of voltage variations.

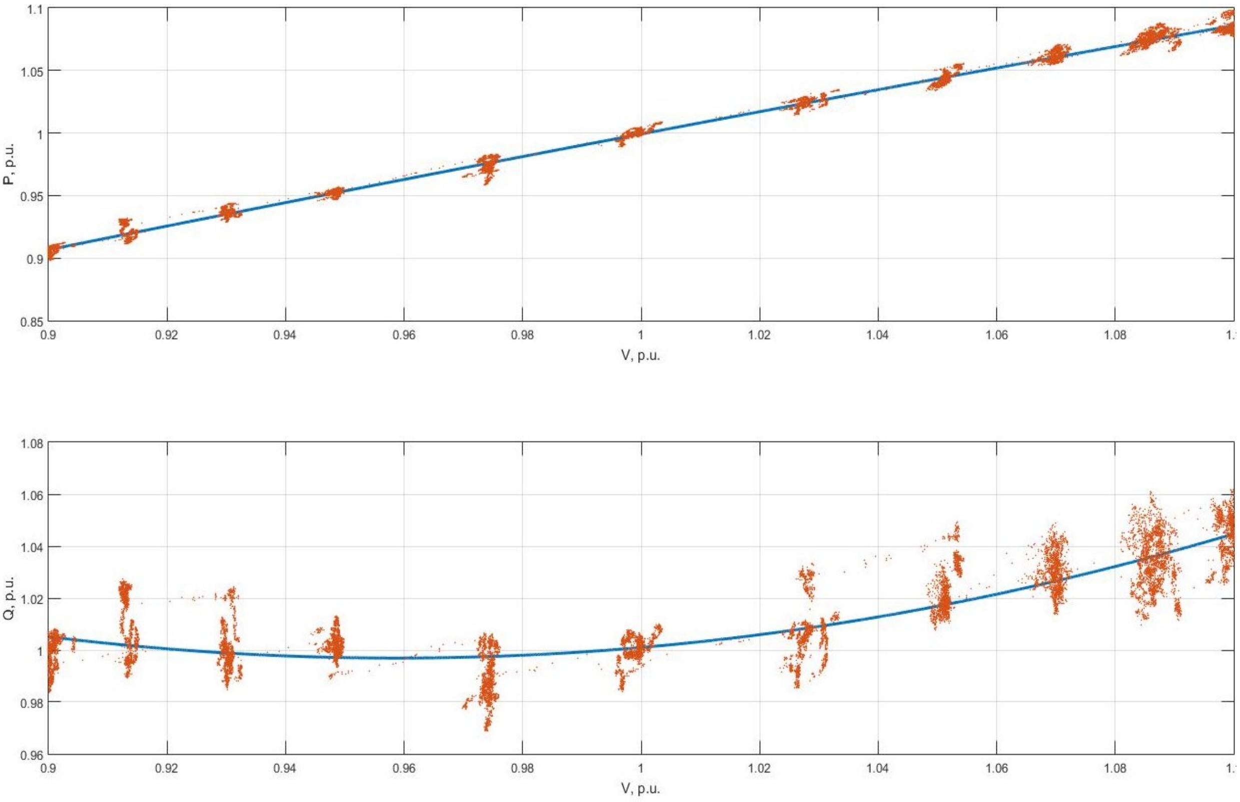


Figure 4.2 – Active and Reactive power versus Voltage (measured points and modeled curve) for CFL

4.1.2 *Fluorescent lamp*

Fluorescent lamps with electronic ballast are still widely used in office buildings and by other commercial customers. They also possess high luminous efficacy and long lifespan [10].

The main disadvantage is that they are bulky and require lot of space to install.

Two types of ballast are used in FLs: electromagnetic and electronic. Both types of ballast are still in use, although electronic one slowly increases its share in market thanks to fact that electronic components are becoming cheaper. The main advantage of EM ballast is low price, while advantages of electronic one are low weight, almost no noise and better power regulation, which is to be proved during the experiment. Both ballast types were tested: Osram Dulux L 36W with EM ballast and

Philips TL-D 36W with electronic ballast. Three tests were performed: each lamp was tested independently and then both of them together.

First experiment was performed with Osram lamp (EM ballast), and the results were clear. The active power as well as reactive power consumption follows input voltage on the whole region. At rated 230V lamp consumes 44W of active power that can be explained by fact that additional power is consumed by EM ballast.

ZIP models were easy to obtain because measurement data is extremely clear. It's worth noticing that the power factor is decreased as voltage increase, that's due to fact that excess voltage is dropped across the ballast coil.

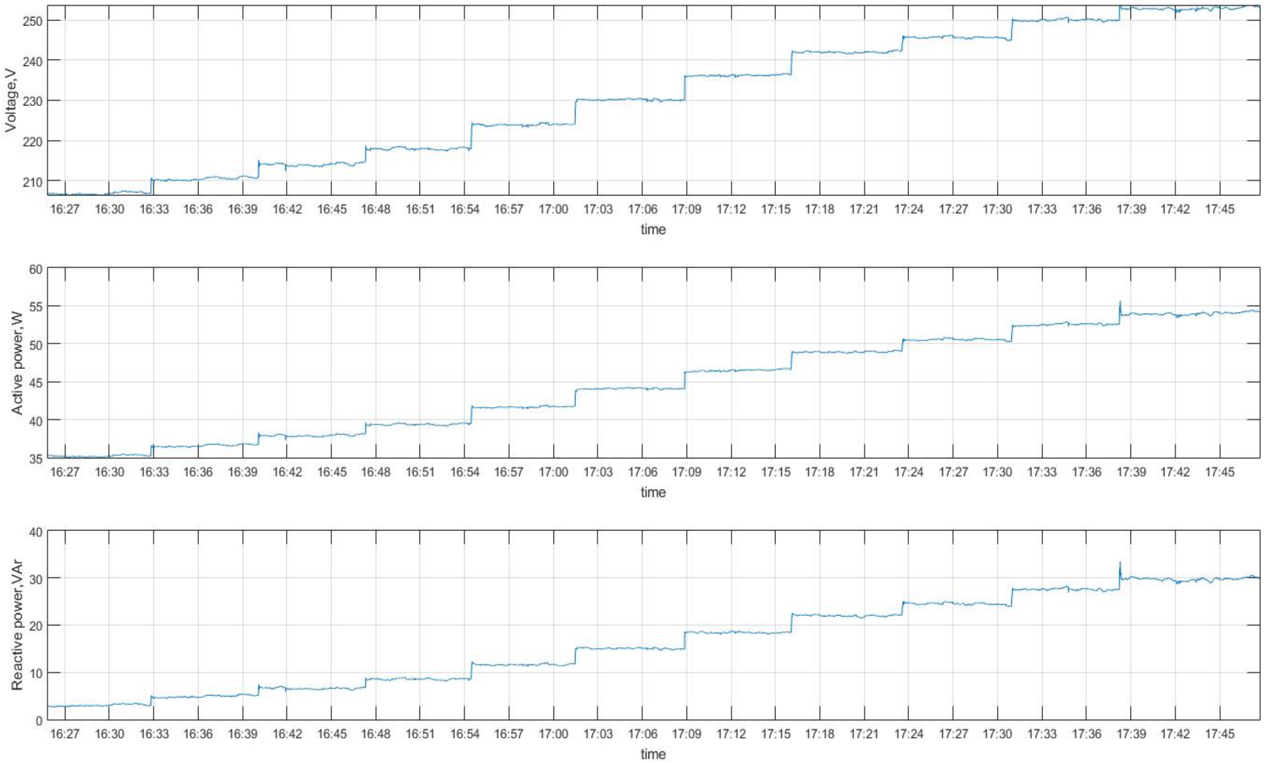


Figure 4.3 – Voltage, Active and Reactive power versus time for FL with electromagnetic ballast

The active power varies between -20% at $0.9V_0$ and +22% at $1.1V_0$. Reactive power varies much more; it rises from -75% up to +100%. That makes FL with EM quite sensitive to changes in voltage, especially if consider reactive power consumption.

Obtained ZIP model is represented below. RMSE is equal 0.2% for active power and 1.2% for reactive. Both curves are parabolas and thus FL with EM represents constant impedance load.

It has to be stated that different lamps can work differently in combination with different ballasts. Only one lamp of each ballast type was investigated, that's not enough to receive statistically proved results.

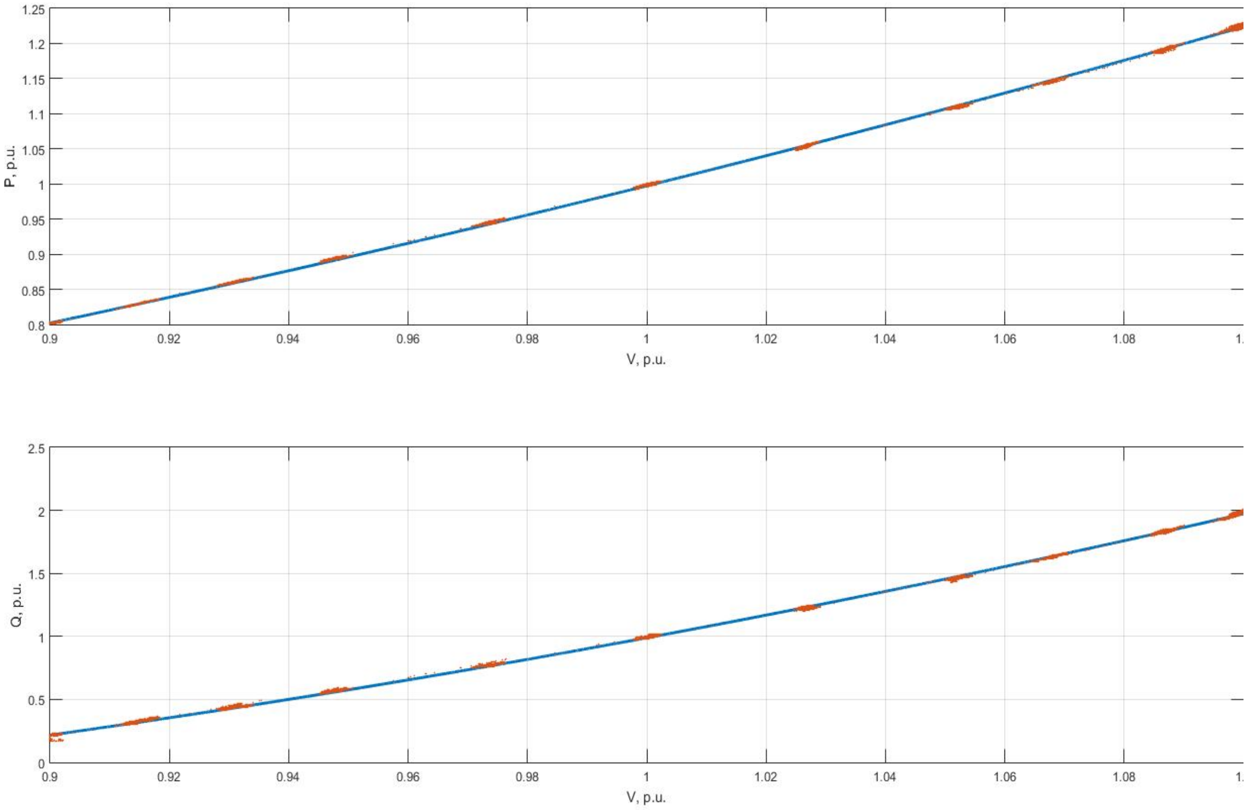
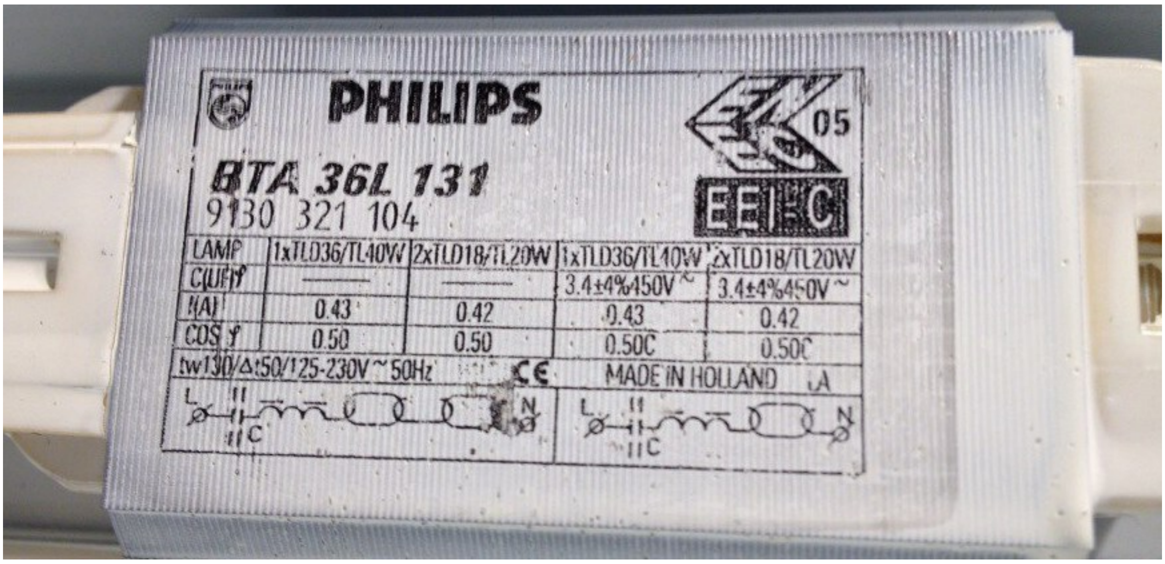


Figure 4.4 – Active and Reactive power versus Voltage (measured points and modeled curve) for FL with electromagnetic ballast



LAMP	1xTLD36/TL40W	2xTLD18/TL20W	1xTLD36/TL40W	2xTLD18/TL20W
C(UF)f	———	———	3.4±4%450V~	3.4±4%450V~
I(A)	0.43	0.42	0.43	0.42
COS f	0.50	0.50	0.50C	0.50C

Figure 4.5 – Electromagnetic ballast with its parameters

The second experiment was performed with Philips LF with electronic ballast. The result differs from previous one a lot. The power factor is capacitive and ballast draws excessive voltage as it rises. Thus the active power consumption remains roughly same over the whole region.

The electronic ballast provides steady power consumption and makes FL almost independent on input voltage, generating small amount of reactive power at the same time.

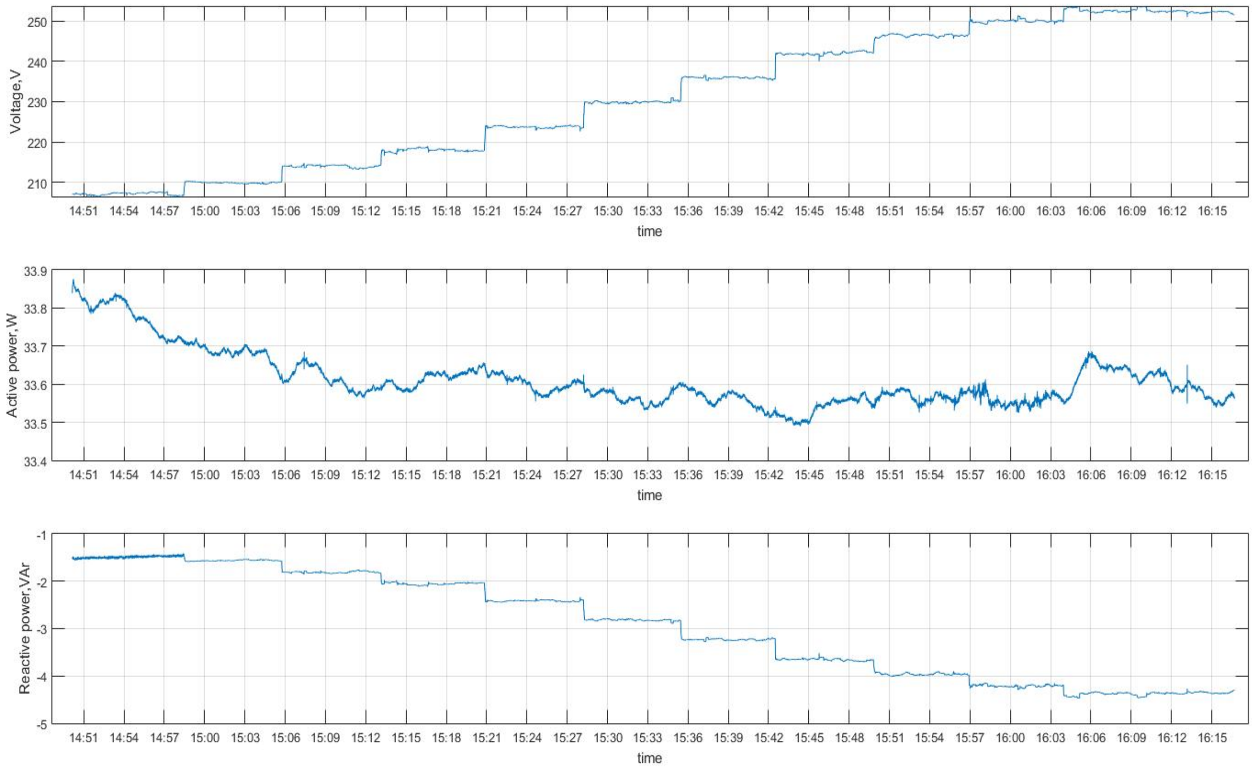


Figure 4.6 – Voltage, Active and Reactive power versus time for electronically ballasted FL

Active power consumption is practically constant, whereas reactive power consumption varies between -50% to +52 (with very low base power value).

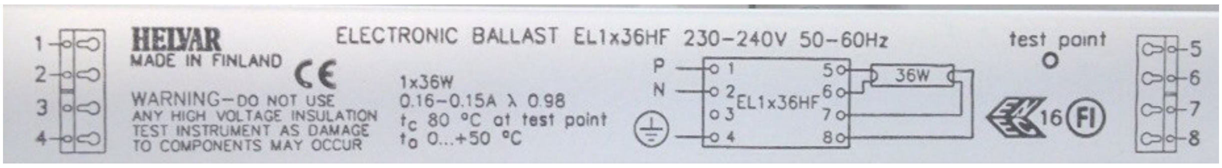


Figure 4.7 – Electronic ballast with its parameters

ZIP model for FL with electronic ballast was easy to get. The lamp behaves as constant power load, while absolute value of reactive power increases proportionally to voltage.

Curve fitting RMS error for active power was 0.1%, for reactive – 0.37%, that means that reasonable results were obtained during the experiment. P and Q against V as well as fitted curves are presented on the figure below

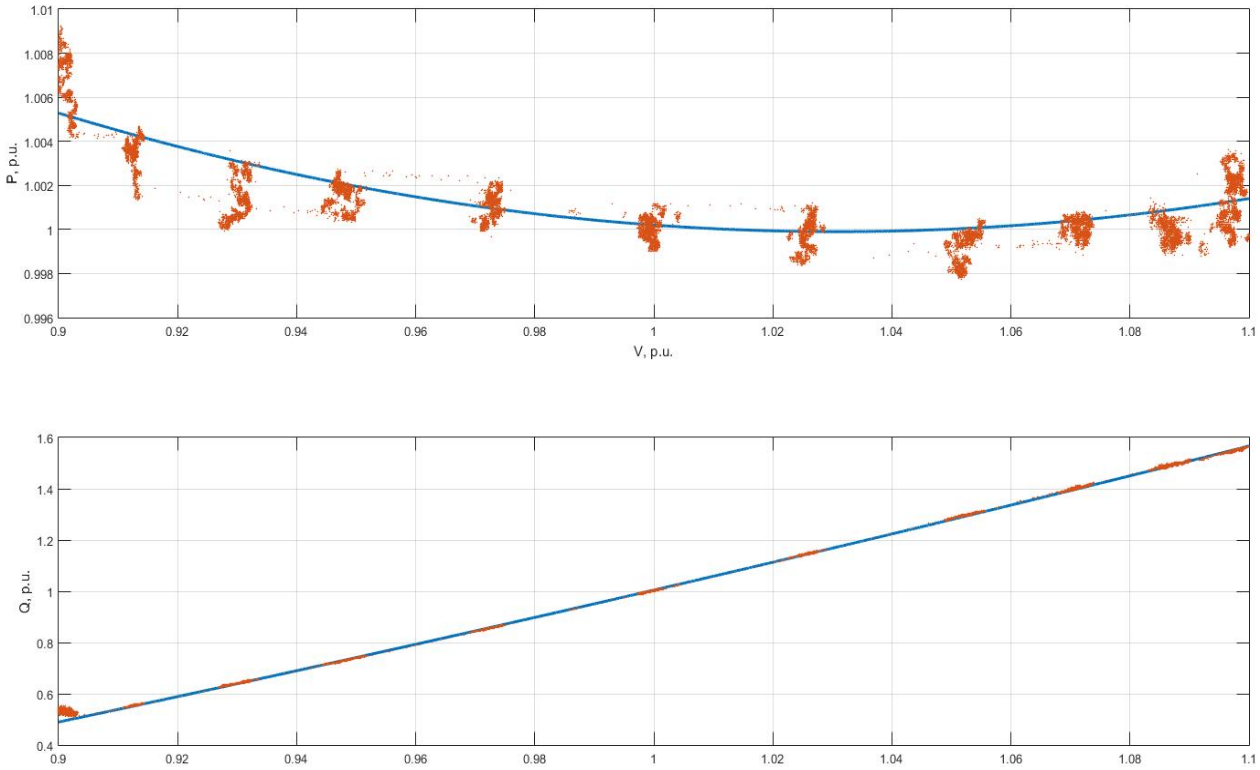


Figure 4.8 – Active and Reactive power versus Voltage (measured points and modeled curve) for electronically ballasted FL

The measurement results show that electronic ballast makes FL invulnerable to voltage variations, while the electromagnetic ballasted lamp behaves as constant impedance load.

The third experiment was performed with both lamps turned on. Basically active power consumption increment is practically equal to the one of FL with EM ballast, while reactive power consumption becomes noisier. That’s due to phase difference in currents of 2 lamps, but what interesting is that combination of two lamps draws more reactive power than both of them independently. That might be caused by phase shift in drawn current. That phenomenon requires further investigation.

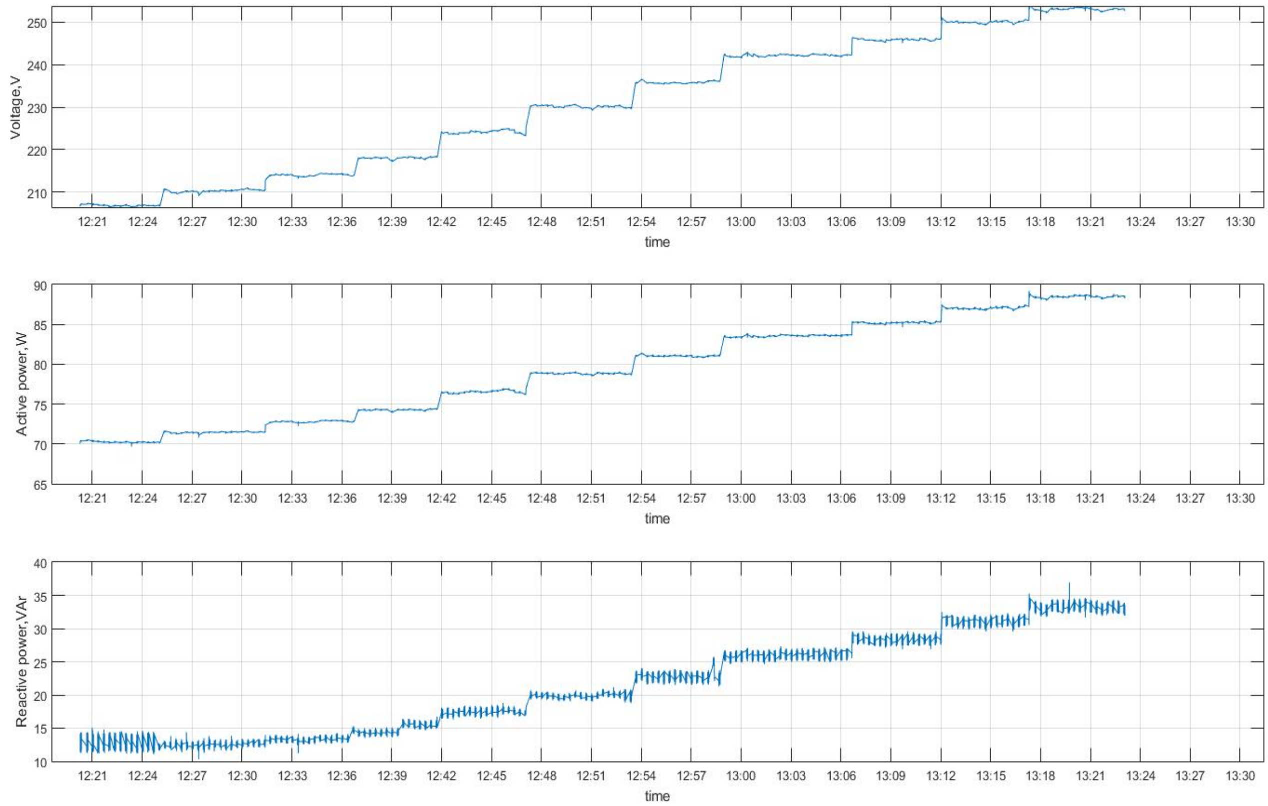


Figure 4.9 – Voltage, Active and Reactive power versus time for combination of both FL

Curve fitting RMS error for active power was 0.099%, for reactive – 2.4%, that means that reasonable results were obtained during the experiment. P and Q against V as well as fitted curves are presented on the figure below.

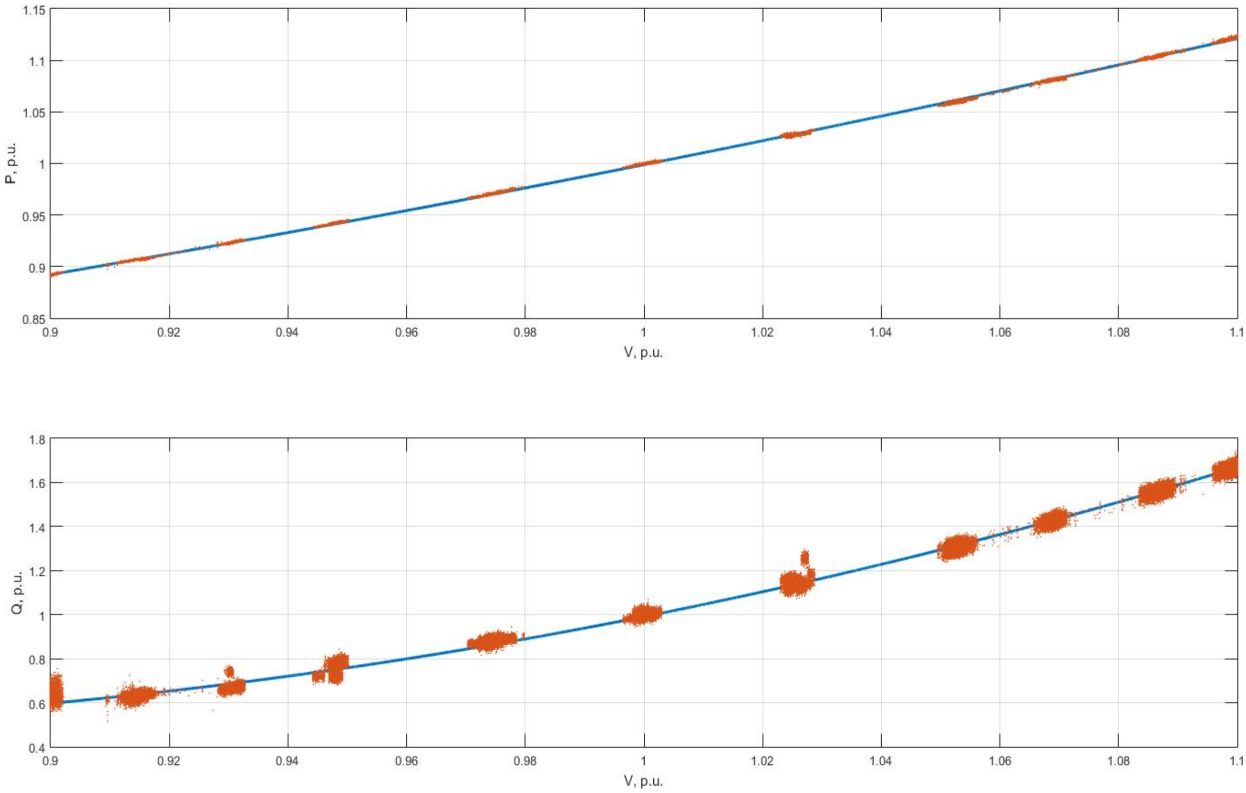


Figure 4.10 – Active and Reactive power versus Voltage (measured points and modeled curve) for both FL

4.1.3 Halogen lamp

Five Osram 100W halogen lamps were used as test object during the experiment. Although halogen lamps were to banned in EU in 2016, EU states voted in favor to postpone the ban to 2018 [12]. That means that halogen lamps will still be the huge share of illumination devices, because ban means that halogen lamps will disappear from markets, but the leftovers will still be used for quite a long time. The behavior of halogen lamps is quite similar to one of incandescent ones. Power factor is very close to 1, Reactive power consumption varies between 6VAr and 8VAr, while some random spikes up to 15VAr were observed. These spikes may be originated by network though and don't change the picture much.

The active power changed between -15% to +16%, the reactive power generally changed from -20% to +20%, although the base value of reactive power was so low that these changes may be neglected.

Active power fitted curve possesses good quality indicators, RMSE is equal to 0.02657%, whereas for reactive power it is higher due to random spikes and is equal to 1.445%.

P and Q vs V curve fitting for halogen lamp is considered convenient and experiment was conducted successfully.

Halogen lamp behaves more as combination of constant current and constant impedance load, because active power is represented by wide parabola.

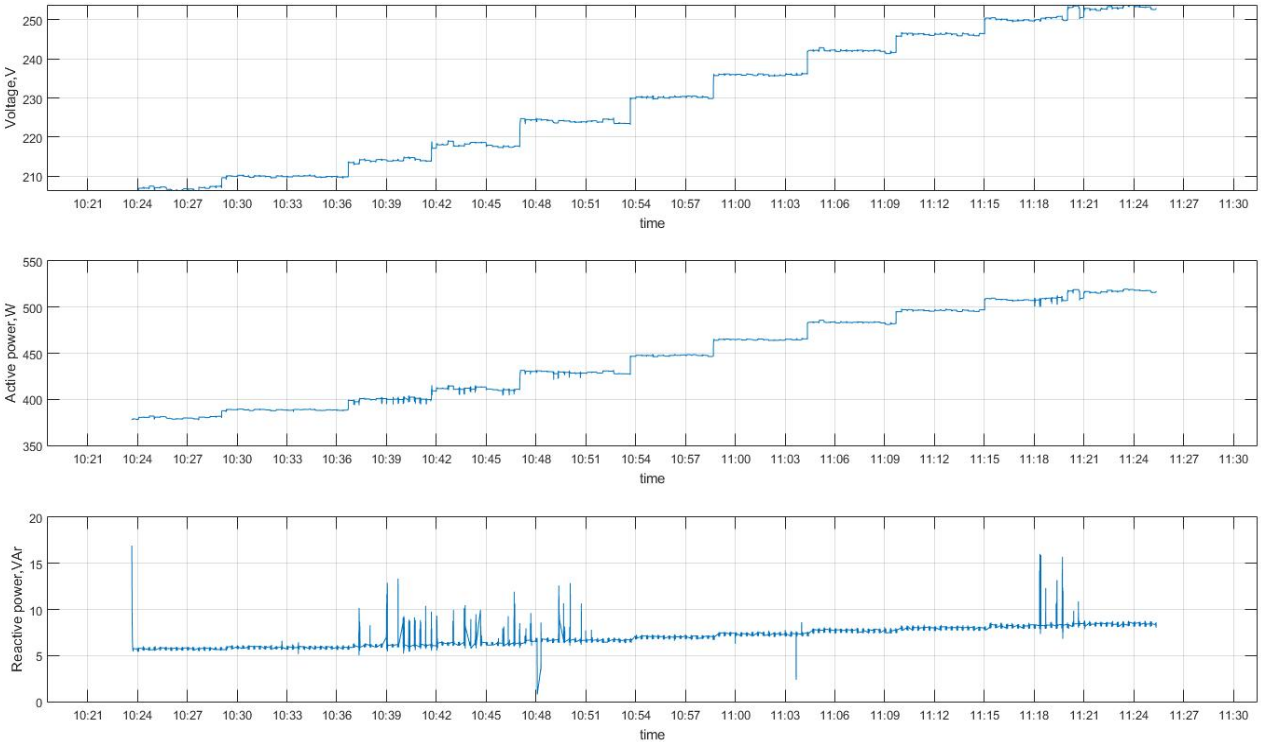


Figure 4.11 – Voltage, Active and Reactive power versus time for halogen lamp

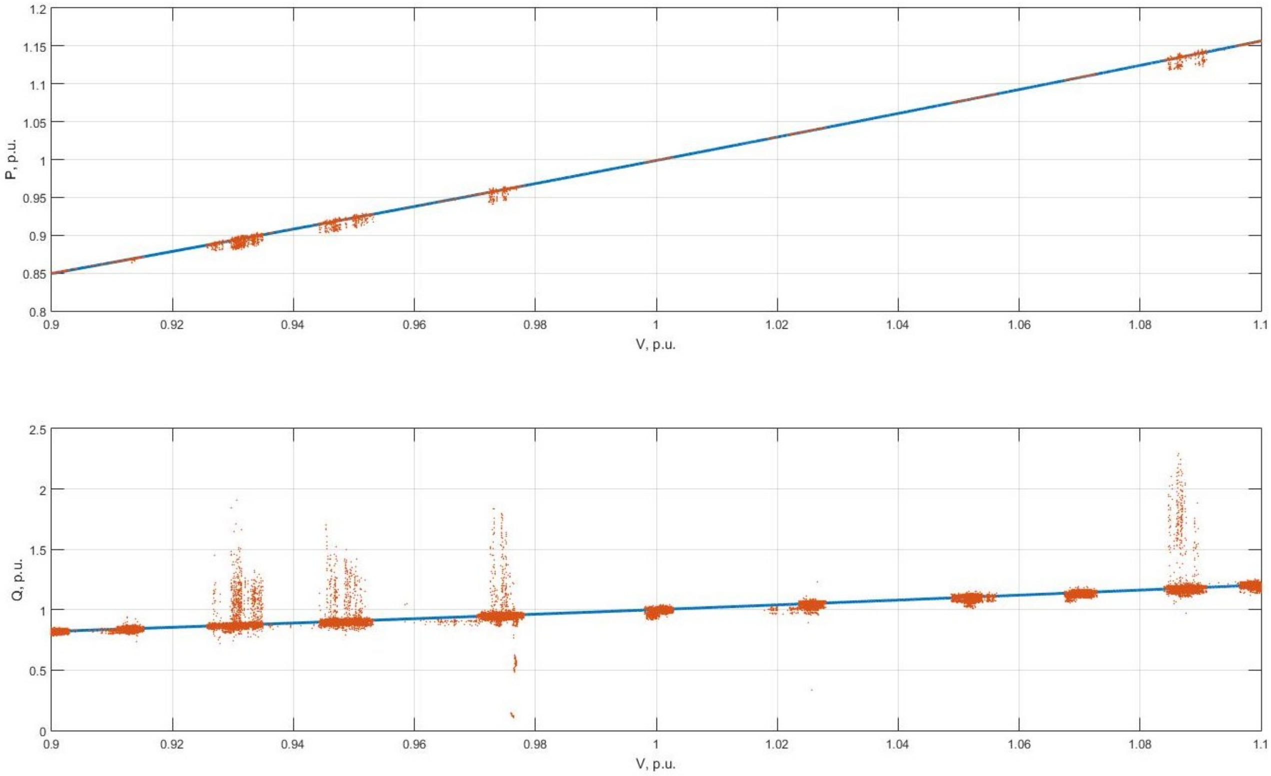


Figure 4.12 – Active and Reactive power versus Voltage (measured points and modeled curve) for halogen lamp

4.1.4 High intensity discharge mercury-vapor lamp

Mercury-vapor lamps are gas discharge lamps, where electric arc is used as a source of light. They are widely used at street illumination due to long lifecycle (~24000 h) and higher luminous efficacy if compared to fluorescent lamps. They are also able to emit good quality white light. The disadvantage is long starting time that varies between 4-7 minutes [10].

Osram HQL 125W was selected as the test specimen.

It can be seen that for 207V voltage level only 2.5 minutes of measurements were taken. The reason is it was actually necessary to filter out the starting cycle that took more time than it was expected. The lack of data didn’t really influence the result because power consumption remained almost constant at each voltage level.

There’s also a measurement gap between 11:35 and 11:39. That happened because the measurement equipment was accidentally plugged off the socket, although didn’t affect the measurement quality either.

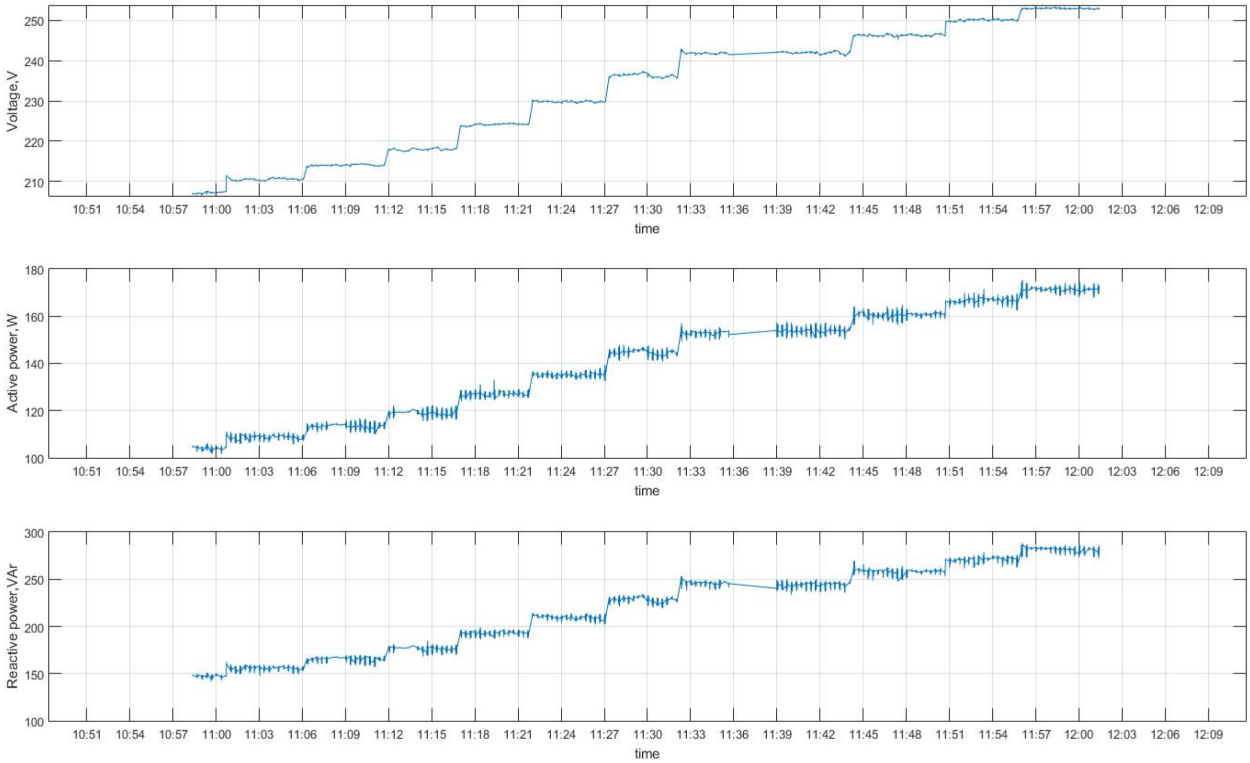


Figure 4.13 – Voltage, Active and Reactive power versus time for HID mercury vapor lamp

HID lamp showed quite steady performance, while the active and reactive power consumption remained constant within voltage levels.

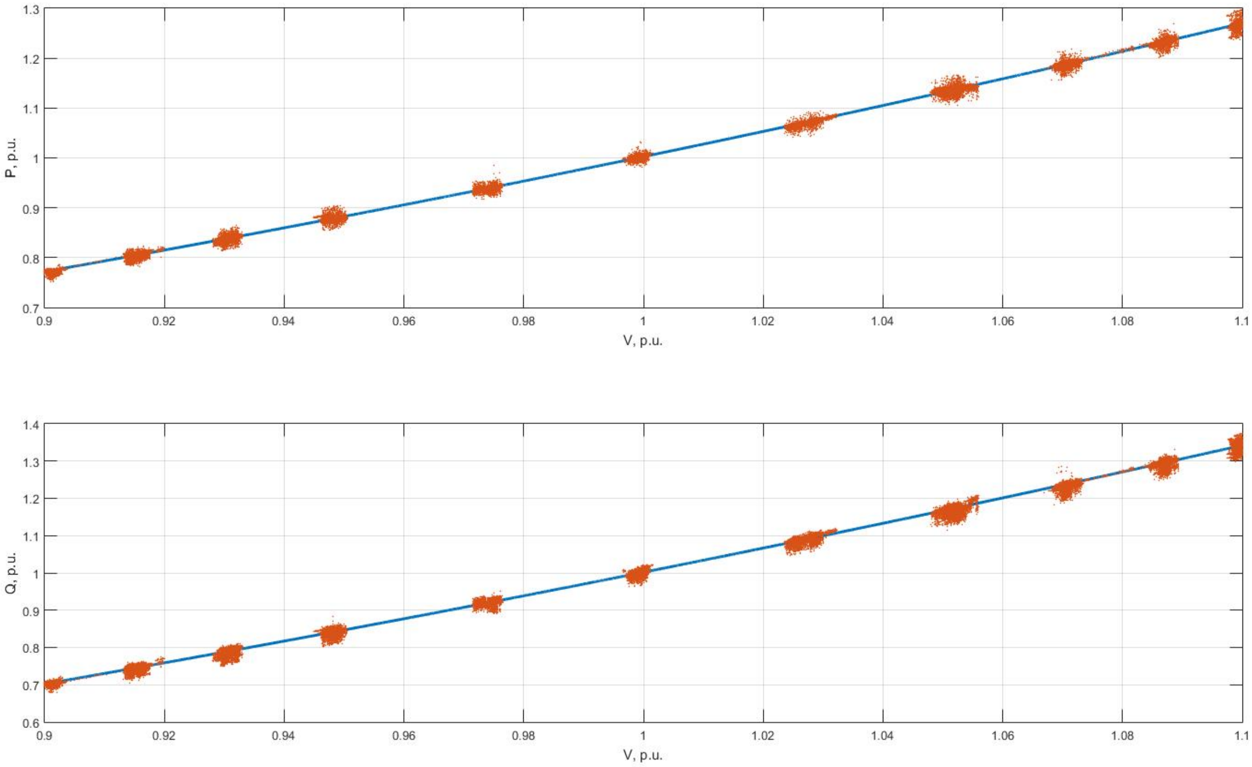


Figure 4.14 – Active and Reactive power versus Voltage (measured points and modeled curve) for HID mercury vapor lamp

Both active and reactive power consumption curves are not linear. They are represented by very wide parabolas, where active power changes between -23% to +26% and reactive one changes within -30% and +34%.

It’s also worth mentioning that the lamp consumes more reactive than active power, so even if the rated power is 125W it still created a huge load at network.

Curve fitting RMS error for active power was 0.47%, for reactive – 0.84%, that means that reasonable results were obtained during the experiment. P and Q against V as well as fitted curves are presented on the figure above.

4.1.5 LED lamp

Light emitting diodes have been improved dramatically during last decade and they already blend in illumination markets quite well. LEDs possess longer lifetime than fluorescent lamps. They also provide good quality adjustable light and decrease power consumption dramatically. The disadvantage is that luminaries for LEDs must contain cooling radiators that take lots of space. However LEDs are still considered as future of illumination and thus investigation of their properties is required [10].

It was necessary to perform two experiments with LED; the first one showed that it takes around 30 minutes for lamp to heat up to steady state temperature. Thus the power measurements were failed, but the measurement visualizes the process of heating. As LED heats up, the conductivity increases and less active power is drawn.

After the LED was heated up, the power consumption remained relatively constant along the whole voltage level.

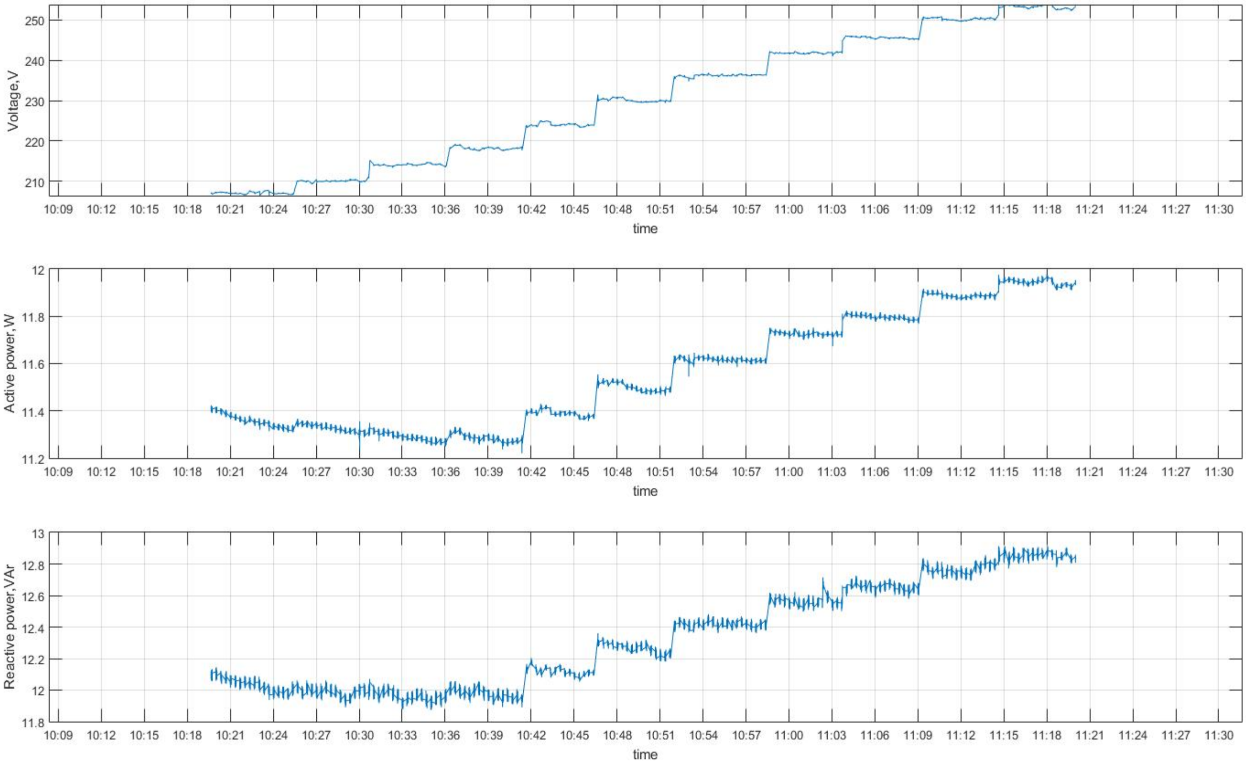


Figure 4.15 – Voltage, Active and Reactive power versus time for the first LED without preheating

The second measurement was performed as follows: 2 Philips 12W LED lamps were preheated during 60 minutes and then the power readings were taken.

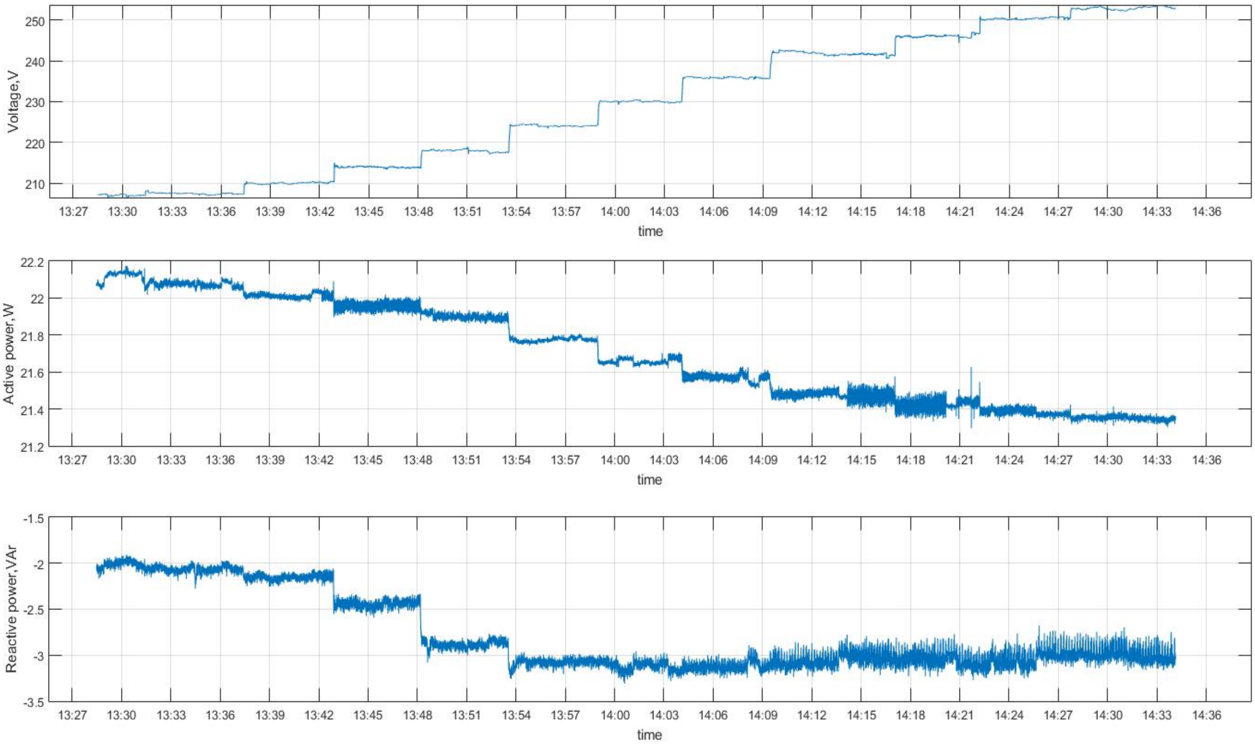


Figure 4.16 – Voltage, Active and Reactive power versus time for second LED (preheated)

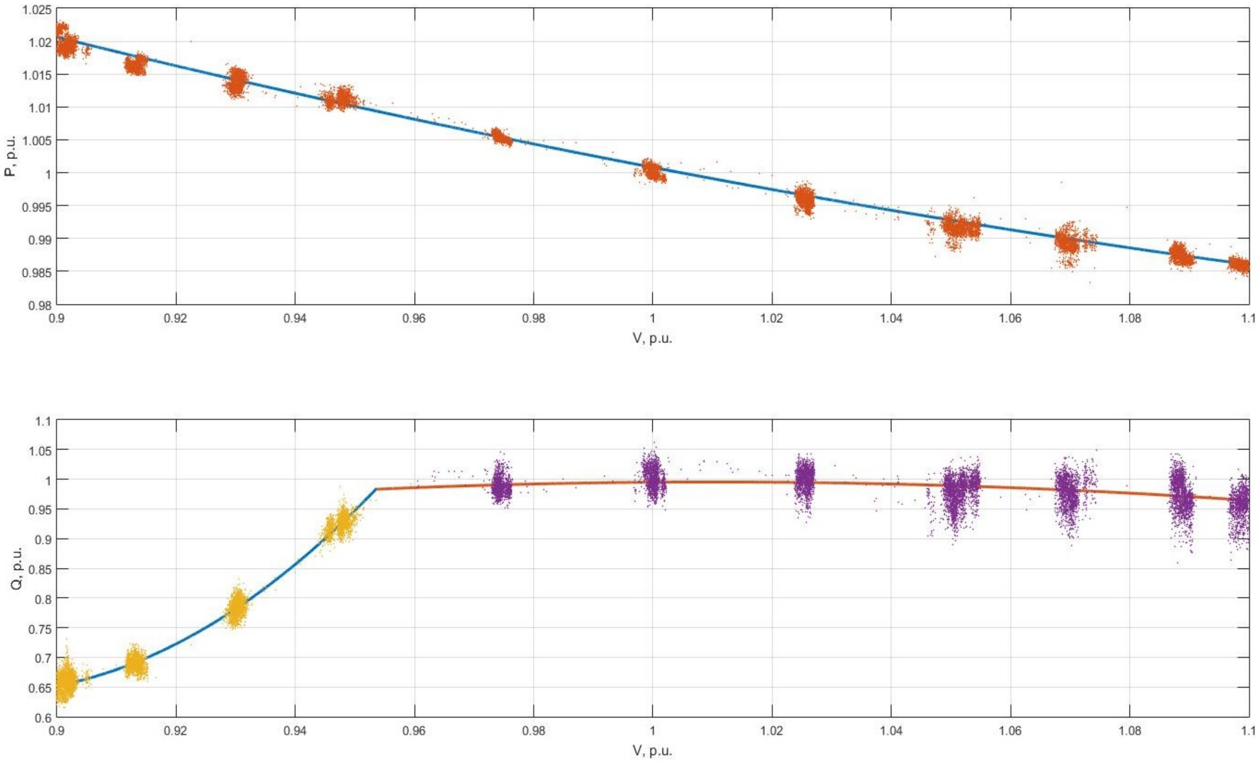


Figure 4.17 – Active and Reactive power versus Voltage (measured points and modeled curve) for LED (preheated)

After the second measurement was performed following conclusion was made: measurement of two different LEDs return dramatically different results. In one case active power consumption went up, following the voltage, in other case it went down.

In first case LED consumed huge amount of reactive power, in second it produced small amount of it. Even measurement of same lamps from the same manufacturer may lead to considerable differences in results, thus measurements of massive amount of specimens is required to obtain statistically reasonable results.

For now, one of useful outcomes is that no matter what type of LED is used, at the measured voltage band the changes in active power consumption changes are only 2-4%

Also analyzing LED's active power curve, the following conclusion can be made: LED lamps are constant power devices and thus voltage variations practically don't influence their operation, but more experiments with measurements of light output and light quality must be performed.

4.2 Power electronic devices

Nowadays power electronics components are must have component of every power supply. Most of office equipment is represented by power electronic devices such as computer screens, PCs, printers etc. Before the experiment no high expectations were put on the results, because power electronic devices usually have complex operation cycle and it's impossible to create same conditions for measurements at different voltage levels.

Thus only four devices were selected for the measurements. Among them there's microwave oven, PC CP unit, PC display and TV.

4.2.1 Microwave oven

Measurement of 1400W microwave oven required continuous reading of RMS values instead of previous system with 20ms RMS measurement for 3s every 20s. The reason is that operation cycle of the device is around 20.5s, out of which around 18s it draws full power from the network, but during the remaining 2.5s it practically draws no active power, producing some reactive power at lower voltages and drawing some of it at higher voltages.

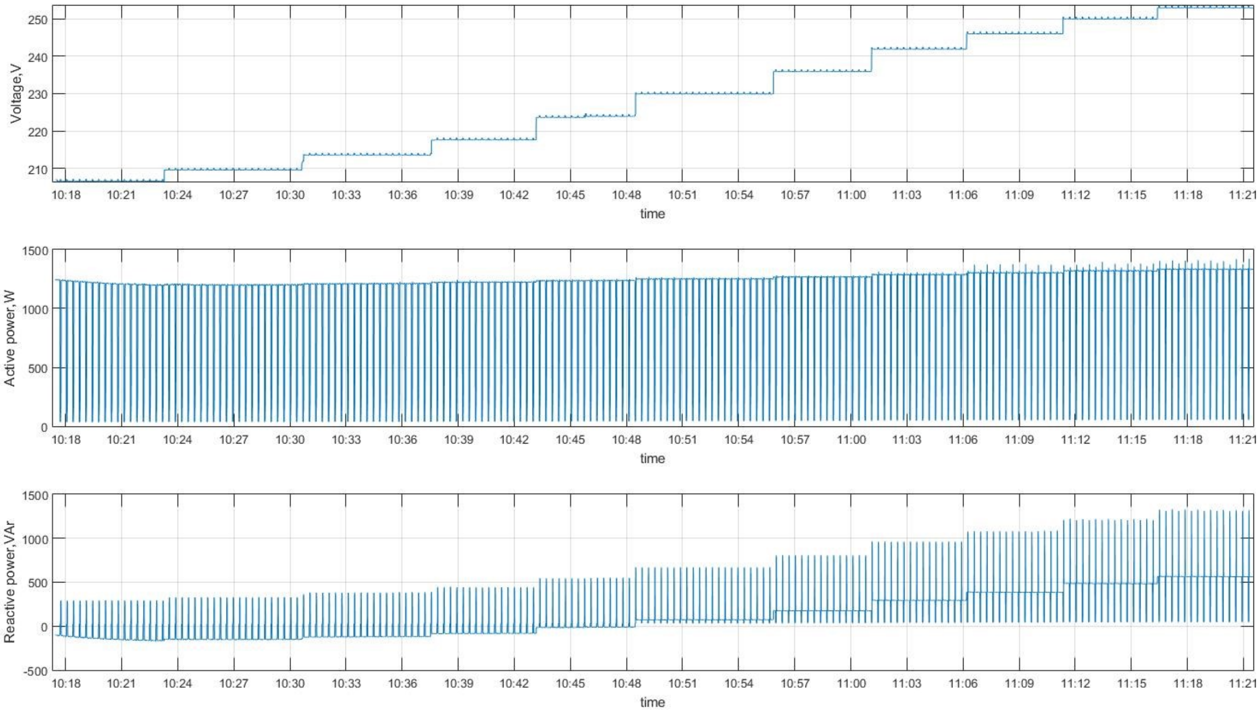


Figure 4.18 – Voltage, Active and Reactive power versus time for microwave oven

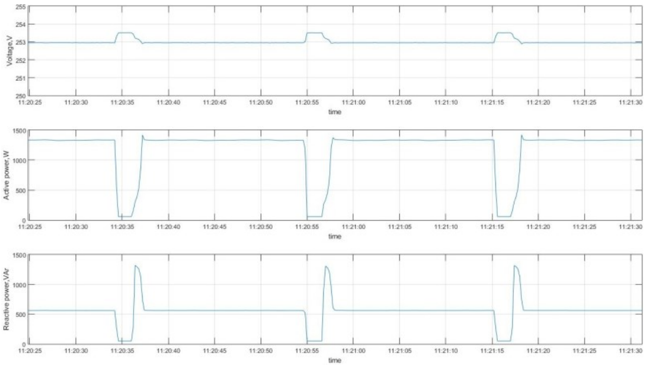


Figure 4.19 – Zoomed in operation cycle of microwave oven

Enlarged region of microwave operation cycle is given. It can be seen that the voltage rises around 0.5V during the power gaps, that's due to slow reaction of power supply. Also reactive power consumption curve experiences a spike when oven starts to consume active power again.

Thus the results of the experiment are not very clear, although ZIP model was obtained and its RMSE for active power curve is 0.866% and for reactive power is 4%. The fit quality parameters are within admissible band and this model can be used to describe average long-term behavior of the microwave oven.

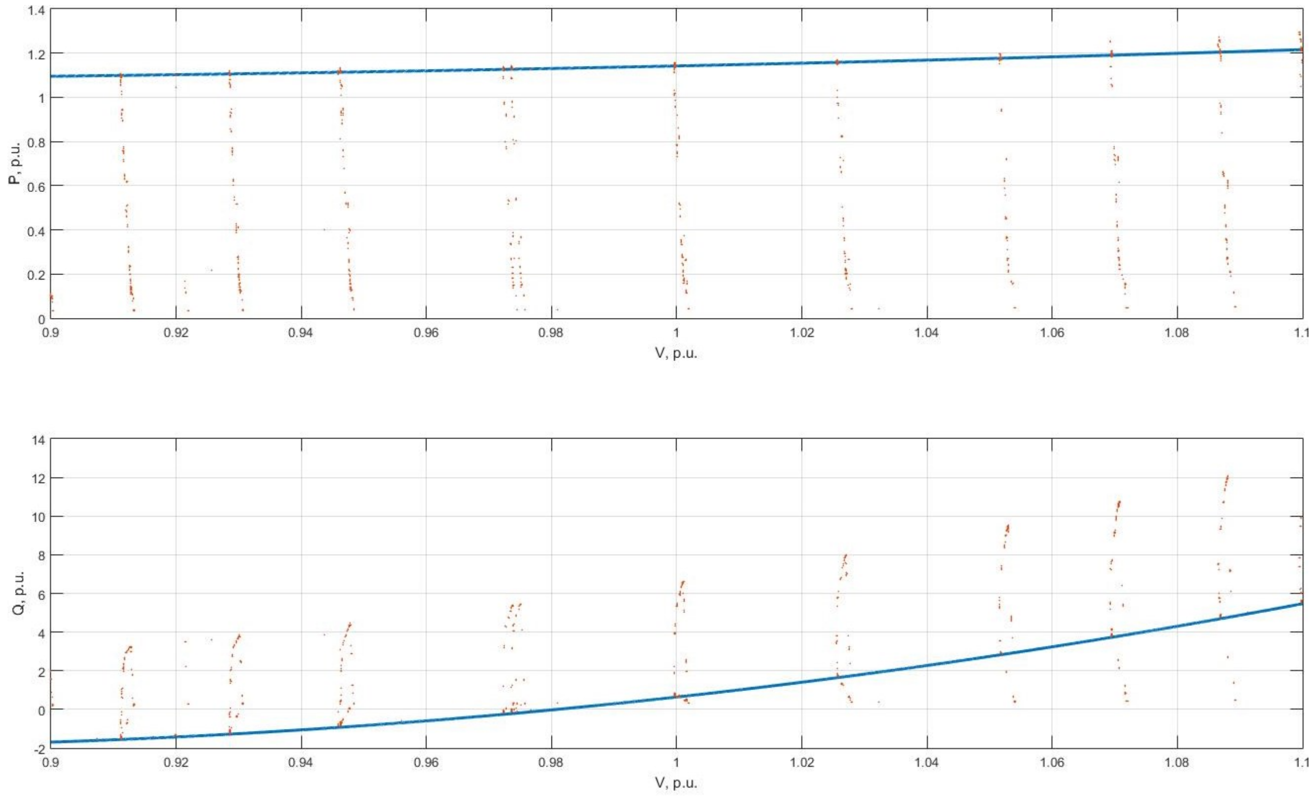


Figure 4.20 – Active and Reactive power versus Voltage (measured points and modeled curve) for microwave oven

4.2.2 PC display

PCs are present in almost every domestic or commercial customer's load mix. In offices it represents considerable amount of total electricity demand.

PC display is one of PC components that draws considerable amount of power. For the tested display rated parameters were 100-240V and 1.5A, nothing was stated about the power. In fact display draws 29.5W and 58VAr at 230V. Since PC display contains power supply, it is not surprising that active power consumption changes only from +3.5% at 0.9Unom down to -1% at $1.1V_0$. Reactive power consumption doesn't vary much either, lowest value is -2.5% at $0.927V_0$ and highest is +2% at $1.1V_0$.

In order to obtain ZIP models it was necessary to split the curve into two regions. Thus each of active and reactive power models is represented by two curves. The shape of active power curve leads to following conclusion: PC display is constant power load.

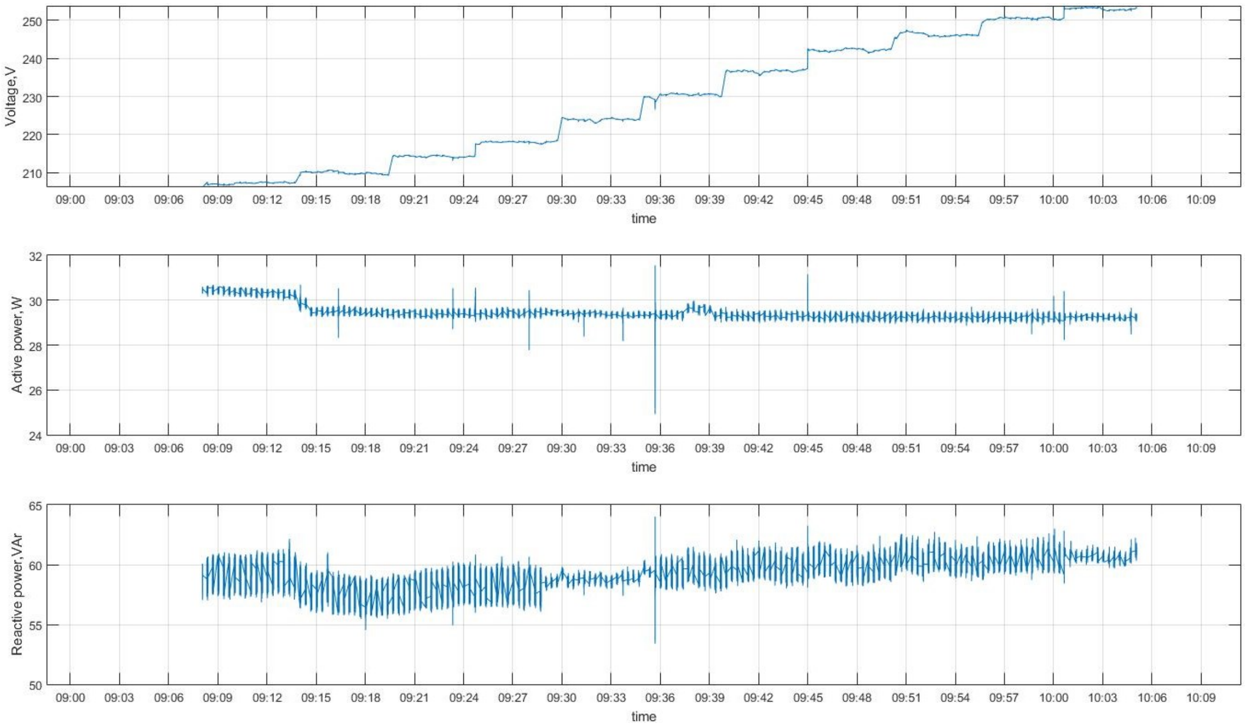


Figure 4.21 – Voltage, Active and Reactive power versus time for PC display

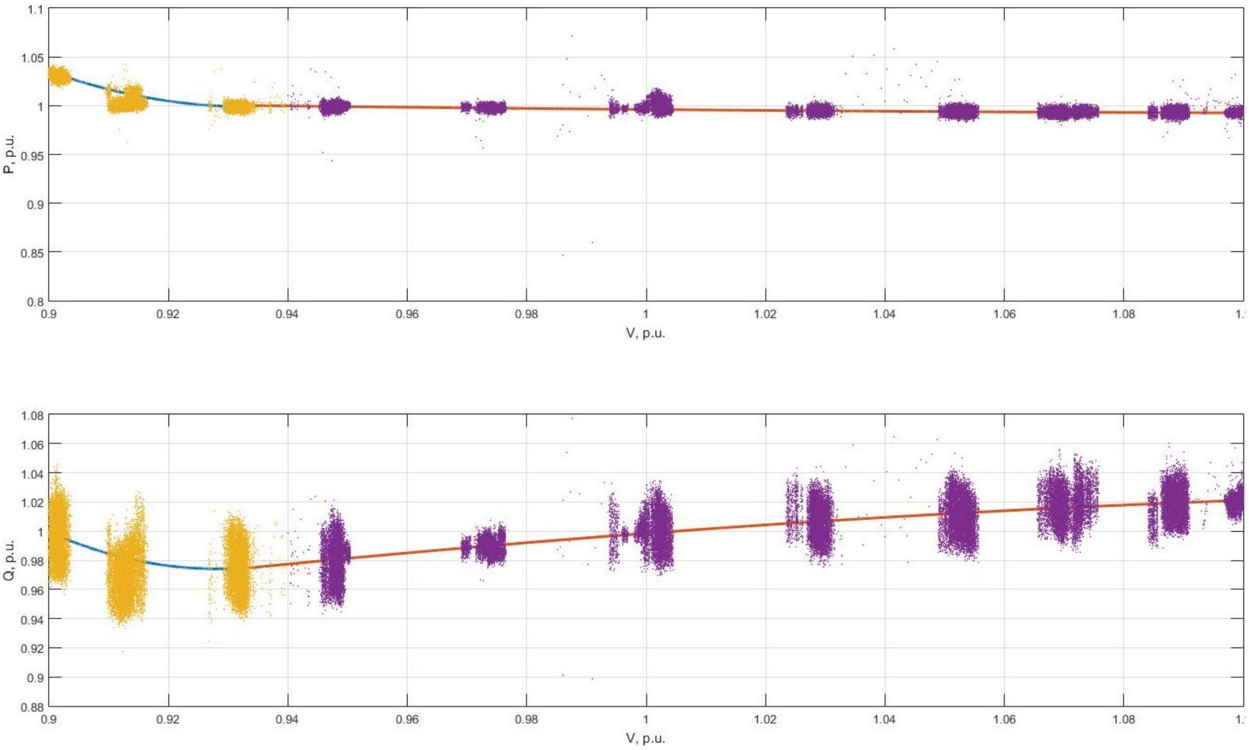


Figure 4.22 – Active and Reactive power versus Voltage (measured points and modeled curve) for PC display

RMSE for active power curves are respectively 0.56% and 0.31%, for reactive they are 1.58% and 1.57%, thus model for PC display can be considered as reliable.

4.2.3 PC system unit

The key components drawing power in PC are Motherboard and CPU, besides these 2 major consumers there are also fans, HDD, video card and CD-ROM. It is very hard to predict power consumed by whole PC because it depends not only on ambient temperature, but also on commands and processes that CPU performs. That's why the experiment was performed twice, first time while computer was running software, second time in locked mode. First experiment didn't provide reasonable results, power consumption was random, and therefore second experiment is considered.

Tested PC consisted of Intel Core2 Q9000 CPU, low-end motherboard and Nvidia NVS295 video card. The nameplate on power supply said that maximum output power is 268W.

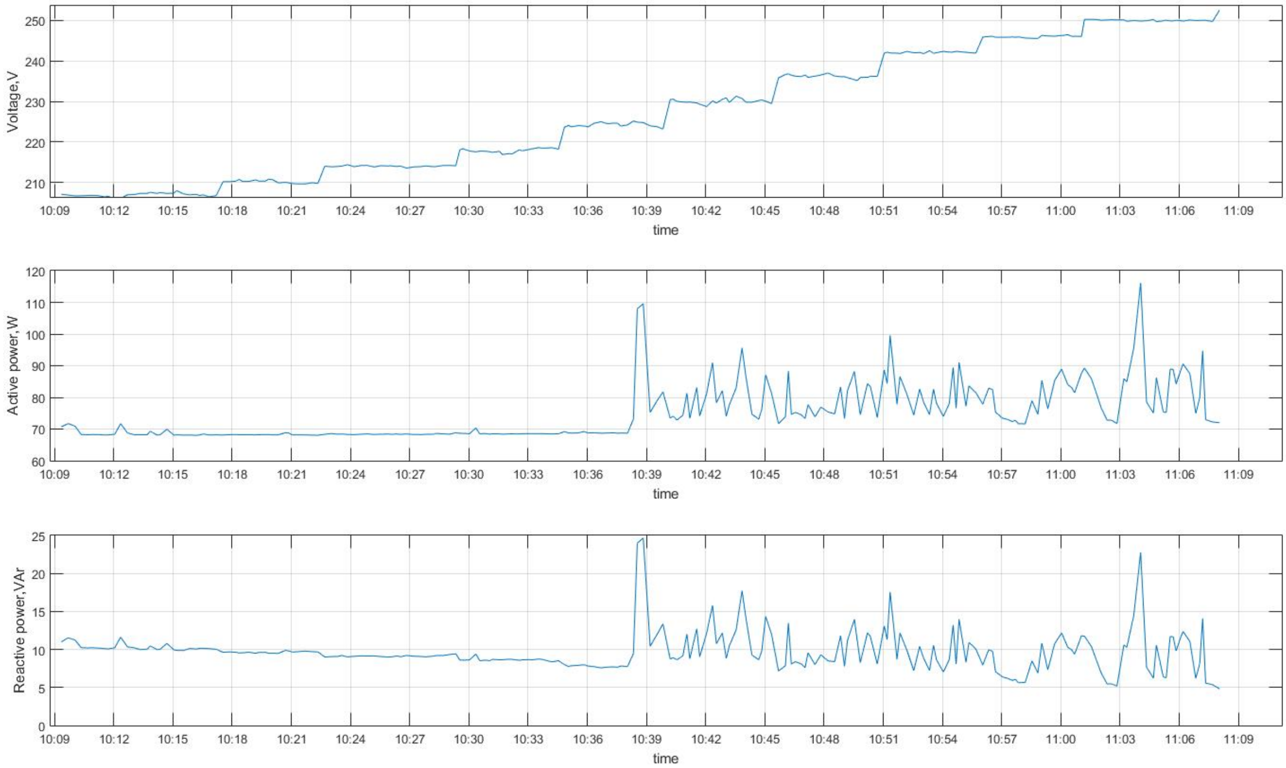


Figure 4.23 – Voltage, Active and Reactive power versus time for PC system unit

From the figures it can be seen that active power consumption curve has the same shape as reactive power consumption one. Also up to 230V consumed power was almost constant, but after certain point it started fluctuating. The measurement was performed in such a way that 20s RMS values were recorded in order to take average values of power. There are although no grounds to make a conclusion that these spikes are caused by certain voltage level. More likely they are caused by CPU operation, which is impossible to predict. The rated dissipated power for tested CPU (Intel Core 2 Q9000) is 35W and that aligns well with value of spikes. Typical power consumption of the motherboard 25-40W [13].

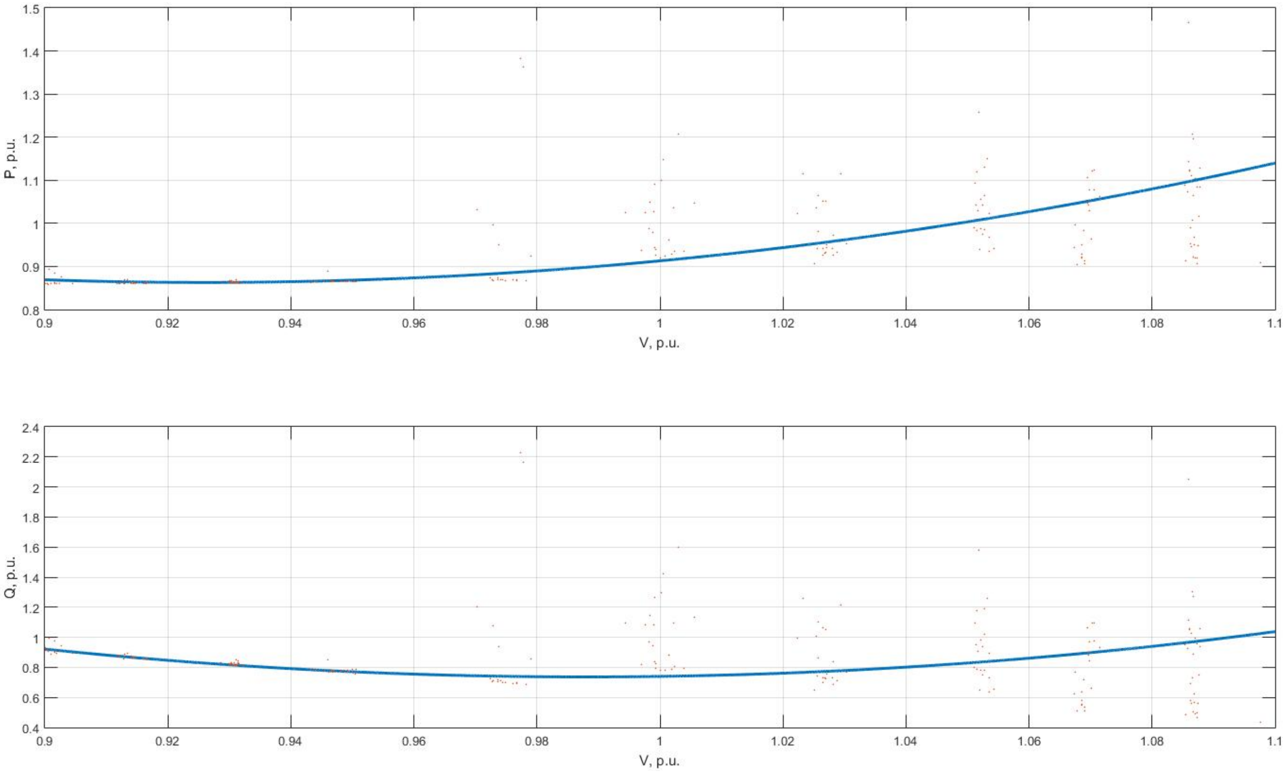


Figure 4.24 – Active and Reactive power versus Voltage (measured points and modeled curve) for PC system unit

PC power supply is able to provide very precise DC output, but depending on input voltage active and reactive power consumption fluctuates quite a lot. At $0.9V_0$ active and reactive power consumptions are accordingly -13% and -9%, at $1.1V_0$ they are +14% and +4%

Despite stochastic measurement results, ZIP model with quite decent quality parameters was obtained. For active power RMSE is 2.45%, for reactive one it’s 8.45%.

4.2.4 TV

TV is one of loads that a present in almost every domestic and commercial consumer's load mix. Power supply in TV is quite complicated, but the test showed that it can maintain almost constant active power consumption along admissible voltage level. Power factor for TV is negative, so it produces reactive power, compensating excessive voltage.

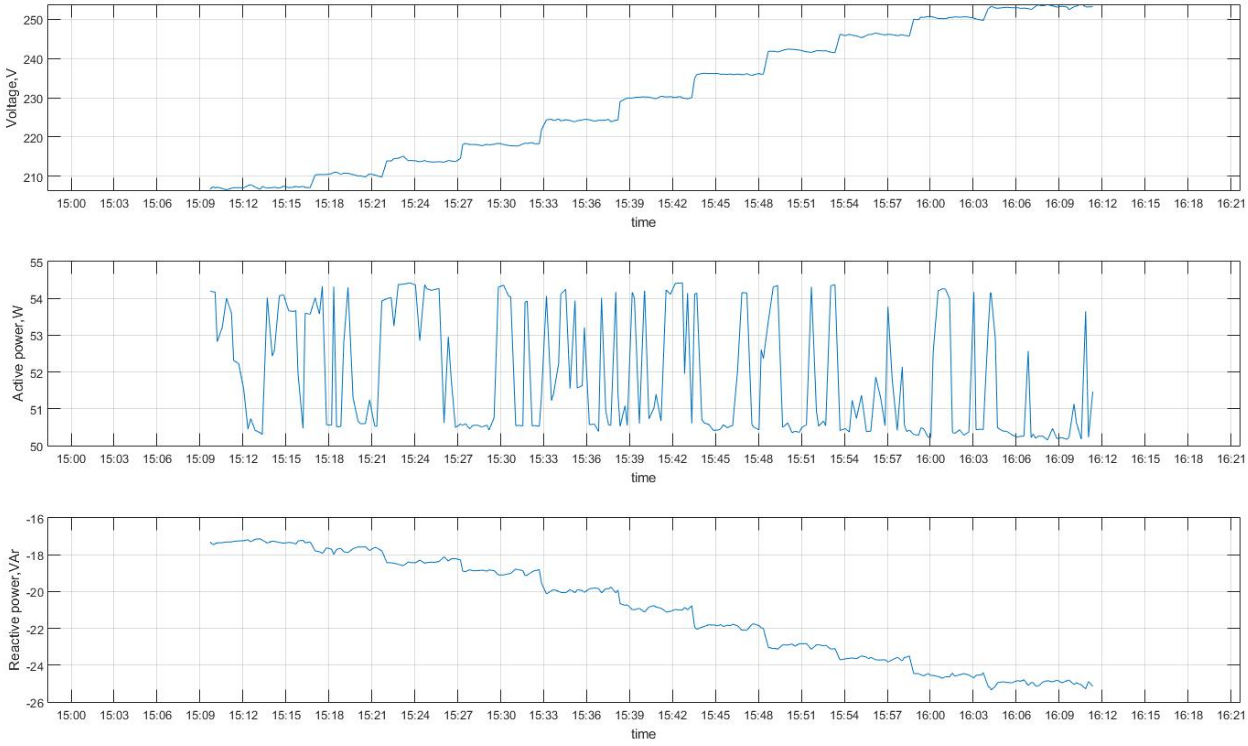


Figure 4.25 – Voltage, Active and Reactive power versus time for TV

The active power clearly fluctuates between 50.2W and 54.4W, not exceeding these values. The reason of these fluctuations is that different power is needed to generate different color on the matrix. The tested TV is LG 32LD350 with rated power 120W, which means that in that case rated power is not the power consumed at rated voltage. Reactive power consumption varied from -17% at $0.9V_0$ up to +19% at $1.1 V_0$. It's hard to refer TV to either constant power, constant resistance or constant current group of loads because active power consumption drops by 1.8% as voltage increases, but that change is insignificant. Thus TV can more likely be referred to as constant power load.

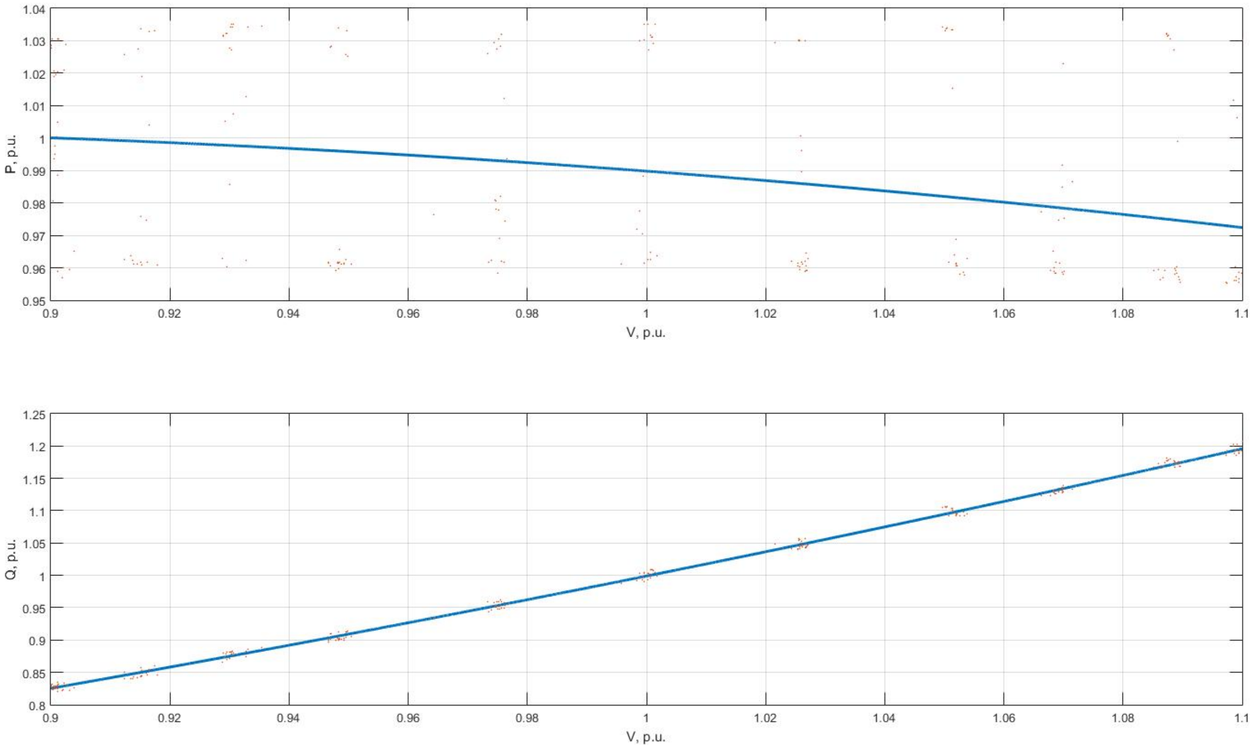


Figure 4.26 – Active and Reactive power versus Voltage (measured points and modeled curve) for TV

4.2.5 *Electric Vehicle charger*

Every year more electric vehicles are being rapidly integrated in energy usage mix so it is also necessary to investigate influence of voltage variations on charging process.

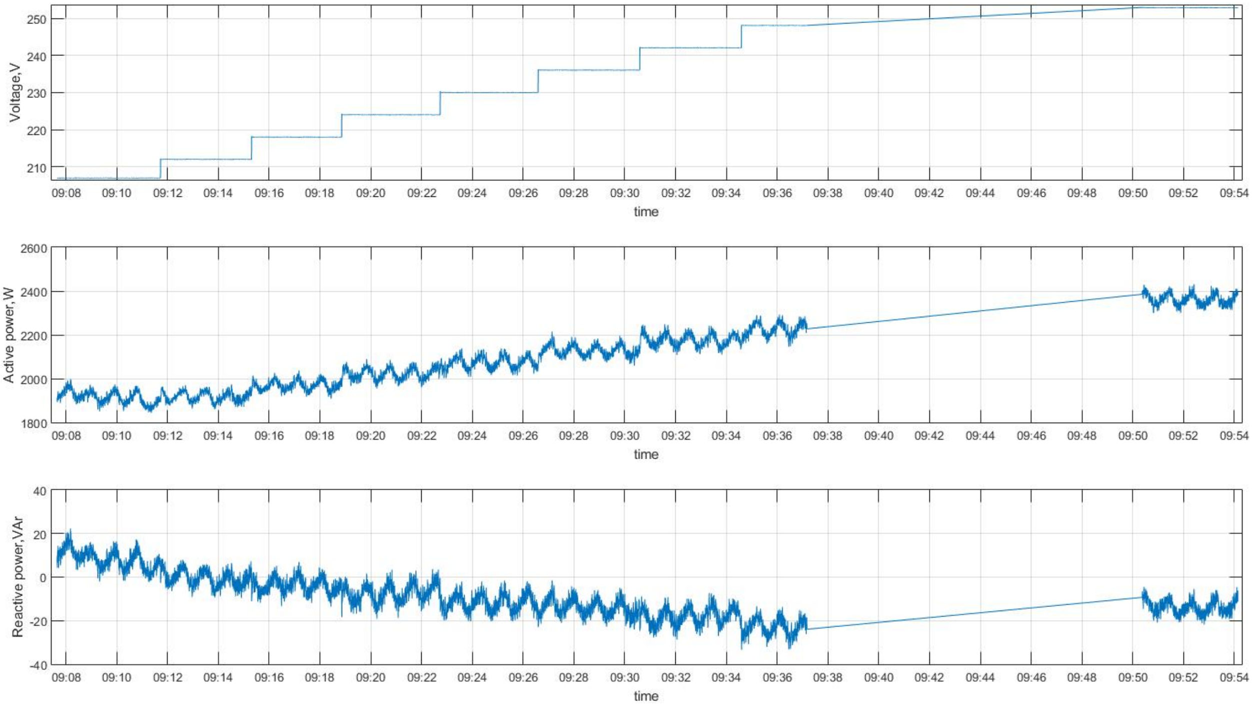


Figure 4.27 – Voltage, Active and Reactive power versus time for Think City charger

The tested car is Think City, electric vehicle produced by Norwegian company Think Global and assembled in US and Finland. The car has 24kWh traction battery and is claimed to be charged at 10A current [14]. The test was performed in the same way as with house appliances, but the voltage step is different.

The average charging current during the whole experiment varied between 8.66A and 9.67A, while average was 9.09A, which is close enough to the specified value.

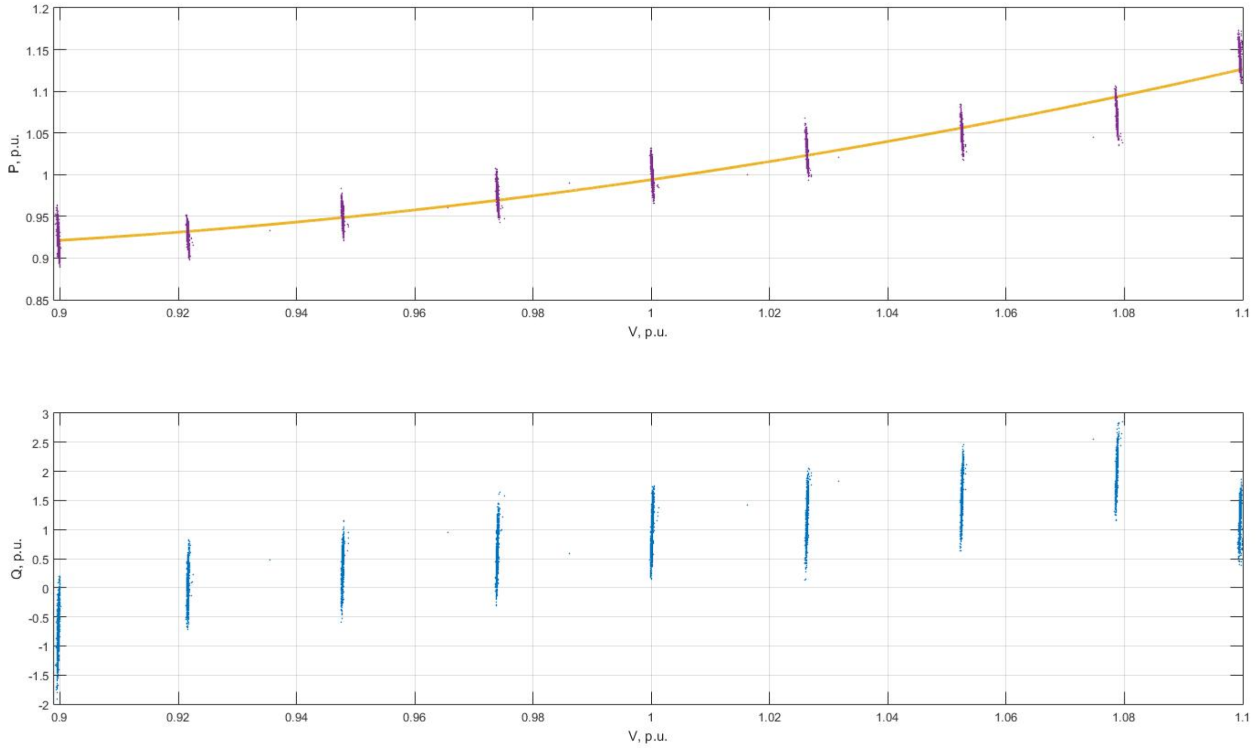


Figure 4.28 – Active and Reactive power versus Voltage (measured points and modeled curve) for Think City charger

First of all, it was totally unnecessary to create a model for reactive power variation as the absolute value changes between -30 and 20 VAr. Thus only the measured points are presented on the graph. Talking about active power, it seems to change almost linearly on the interval -8% to +8%, but at -10% and +10% the current is a bit higher, that transforms the curve into parabola. Therefore electric vehicle charger can’t be referred to as pure constant current load. Nevertheless, it shows comparatively small changes of active power consumed: -7.5% at $0.9V_0$ and +13% at $1.1V_0$.

4.3 Electric Drives

The biggest consumers of electric power are electric drives. Electric motors are used in AC, refrigerators, dishwashers, washing machines and cloth dryers. Since all of them have complex operating cycle only conventional office fan was chosen to represent that group during measurements.

4.3.1 Fan

The selected fan is capacitor-run single-phase skewed cage induction motor with rated power of 41W. The rotational speed is controlled by three buttons, each one of them changes amount of fed turns in winding, changing rotational speed. The investigated fan’s control has three positions:

- position 1 corresponds to slow speed mode;
- position 2 corresponds to medium speed mode;
- position 3 corresponds to maximum speed mode.

All 3 modes were investigated during the experiment. First of all, the active power consumption pretty much always follows the input voltage. As angular velocity is increased, fan starts consuming more active, but less reactive power. At position 3 it practically consumes negligible amount of reactive power, while active power consumption at rated voltage is 37W.

In general, for modes 1 and 2 reactive power consumption is also proportional to input voltage.

4.3.1.1 Fan with control set at position 1

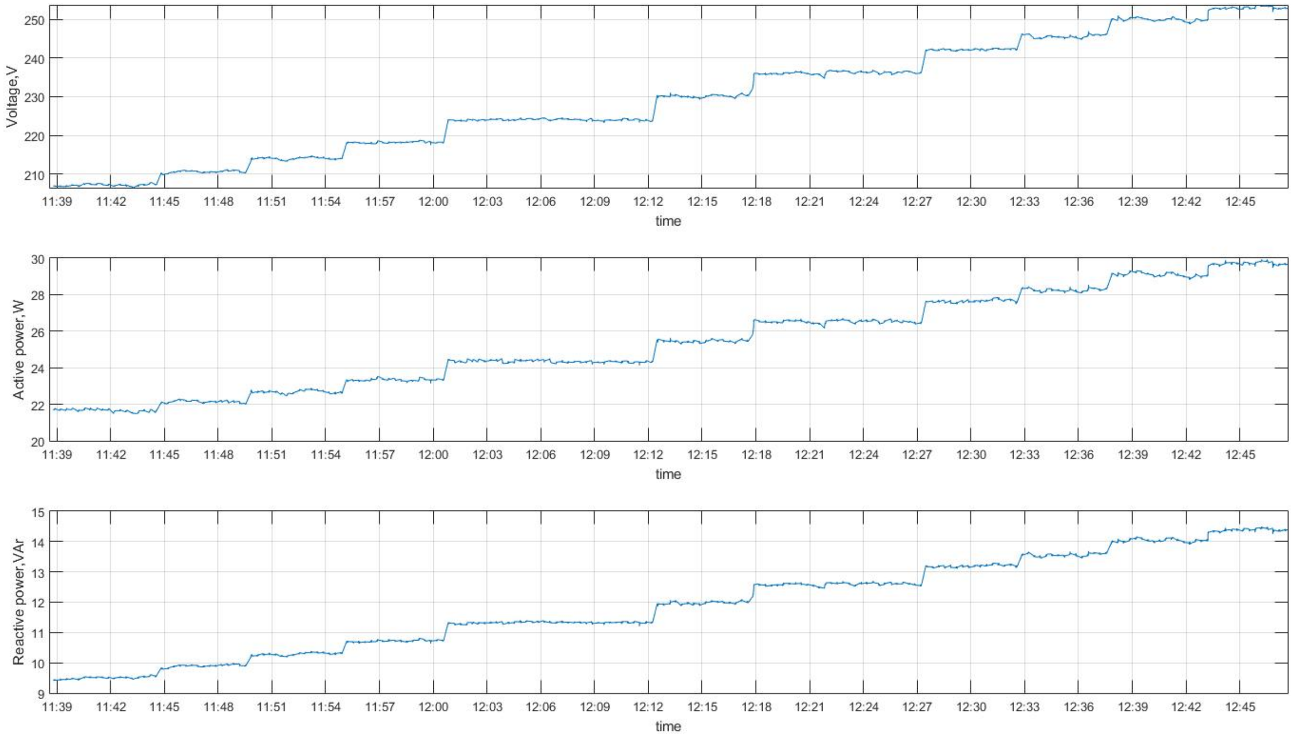


Figure 4.29 – Voltage, Active and Reactive power versus time for fan (slow speed mode)

During the experiment it was possible to clearly hear the difference in the noise frequency, which means that the speed varied a lot depending on supply voltage. In mode 1 the active power consumption behaves as very wide parabola, changing from -15% at $0.9V_0$ up to +17% at 1.1Unom, while reactive power consumption is represented by straight line, rising from -20% to %20%. That kind of active power curve’s shape can be explained as follows: when the input voltage is decreased, rotational speed also drops, thus the load becomes smaller, and motor draws less current.

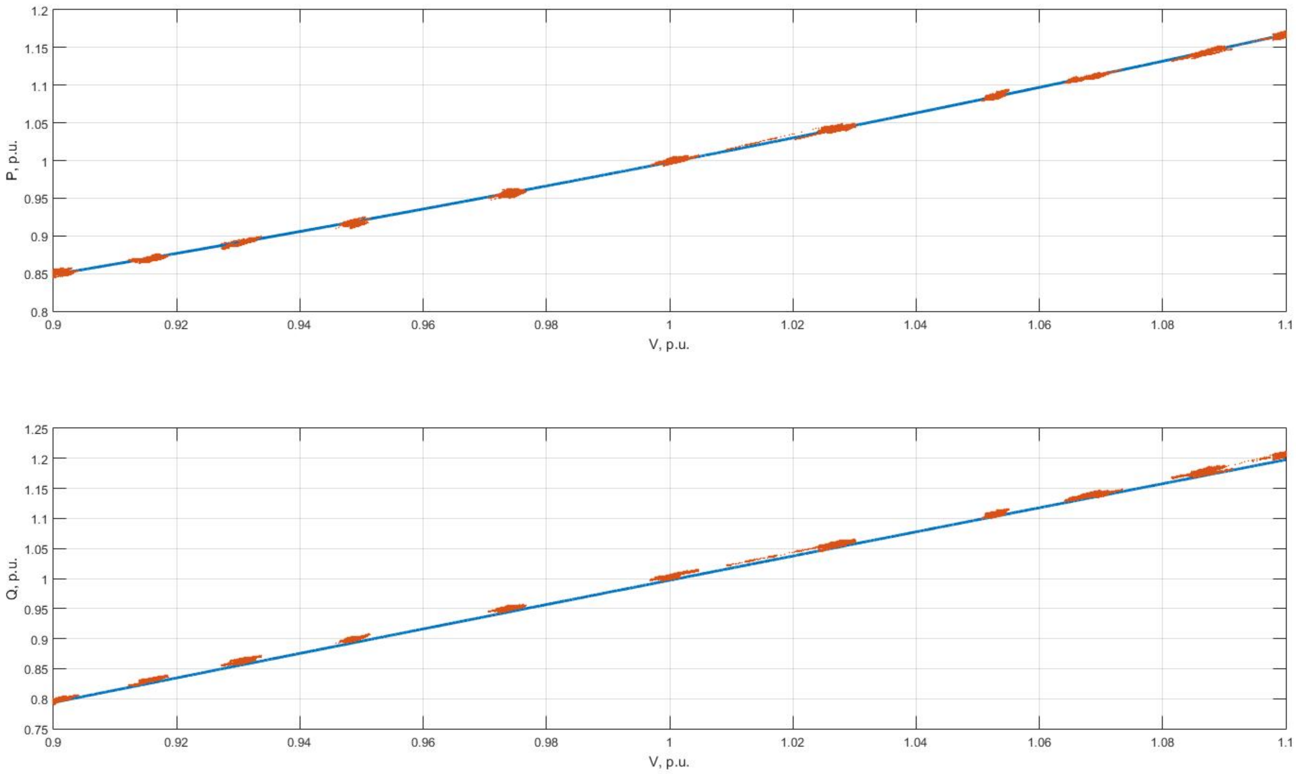


Figure 4.30 – Active and Reactive power versus Voltage (measured points and modeled curve) for fan (slow speed mode)

4.3.1.2 Fan with control set at position 2

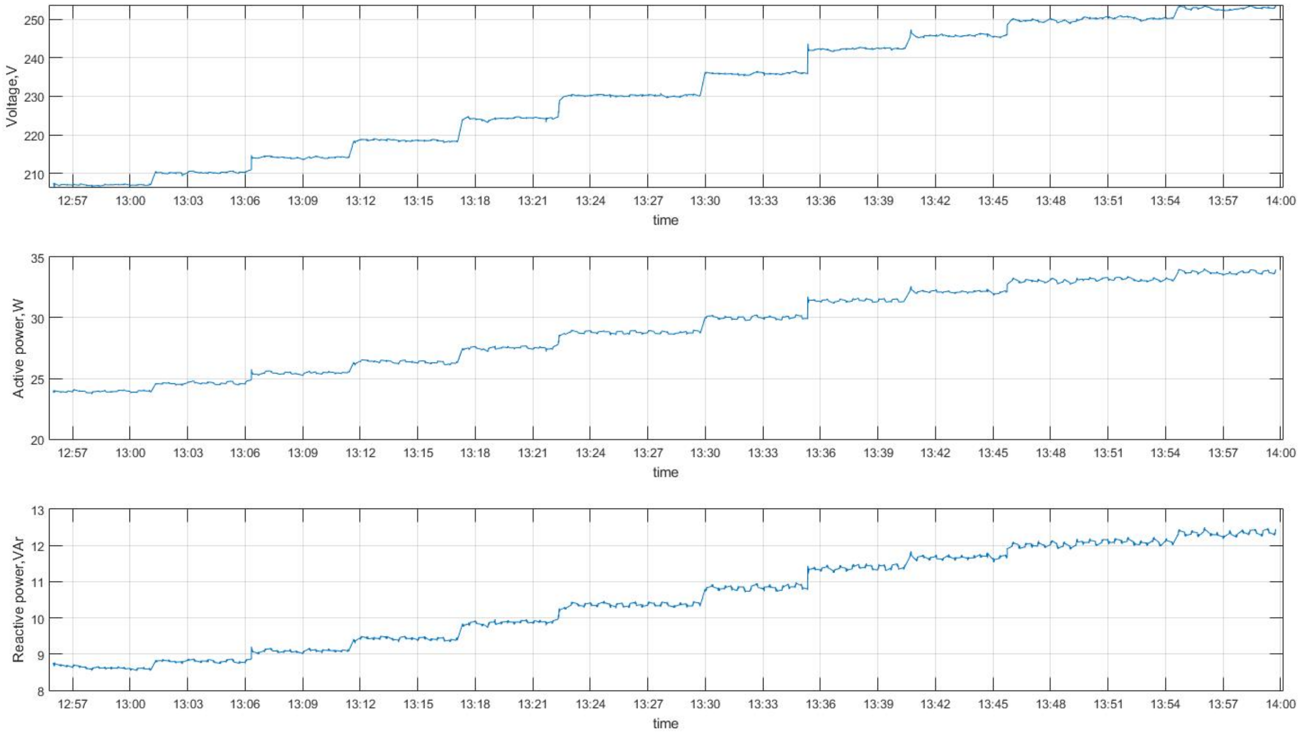


Figure 4.31 – Voltage, Active and Reactive power versus time for fan (medium speed mode)

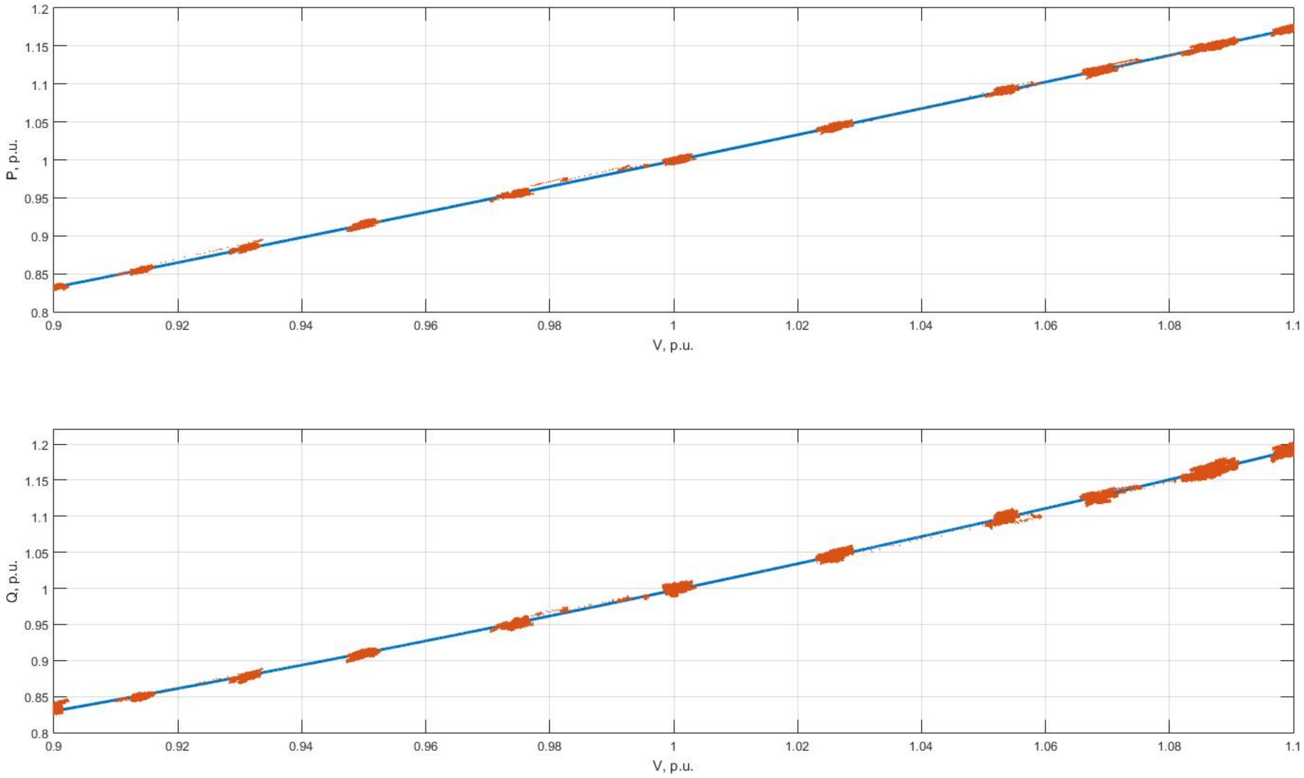


Figure 4.32 – Active and Reactive power versus Voltage (measured points and modeled curve) for fan (medium speed mode)

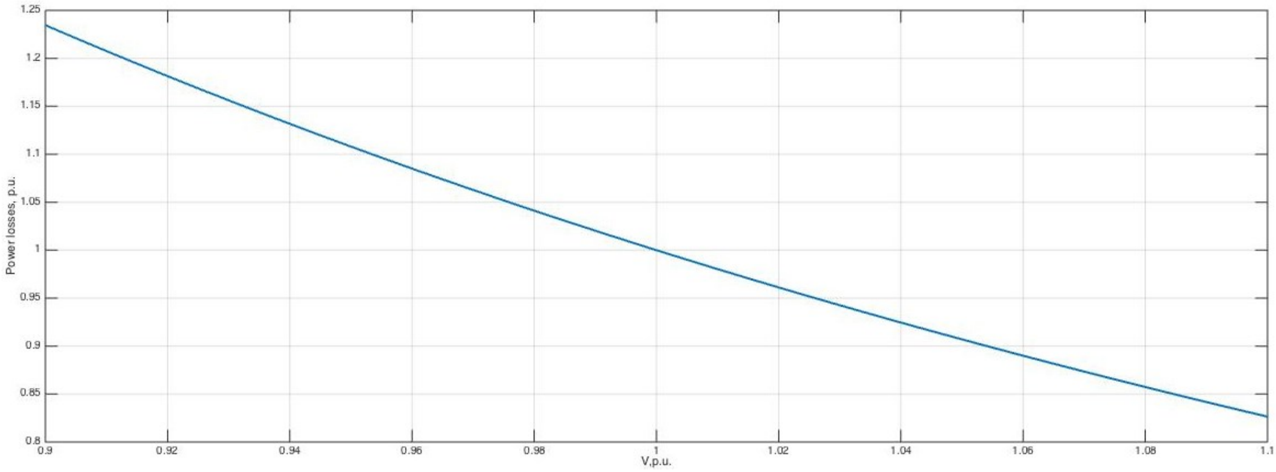
At medium speed the investigated fan consumes more active power than in mode 1, but in general power consumption behaves in the same way. The active power consumption is represented by almost straight line, reactive one is represented by very wide parabolic curve. Active power variation is from -17% to +17%, reactive one from -17% up to +19%.

4.3.2 Induction motor with constant mechanical load

Constantly loaded induction AC motors are part of various house appliances such as water pumps, HVAC, refrigerators, washing machines etc. There is a huge variety of models, so it's very difficult to create universal model, so the simplest case will be considered, where core losses will be neglected. As the power output is more or less constant, the current is reversely proportional to voltage. The copper losses depend only on square of current, thus power losses are equal to

$$P_l = \left(\frac{1}{V}\right)^2 \cdot r_{eq}$$

As r_{eq} can be taken as p.u., there remains just reverse proportionality to square of voltage. Then the obtained model can be multiplied by typical values of losses percentage for low power induction motors and thus proper active power consumption versus supply voltage model can be obtained.



4.3.2.1 Fan with control set at position 3

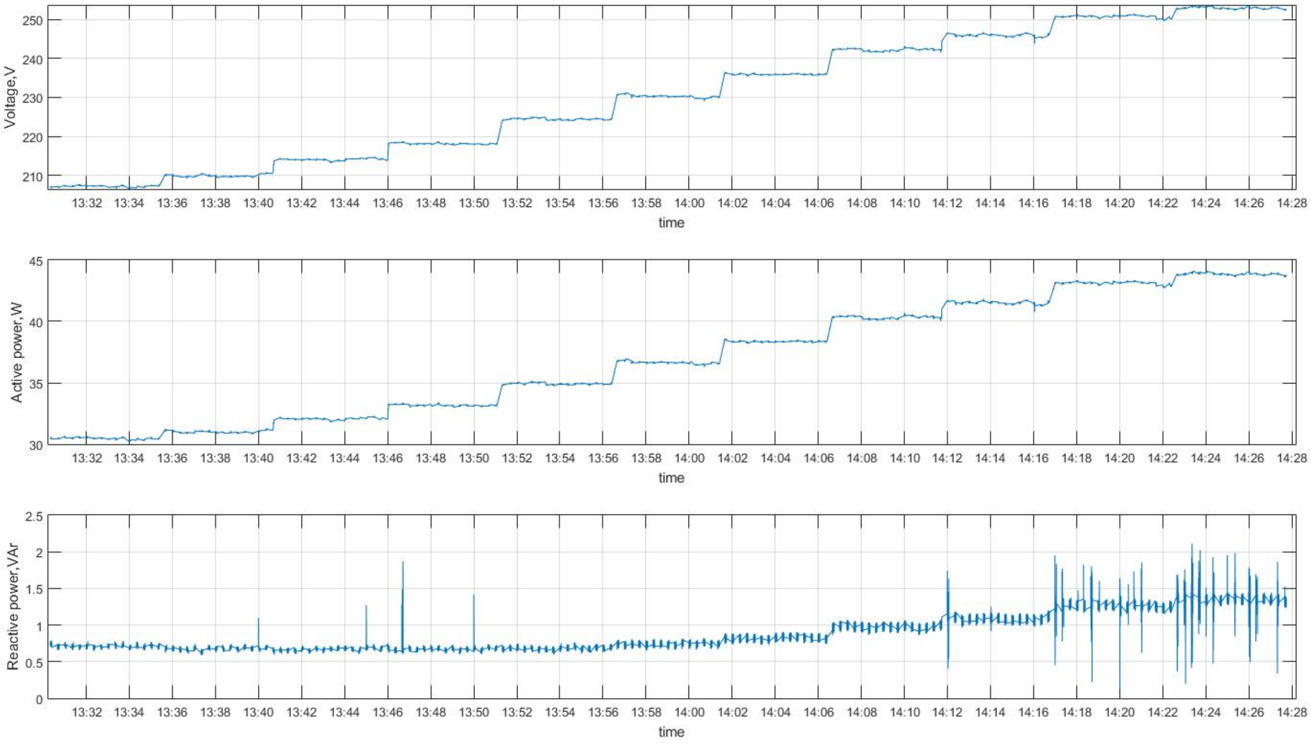


Figure 4.33 – Voltage, Active and Reactive power versus time for fan (high speed mode)

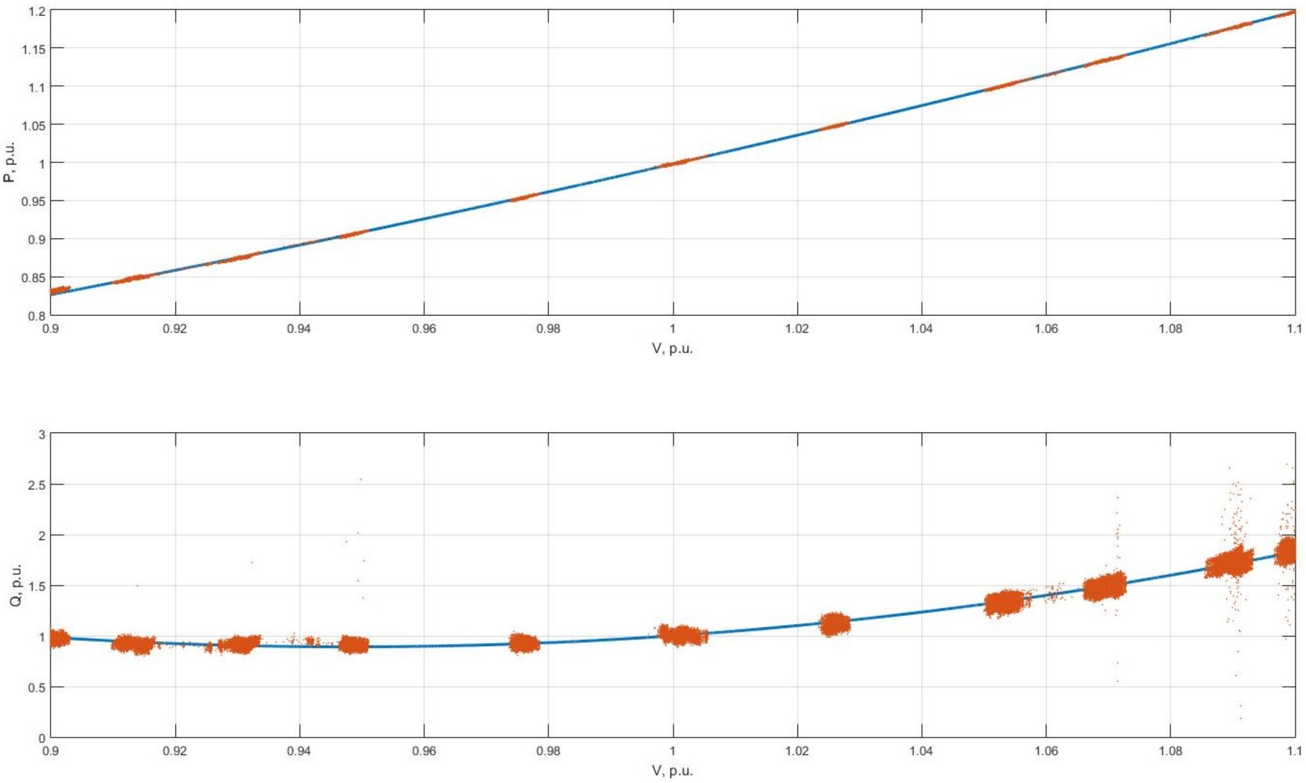


Figure 4.34 – Active and Reactive power versus Voltage (measured points and modeled curve) for fan (high speed mode)

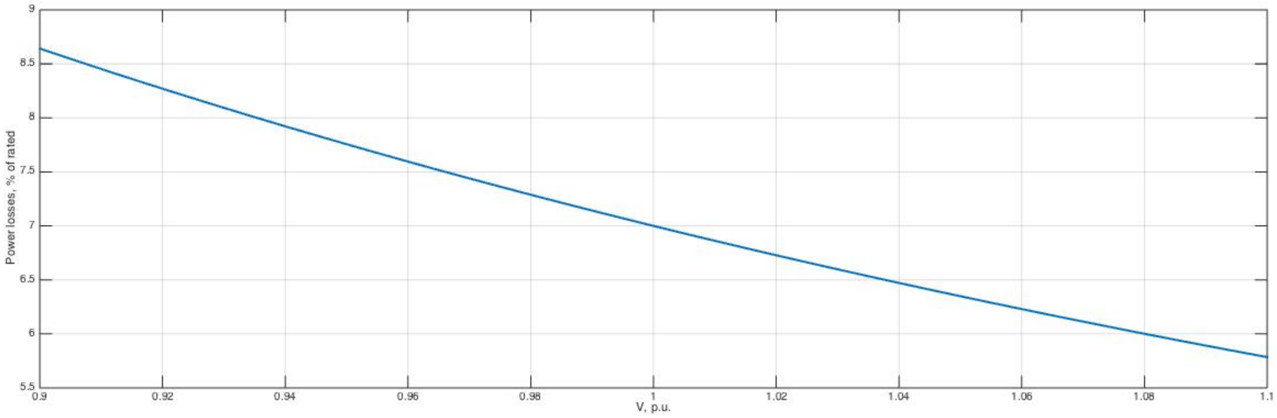
At full speed fan consumes less than one VAr of reactive power, while consuming 37W. Since fan is very fast response load, the active power measurements fit into curve very well, showing that fan is quite susceptible to voltage changes; active power consumption varies between -17% and +20%, so bigger changes happen due to overvoltages than due to undervoltages.

4.3.3 AC induction motors with constant mechanical load

As there is various selection of AC induction motors and losses significantly vary and depend on equivalent circuit of the motor, it's very hard to create universal model. Thus simplified model where only stator winding losses will be taken into account is created. As current *I* is inversely proportional to supply voltage *V*, and losses are proportional to I^2, the losses equation will look as follows:

$$P_l(V) \sim \frac{1}{V^2}$$

It's worth mentioning that iron and rotor losses are not included to this model due to high complexity of their calculation and myriad of parameters to determine. The created model only shows how stator losses behave. The following graph represents variation of losses as percentage value of the whole power consumption in the motor with rated efficiency equal 93% and all losses are considered to happen in stator. Thus the losses are represented as percentage of rated 7% losses.



It can be observed that some 1.7% increase in losses occurs at 0.9U_{nom}, as well as 2.2% decrease at 1.1U_{nom}, thus voltage variations do not cause too much troubles to low power AC induction motors, although bigger problems occur when motor heat up at low voltages. These issues are to be discussed in Chapter 6. Also proper testing of house appliances containing AC drives is necessary to create sustainable ZIP models.

4.3.4 Resistive loads

Resistive loads are usually used for heating. This group requires unique approach because classical Joule losses are actually useful energy in case of resistive loads. Thus even knowing the power-voltage response characteristics it’s hard to say how much harm voltage variations cause. Thus only one typical resistive load was tested in order to experimentally prove that resistive devices behave as constant impedance loads.

4.3.5 Resistive heater

Resistive heater with rated power of POWER was used for testing, following graphs prove that the device practically consumes negligible amount of reactive power, while active power consumption varies between -19% and +19%. That could be predicted by the theory, as $P = \frac{U^2}{R}$. Thus setting the voltage to 0.9 p.u. will result in 0.81 p.u. power consumption.

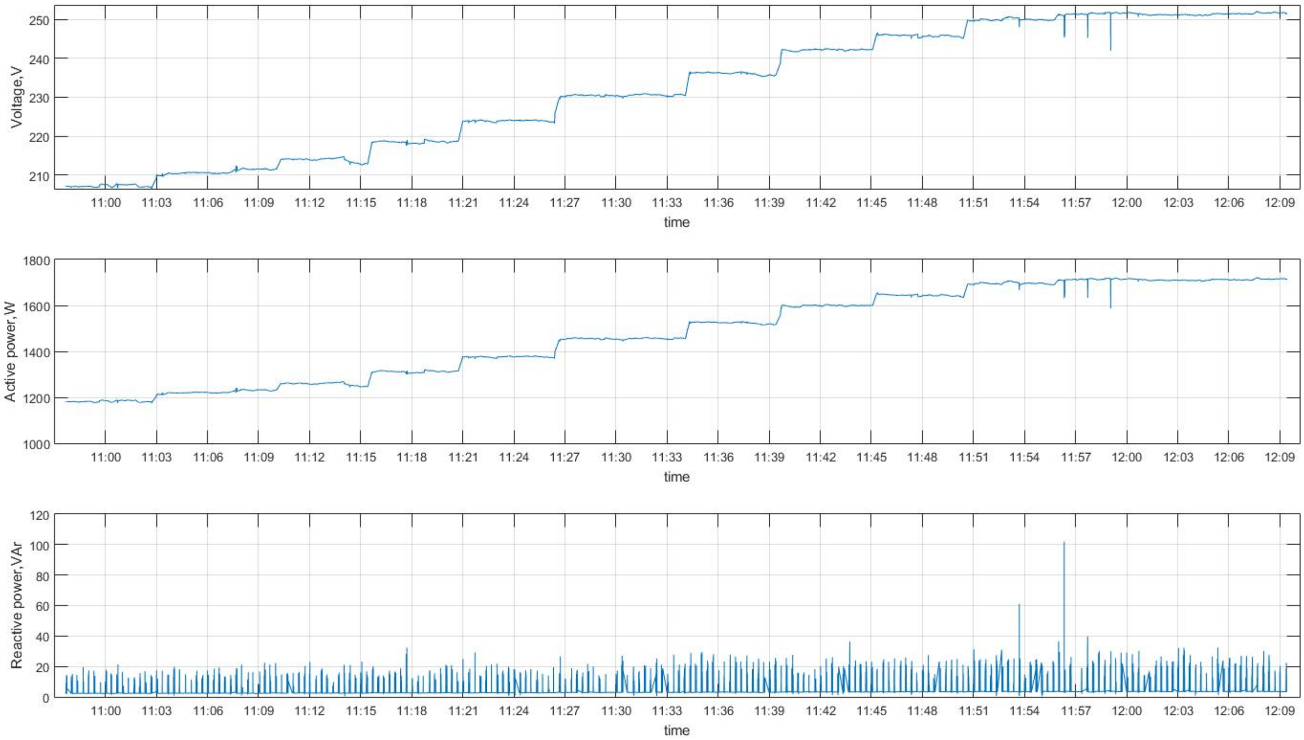


Figure 4.35 – Voltage, Active and Reactive power versus time for resistive heater

The measurement results were clear, thus curve fitting has been performed successfully. Curve for reactive consumption doesn't possess high quality parameters, but it's not necessary to have a proper Q-V curve for resistive heater.

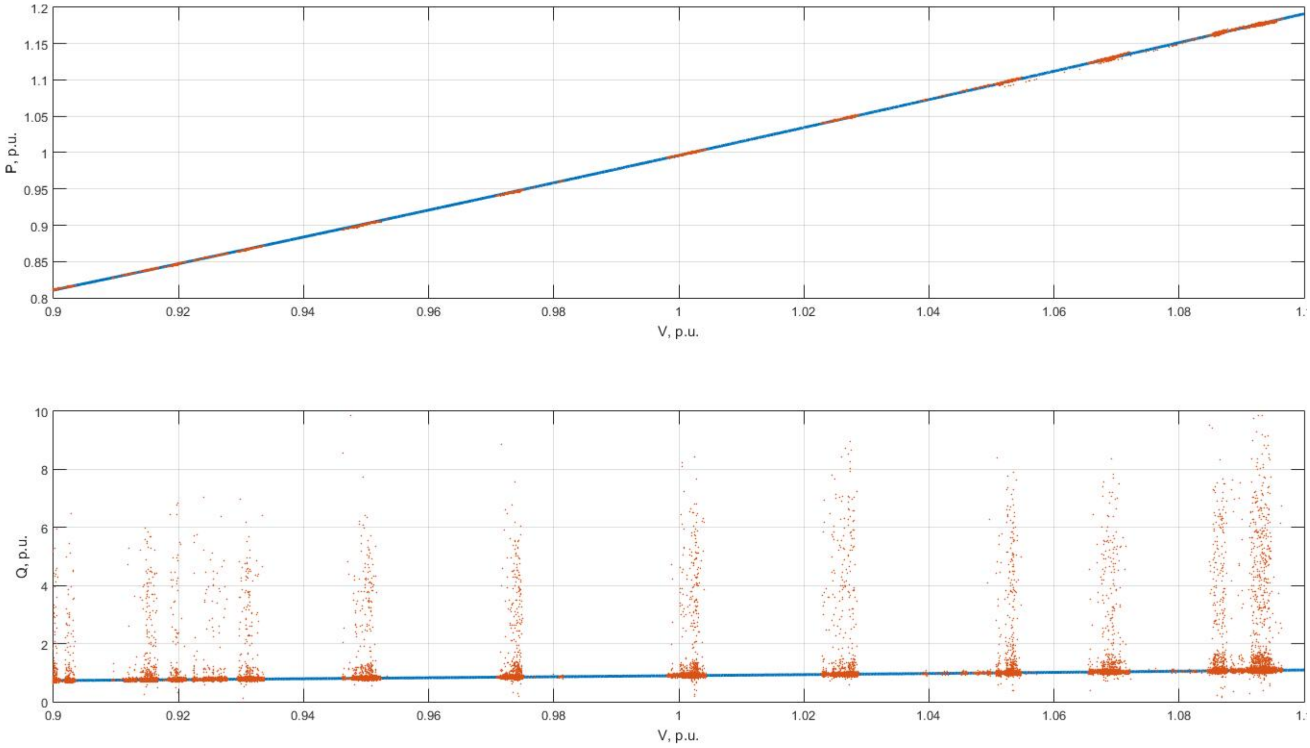


Figure 4.36 – Active and Reactive power versus Voltage (measured points and modeled curve) for resistive heater

4.3.6 *Final table*

To conclude the experiment, all ZIP coefficients for tested loads are presented in table below, where P_r is rated power of device, stated at the nameplate.

Table 2 - ZIP coefficients for different loads' active and reactive power calculation

Load	P_r,W	Active Power			Reactive Power		
		Z	I	P	Z	I	P
Compact fluorescent (<0.93V)	20	1.173	-2.347	2.281	3.03	-4.311	2.288
Compact fluorescent (>0.93V)	20	5.176	-11.25	7.071	3.03	-4.311	2.288
Fluorescent lamp (Electronic)	36	0.3144	-0.6482	1.334	2.365	0.6545	-2.015
Fluorescent lamp (EM)	36	1.557	-1.006	0.4464	10.58	-12.38	2.789
Halogen lamp x5	100	0.4268	0.6823	-0.1104	1.158	-0.3901	0.2332
High intensity discharge lamp	125	1.857	-1.223	0.3685	2.05	-0.8994	-0.1488
LED lamp (<0.953V) x2	12	0.2512	-0.6754	1.425	79.41	-141	63.23
LED lamp (>0.953V) x2	12	0.2512	-0.6754	1.425	-3.851	7.779	-2.933
Microwave oven	1400	1.357	-2.111	1.896	124.7	-213.6	89.54
PC system unit	-	9.147	-16.94	8.706	23.94	-47.3	24.1
PC display (<0.933V)	-	32.12	-59.98	29	32.03	-59.45	28.56
PC display (>0.933V)	-	0.1553	-0.3612	1.202	-0.783	1.871	-0.0894
TV	120	-0.3561	0.5739	0.772	1.157	-0.4614	0.3034
Office fan (low speed)	41	1.027	-0.4598	0.4305	-0.1439	2.308	-1.167
Office fan (medium speed)	41	0.3768	0.9521	-0.3301	1.338	-0.8651	0.5245
Office fan (high speed)	41	1.436	-1.013	0.5749	40.67	-77.12	37.45
Resistive convection heater	1500	0.4727	0.9577	-0.4342	1.399	-0.9847	0.48158

In order to visualize results a chart showing maximal and minimal power deviations at critical points was created.

The loads were sorted according to voltage change range, lowest on bottom. According to the chart there are only 4 loads that are not susceptible to voltage variations, these loads are electronically ballasted FL, LED, PC display and microwave oven. These loads are subjected to active power changes less than 6% at 0.9-1.1V_0 range. CFL's power consumption varies 17%, which is still less than voltage variation. There's a solid block of loads, power consumption of which varies from 26% up to 42%. The worst reaction to voltage changes was shown by high intensity discharge mercury vapor lamp.

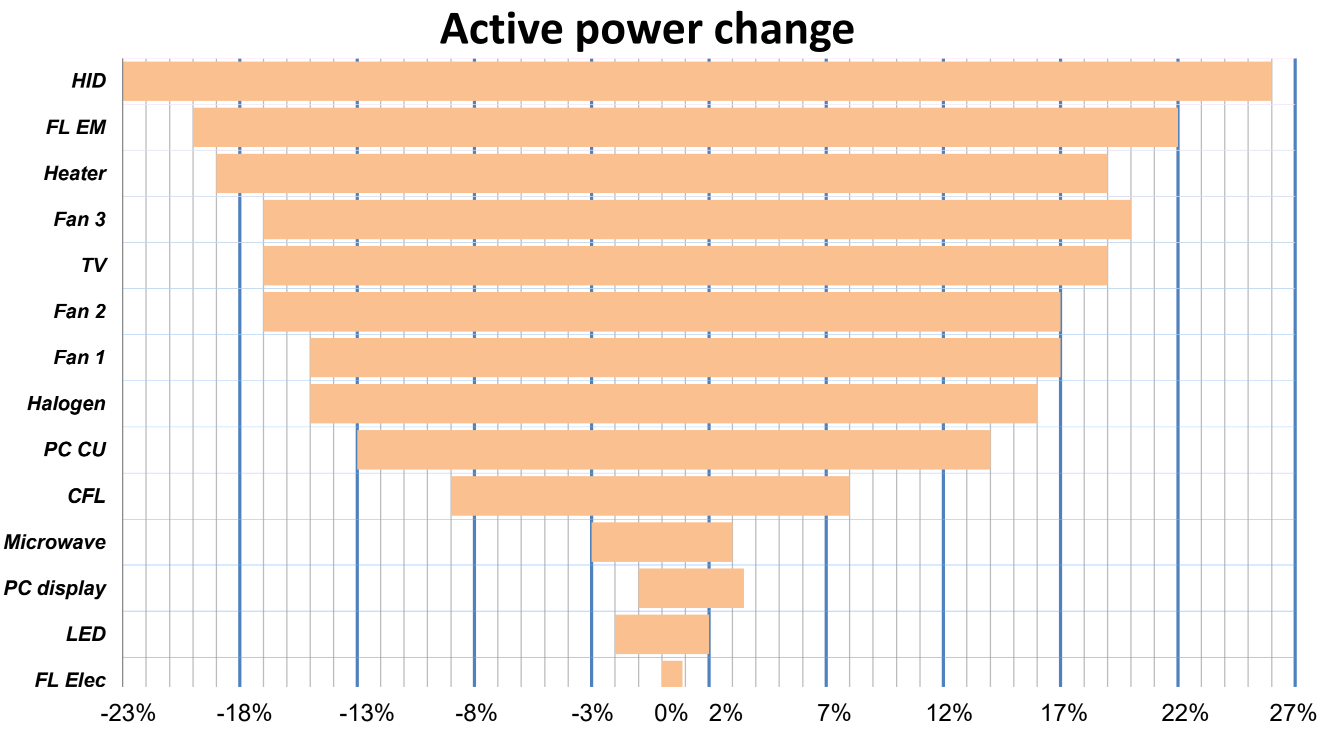


Figure 4.37 – Ranges of active power consumption change for investigated appliances

5 ESTIMATION OF MONETARY LOSSES DUE TO VOLTAGE VARIATION

5.1 Case of domestic customer

Since some of devices have different power-voltage curves, it is possible that during operation these devices actually compensate each other, resulting in very good voltage response. In order to determine average number of each type of appliance in one household, statistical data was used and mix for average Finnish household was investigated [15]. The existing models from [8] were used for appliances that were not tested. The rated power for appliances was taken same as one for tested devices. Two models were created, first one for the case with all the appliances operating at maximal power (the worst case) and the second one for case when all appliances operate at mean power. For calculation of mean power average appliances usage per day data was taken from [16]. Power consumption was calculated for each appliance separately along voltage equal V_{nom}±10% and then powers were added together to obtain total household's consumption. These calculations were performed in Excel spreadsheet. After that, obtained power and voltage vectors were imported in MatLab and the following curve was obtained by means of curve fitting:

$$P(p.u.) = 0.7733 \cdot V^2 + 0.04105 \cdot V + 0.1856$$

The following graph represents the first model:

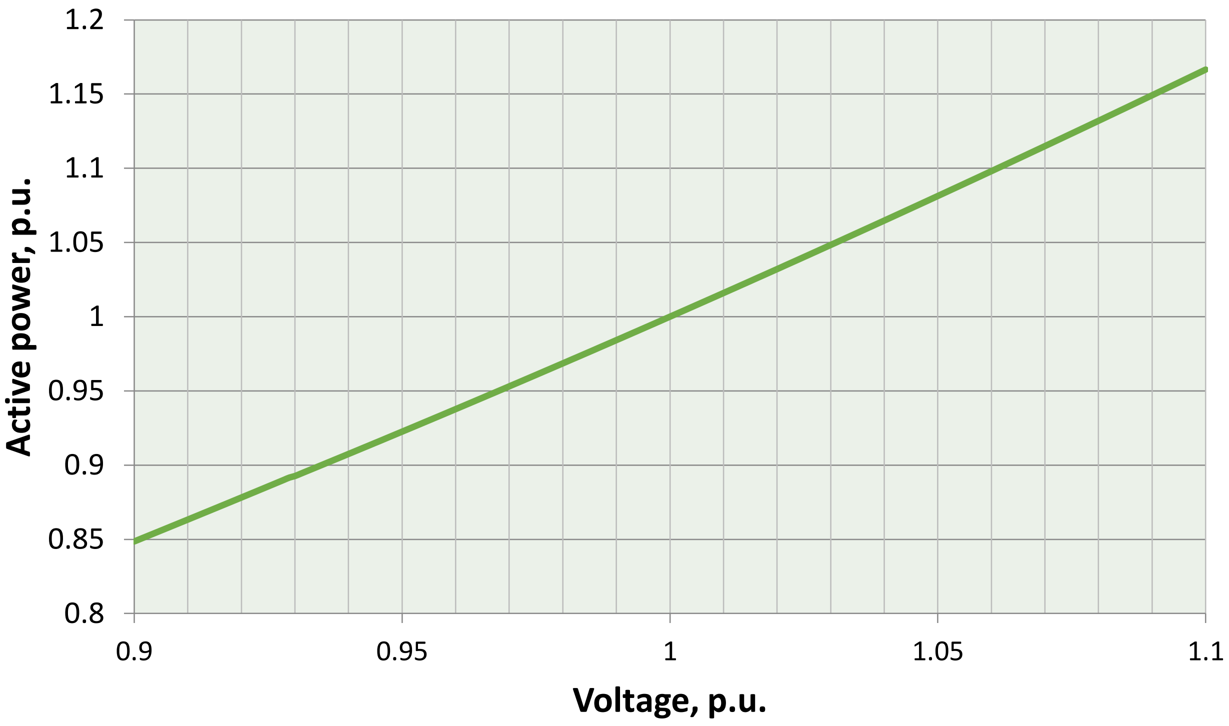


Figure 5.1 – Dependence of active power consumption on supply voltage for typical household for the case of maximal power consumption

From the obtained graph, it can be observed that at 0.9 p.u. the active power consumption drops by 15%, while at 1.1 p.u it increases by 17%. That shape of curve can be explained by domination of resistive and motor loads in energy mix.

The second model that takes into account operation of appliances at mean power is represented by the following formula:

$$P(p.u.) = 1.048 \cdot V^2 - 0.4235 \cdot V + 0.3755$$

The visual representation of the model is presented below:

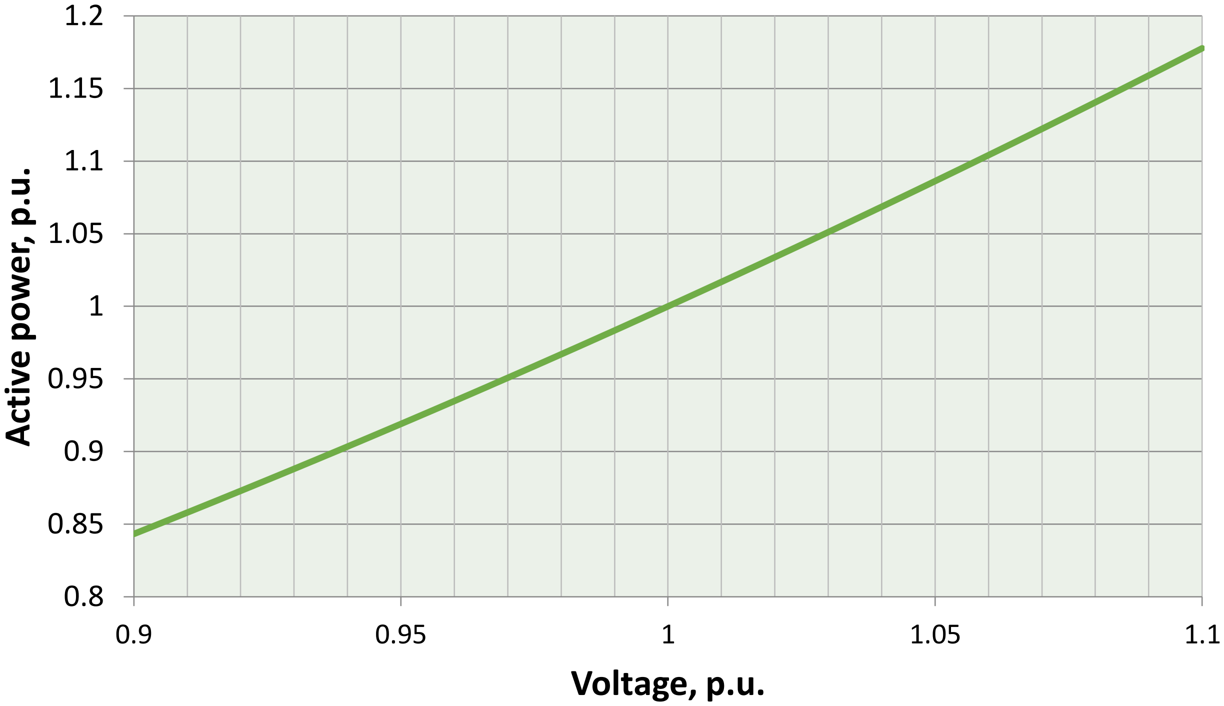


Figure 5.1 – Dependence of active power consumption on supply voltage for typical household for the case of mean power consumption

Slight differences between two models can be observed, in the mean power model active power consumption varies between -15.5% up to 17.5%, so both limits are 0.5% higher then first model's ones.

For the cost analysis the mean power model will be used because it actually represents the average values of power consumption, not critical. For creation of penalty function resistive loads were excluded from the model as there are no losses caused by voltage variations. Basically the losses penalty function was calculated as follows:

$$q_1 = [P(V) - P(V_0)] \cdot c$$

where q_1 is penalty,

c is cost of electricity, $c = 3.11\ cent€/kWh$

P is active power consumption (p.u.)

At the same time there's a penalty component caused by loss of life of electrical motors (especially constantly loaded AC induction motors). The penalty function was estimated based on life expectancy curves, represented in Paragraph 6. Monetary value of loss of life equation looks as follows:

$$q_2 = \frac{(L.E._{p.u.} - 1) \cdot 100\%}{t_{rated} \cdot \left(2 - L.E._{p.u.}\right)} \cdot price$$

where $L.E._{p.u.}$ is life expectancy in p.u.

t_{rated} is rated service life

$price$ is average price of motors in $€/kW$

The average motor price was estimated based on data from [17], only motors with rated power up to 1.1 kW were investigated.

The next figures represent the penalty for power losses, penalty for loss of life and 2 combined penalty models. In the first one total penalty equals just sum of $q_1(V)$ and $q_2(V)$, in the second model the negative regions of $q_1(V)$ and $q_2(V)$ equal zero, which is more favorable for customers, but less favorable for distribution companies. In both models components $q_1(V)$ and $q_2(V)$ are multiplied correspondingly by W_1 and W_2. These coefficients represent respectively share of non-resistive devices in the total household mean power consumption and share of motor loads.

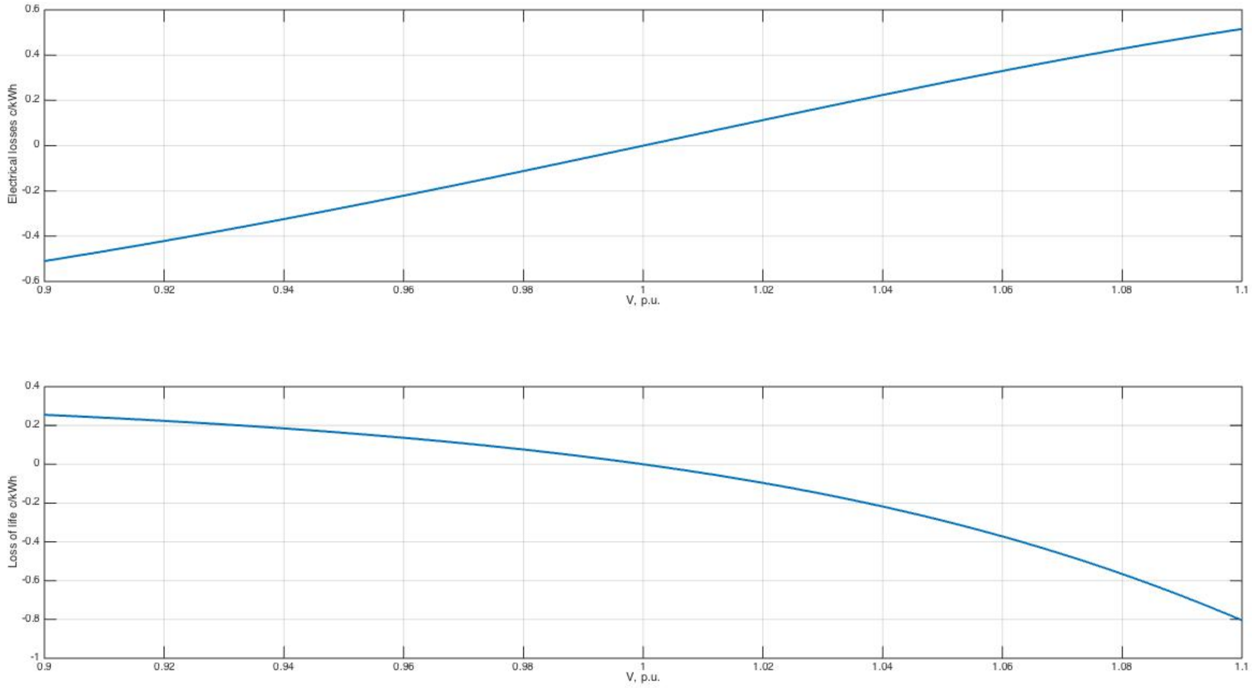


Figure 5.2 – Penalty due to power losses and loss of life functions

It can be seen that without weight coefficients W_1 and W_2 penalties due to loss of life seem to be significantly higher than for electrical losses, but coefficients were taken as $W_1 = 67.73\%$ and $W_2 = 21.61$, so in the typical household power losses have more significant economical impact.

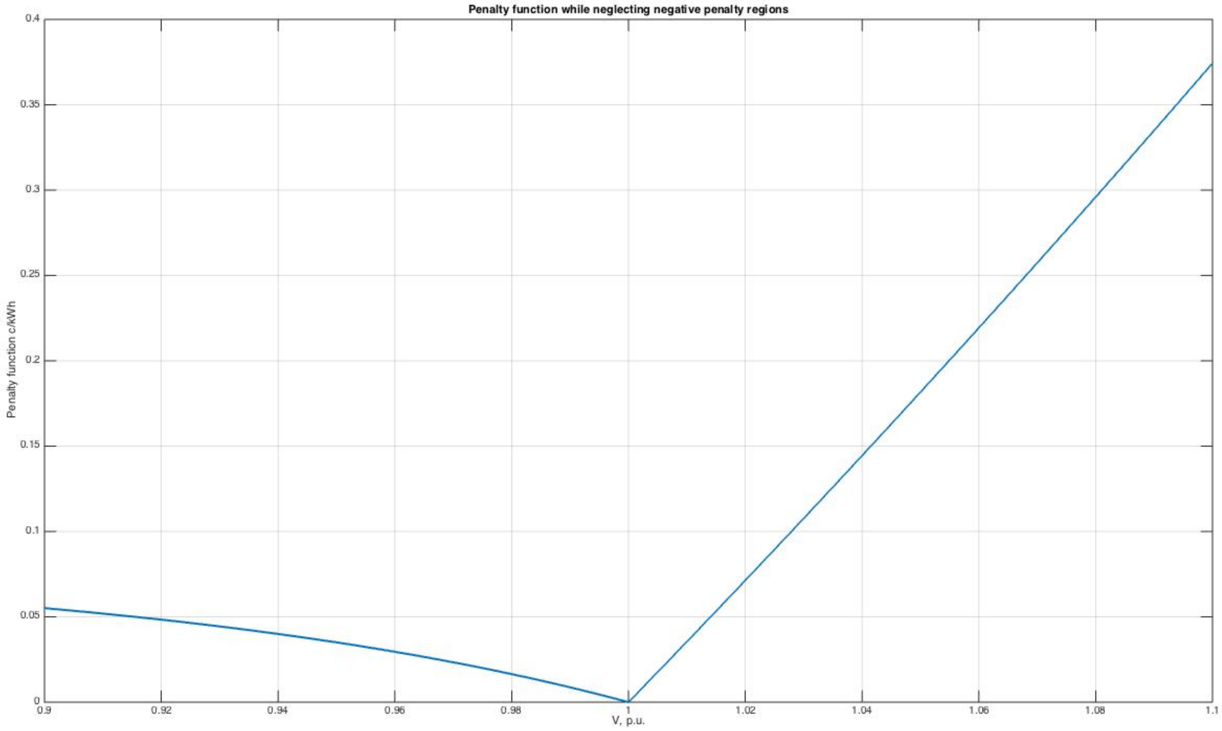


Figure 5.3 – Combined total penalty function while neglecting negative penalty regions, c/kWh

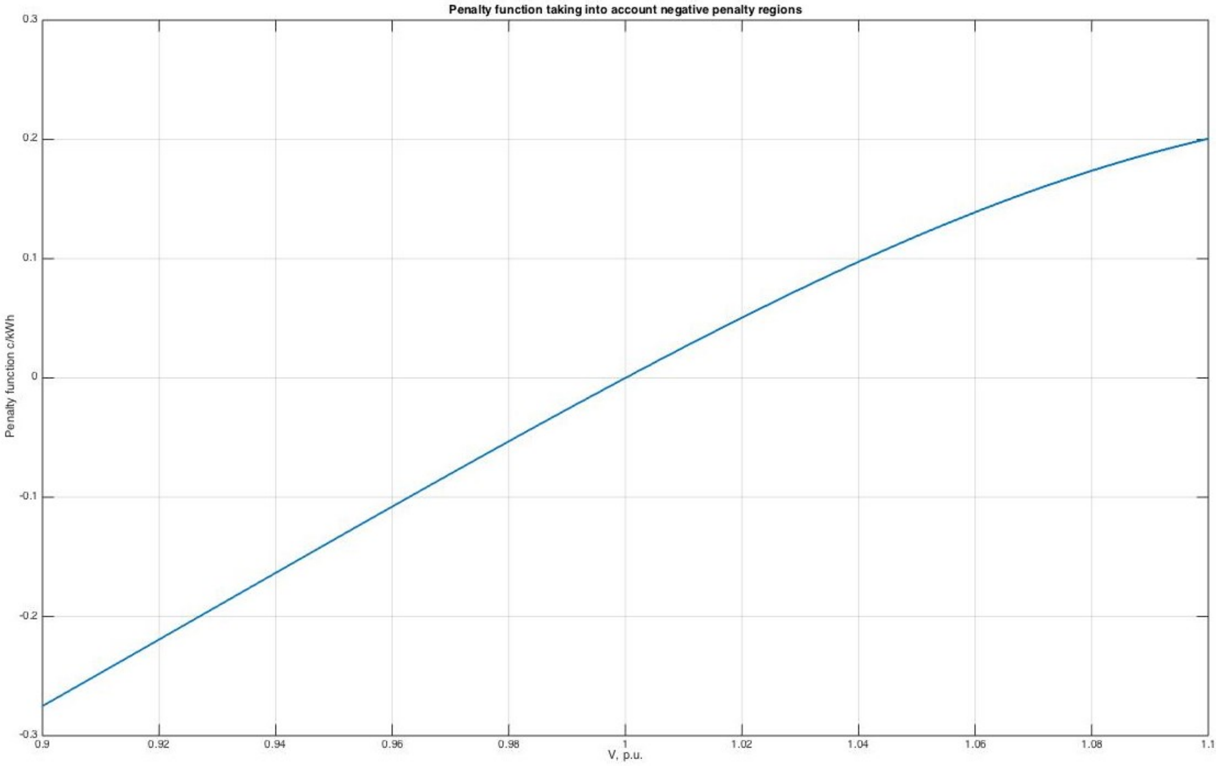


Figure 5.4 – Combined total penalty function while taking into account negative penalty regions, c/kWh

As it can be observed from the graph, the region of positive voltage deviations doesn't differ significantly in both models, while there are crucial changes in negative deviations region. In the first case distribution company has to pay the fee from 0 up to 0.37 cents/kWh, in the second case company is actually allowed to charge the customer in case of low voltage, that doesn't make much sense from customer's point of view as it does not motivate distribution company to keep voltage at 1 p.u.

Thus for final p.u. graph first scenario was chosen:

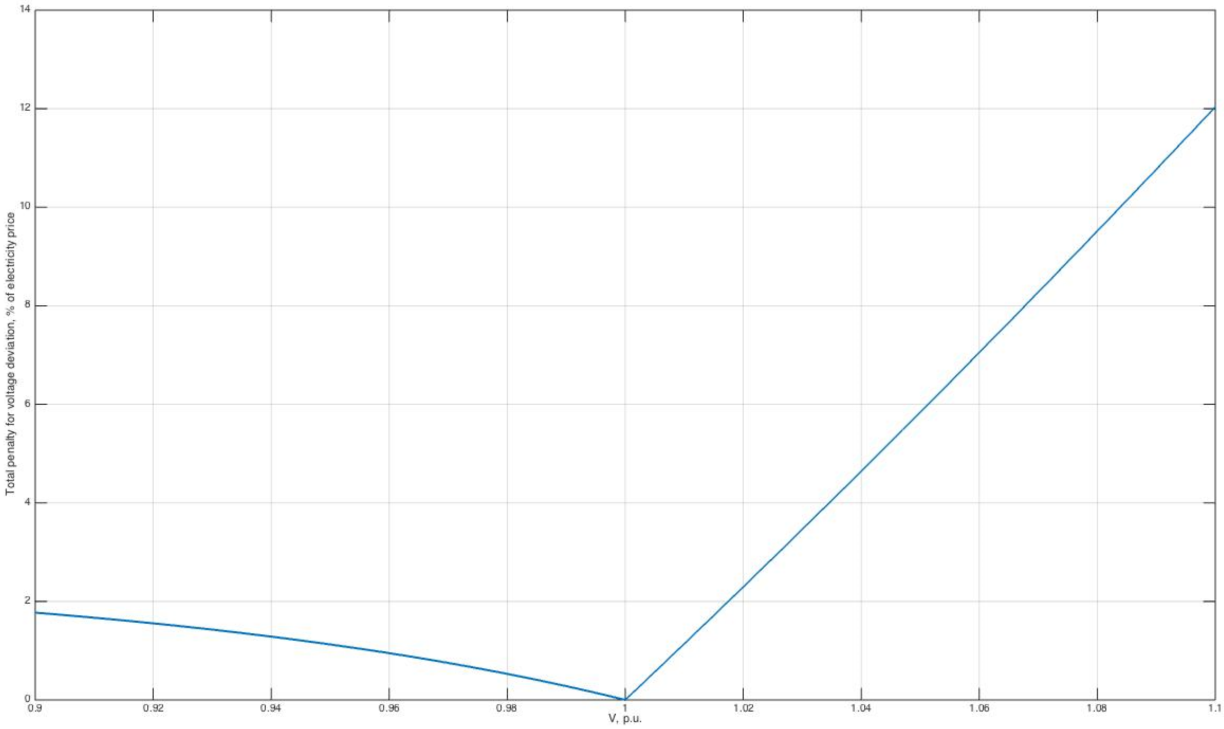


Figure 5.5 – Total penalty charged from distribution company for voltage deviations, % of electricity price

Thus significant fees may be applied to electricity distribution companies for voltage deviations, therefore decreasing of allowed voltage band might be considered.

5.2 Case of commercial customer

In this study a typical office for 20 people working with the computers was selected as commercial load as no statistical data was found about appliances' saturation. The selected office is similar to typical University's research facility, it consists of 5 working rooms for 4 people each and a lounge room with kitchen in it. Each working room is illuminated by 8 electronically ballasted FLs, while 16 are used for lounge room and 24 are used for corridor. Each of 20 people has one PC and at least one display (half of personnel are assumed to have 2). Same algorithm is used as in domestic load's analysis, except only mean power model was created.

The mean power consumption is described by following formula:

$$P(p.u.) = 6.989 \cdot V^2 - 12.86 \cdot V + 6.868$$

The graphical representation of model:

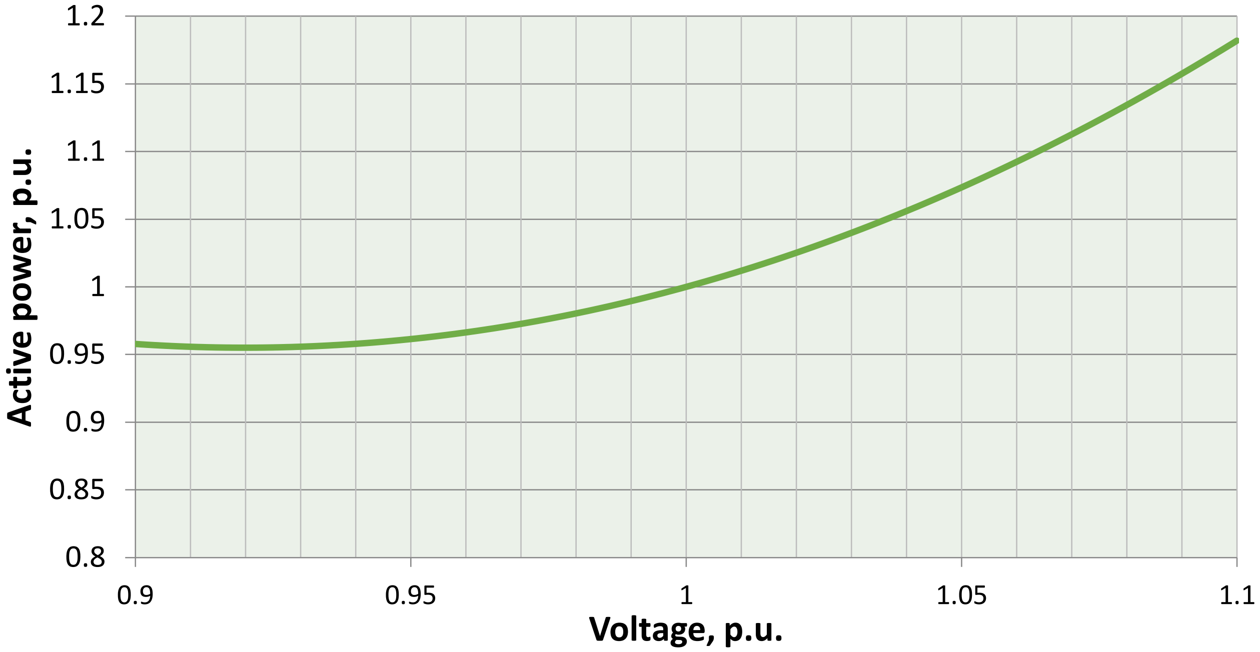


Figure 5.6 – Dependence of active power consumption on supply voltage for commercial customer

It can be seen that active power consumption does not vary as much as it did in case of domestic load, it also has strong non-linearity. That's caused by absence of resistive loads and low number of motors.

The penalty can now be calculated based on the model, weight functions here will be $W_1 = 100\%$ and $W_2 = 6.36\%$. Again 2 scenarios were taken into account: one taking into account negative fees region and another one neglecting it.

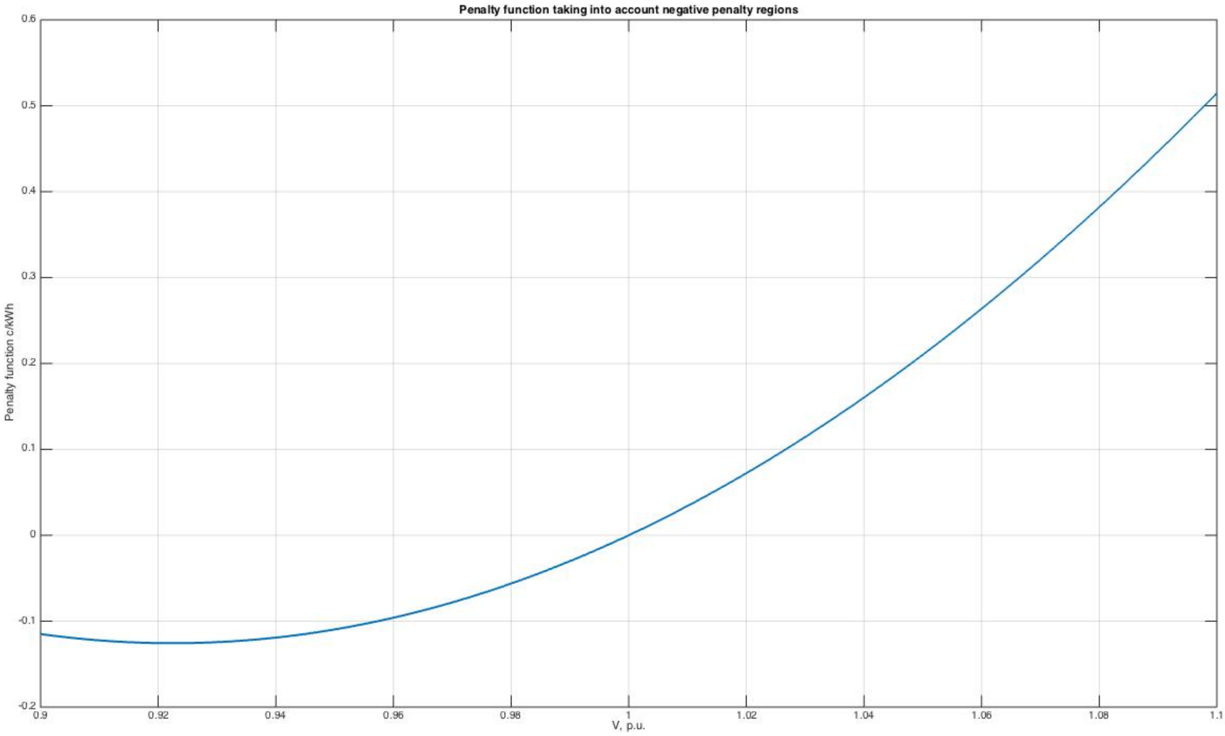


Figure 5.7 – Combined total penalty function for commercial customer while taking into account negative penalty regions, c/kWh

The penalty for overvoltages appears to be higher than in case of domestic customer. The reason is very low amount of resistive loads in commercial customer's appliances mix, so all the excessive power usage is considered to be losses.

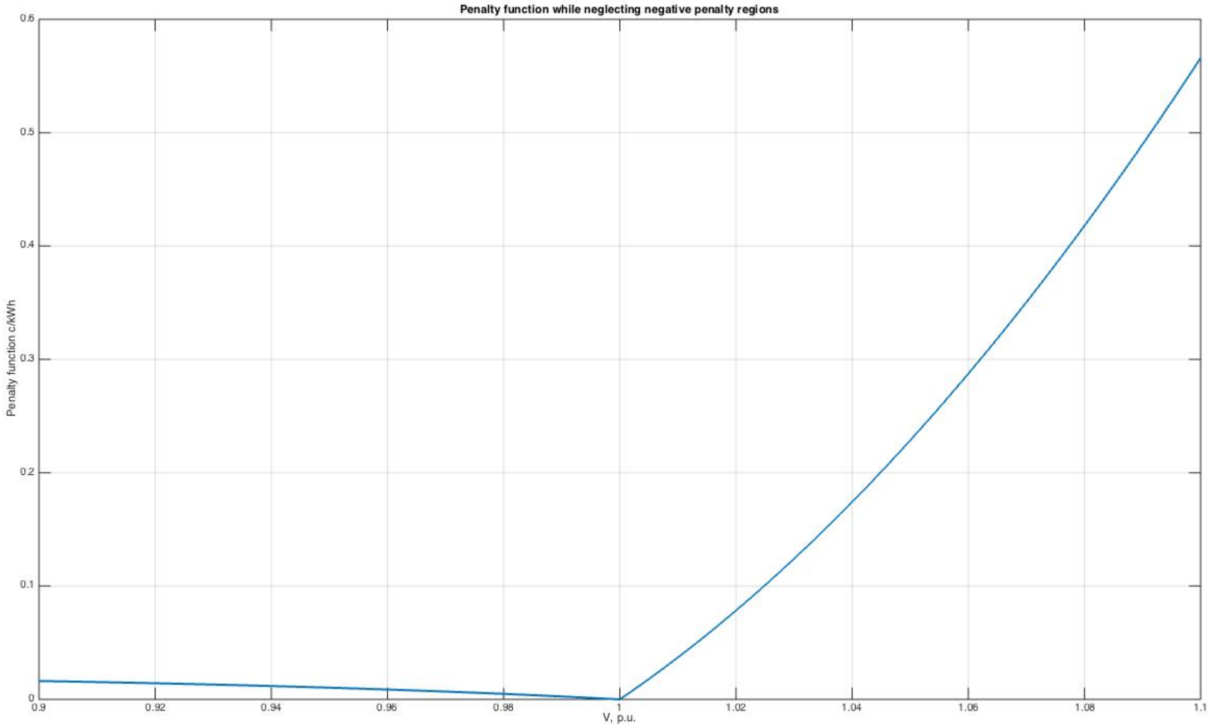


Figure 5.8 – Combined total penalty function for commercial customer while neglecting negative penalty regions, c/kWh

The graph in case when negative penalty regions are neglected is presented above, the penaly varies from 0 cents/kWh up to 0.56 cents/kWh.

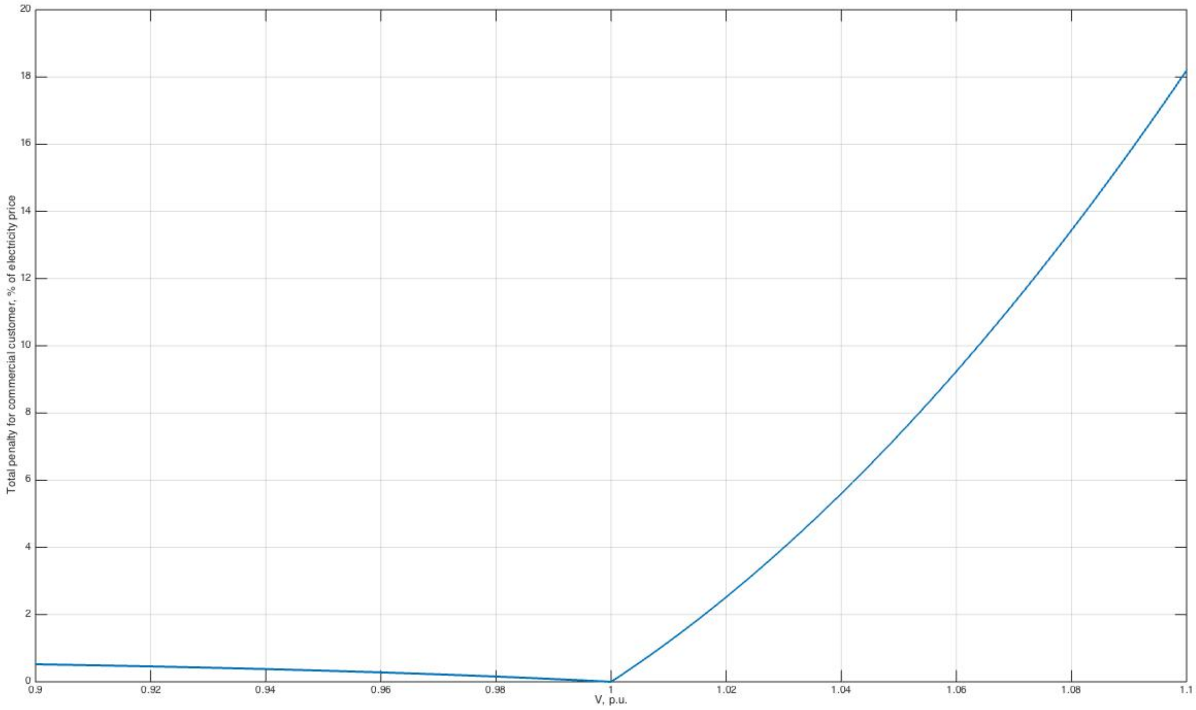


Figure 5.9 – Total penalty for commercial customer charged from distribution company for voltage deviations, % of electricity price

Per unit representation of penalty is presented above, the second case was taken into consideration again. The value of penalty reaches 18% of electricity price at voltage 0.9 p.u., that makes it considerably larger than one for domestic customer which is 12%.

6 LOSS OF LIFE ESTIMATION

6.1 Motors

The other issue, caused by voltage variation is reduced service life of appliances. The most susceptible devices are motors, because even small change in voltage may cause overcurrent that harms insulation, condition of which practically defines the service life of the machine. Thus thermal test of office fan was performed. The test installation was as follows: fan was supplied via autotransformer, while data acquisition device was reading measurements of K-type thermocouple, installed in proximity to stator winding. It was expected that temperature is higher at undervoltages, thus experiment was started from 253V, going down. First fan was running for 30 minutes in order to reach steady-state temperature (less than one degree change in one hour). Then thermocouple's readings were recorded and voltage was decreased to the next voltage level. At each voltage level it was necessary to wait for 20 minutes to make sure that temperature is steady. Despite assumptions that the temperature will rise as voltage decreases, the temperature decreased as well. That can be explained by fact that as voltage goes down, rotational speed also decreases, decreasing load. Thus current was falling as well, as showed on graph.

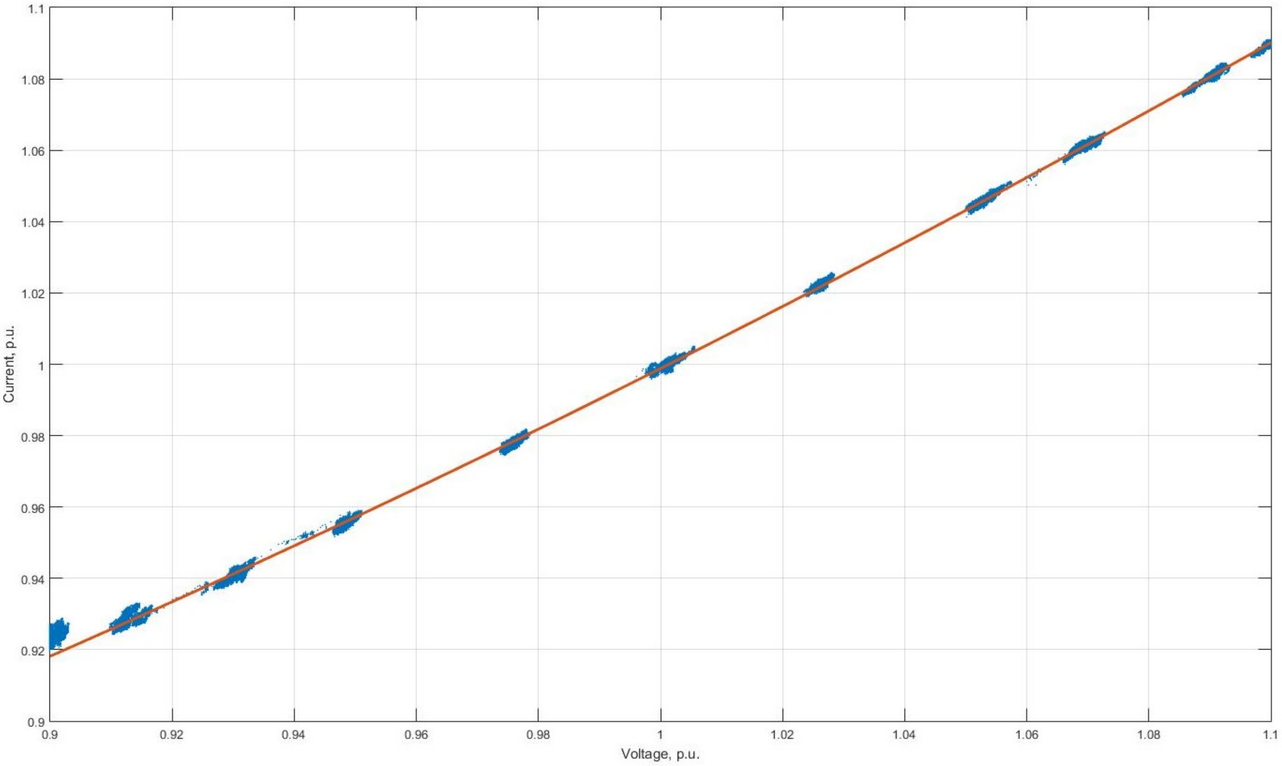


Figure 6.1 – Dependence of fan current on supply voltage

That way temperature reading was recorded at 9 different voltage levels and curve fitting was performed in MatLab. The obtained function is close to linear, but to provide less error, curve fitting of 3rd degree polynomial was done. Received function was substituted in Arrhenius' equation in order to estimate the loss of life. Arrhenius' equation was selected as loss of life model in order to simplify calculations and because it's proved to provide reliable results [18]. That way temperature at rated 230V was taken as rated temperature. Insulation class, used in fan, is A, thus admissible temperature is 105 degrees. The obtained curves, representing temperature-voltage and life expectance-voltage relationship are given below.

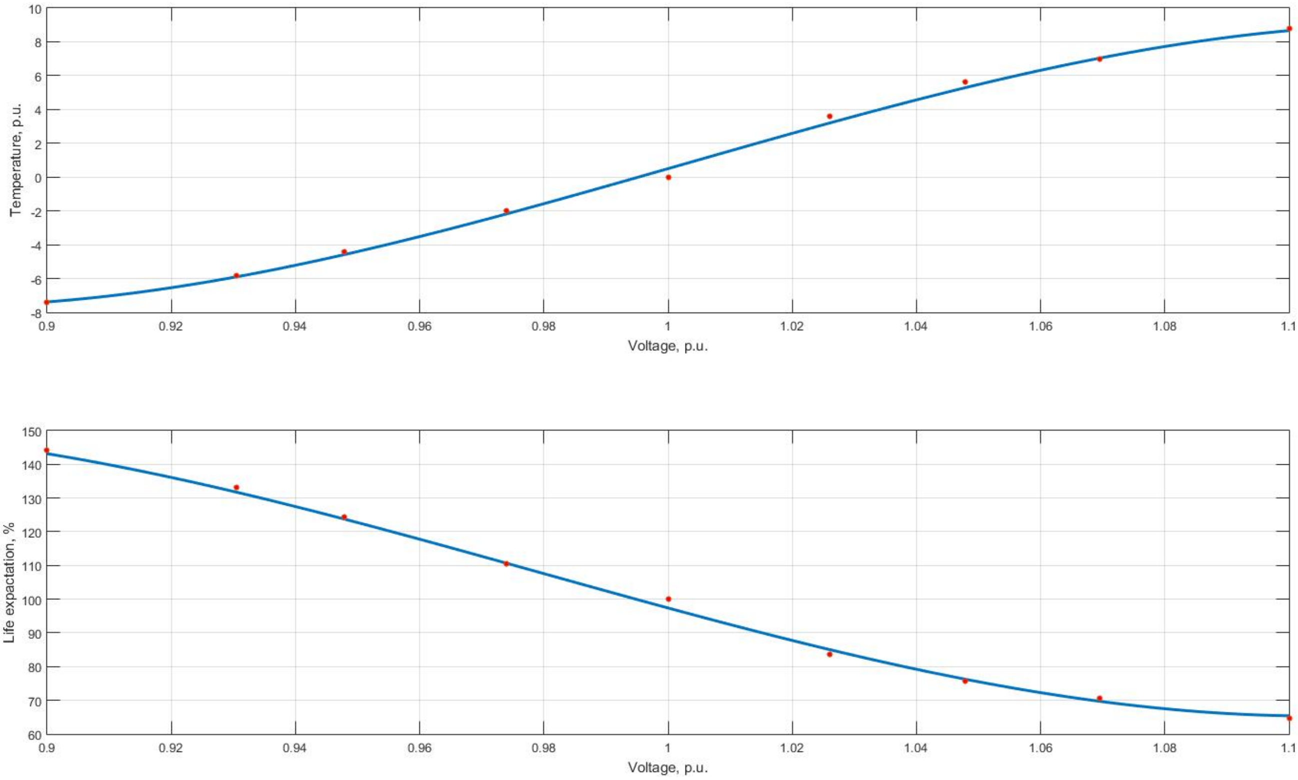


Figure 6.2 – Temperature of fan stator winding insulation and life expectancy on supply voltage

The same data represented in per unit is described by following equation.

$$LE_{p.u.} = 111 \cdot V^3 - 327 \cdot V^2 + 315.1 \cdot V - 98.39$$

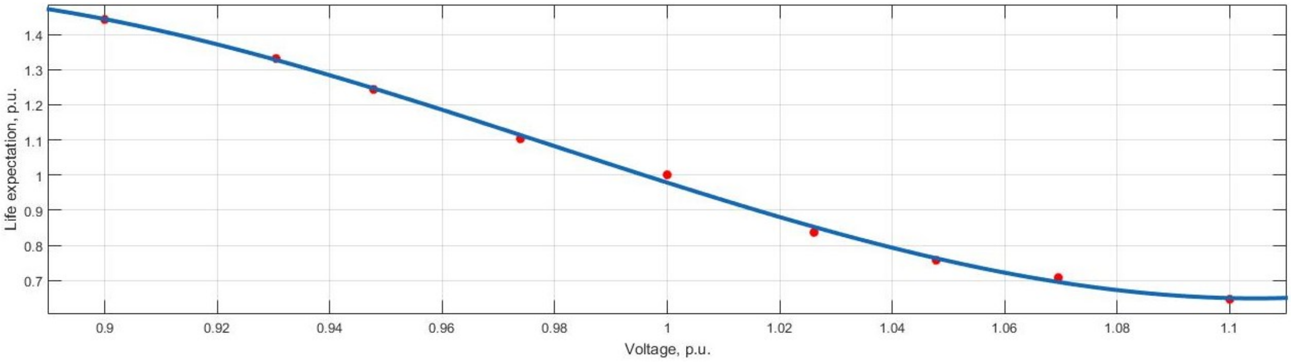


Figure 6.3 – Live expectancy versus voltage in p.u.

It can be observed that continuous operation of fan at 10% overvoltage leads to 35% loss of life, while continuous operation at 10% undervoltage allows increasing fan's life expectancy for 45%. The disadvantage of operation at undervoltage is that the fan doesn't accomplish his direct function properly, providing less air movement and thus discomfort to human.

These life estimation curves concern only fans, because their load depends on cube of velocity. If we dealt with constant load drives, the current would have increased as voltage went down, thus increasing the Joule losses in stator and possibly rotor winding, rising the temperature and decreasing the life expectancy. According to data given at [19] the temperature rise of motor's stator increases by 23% at $0.9V_0$ and drops by 14% at $1.1V_0$. Exponential model based on 3 points was created for class A insulated high-efficiency motor with rated temperature rise 60ºC. The following model was obtained using MatLab environment:

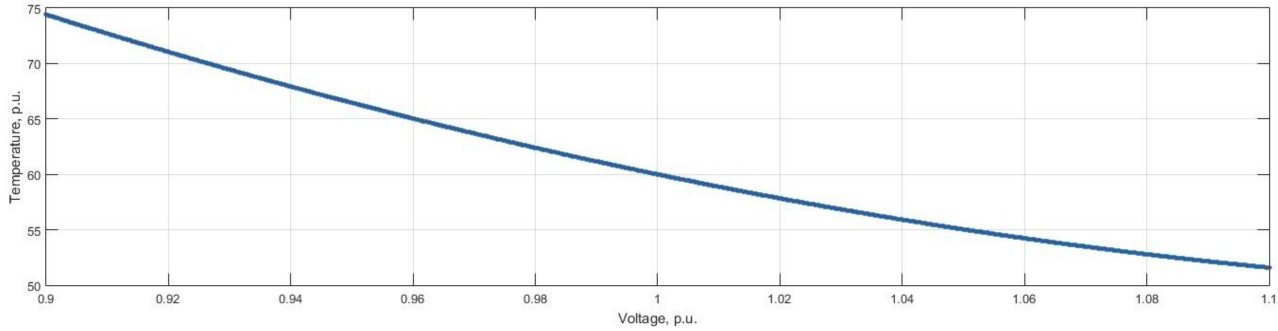


Figure 6.4 – High efficiency motor's temperature versus supply voltage

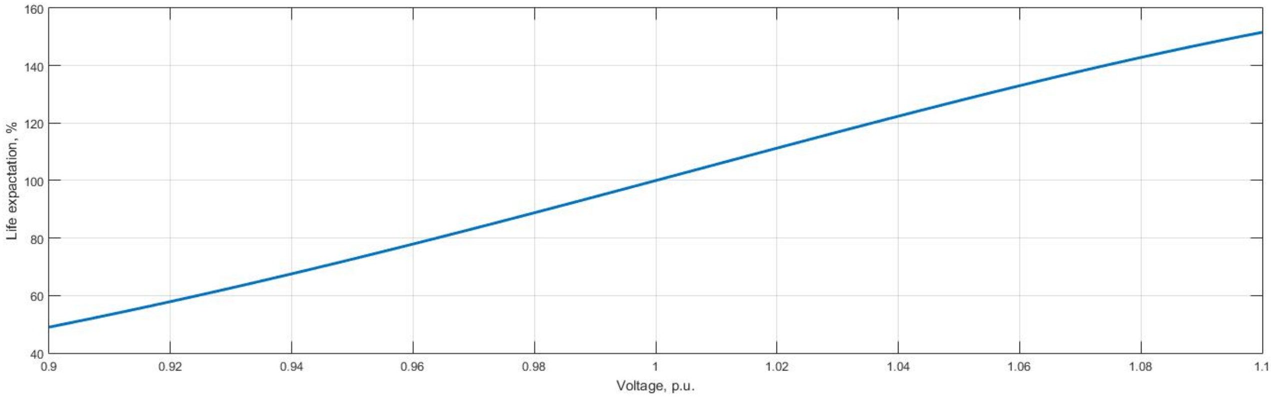


Figure 6.5 – The dependence of life expectancy on motor's supply voltage

Thus performance of high-efficiency motor with constant load is totally opposite to one of fans with variable load. The life expectancy decreases to 50% at $0.9V_0$.

6.2 Power electronics devices

In order to estimate loss of life of power electronic devices the major reasons must be investigated. According to [20], the reliability and life expectancy of semiconductor valves is directly linked to junction temperature and current. For example, even small voltage deviation in PC chip may cause massive overheating and failure of the device. On the other hand, all the electronic devices are supplied from power supplies, which are designed to provide output close to ideal even during variations of supply voltage by changing the control angle, so it can be assumed that no harm is caused to electronic devices due to overvoltages or undervoltages and life expectancy remains constant.

6.3 Illumination devices

Voltage variation influences life expectancy of illumination devices a lot. For incandescent lamp operation at $1.1V_n$ leads to 3 times decrease in life cycle, operation at $0.9V_n$ increases the life expectancy by 5 times, but decreases luminous flux by 30% [21].

Unlike incandescent lamps, EM ballasted fluorescent lamps are less sensitive to voltage variations, at ±10% deviations of voltage life expectancy is decreased by 20-25%. Life expectancy decreases even at low voltages because low voltage causes difficulties to start the lamp and makes harm to starter contacts [21].

For HID mercury vapor lamps for every percent of voltage drop the life expectancy increases by 1.3% and vice versa, thus making it +13% at $0.9\ V_0$ and -13% at V_0 [21].

7 CONCLUSION

It is a big challenge to categorize loads and estimate the economical impact of voltage variations. The economical losses are caused by overconsumption of active and reactive power, decreased life expectancy of device and inability of device to fully of partially fulfill its function. Huge amount of time was spent in order to investigate dependence of devices' power consumption on the supply voltage, some experiments had to be repeated because of insufficient preparations (for example, LED was not preheated, too low RMS averaging time was selected for PC central unit etc.), but all acceptable and valuable results were obtained. FLUKE Topas proved to be high quality power monitoring equipment, but the software kept delaying the outcomes. After all the functions of active and reactive power of supplied voltage were obtained using MatLab built in curve fitting tool, so were ZIP coefficients. These coefficients will enable more precise modeling of domestic and commercial customers' response to voltage variations and thus save electrical energy. They also may be useful while matching different loads in order to obtain close to 'ideal' constant power customer, insensitive to voltage variations.

During the experiments loads were categorized and each category was investigated: illumination, motor, power electronic and resistive loads. That division has its minuses, for example, illumination loads behave in totally different way depending on the lamp type, not all the power electronic devices are constant power loads etc. That way mentioned above categorization is not valid anymore and can be used to describe the purpose, but not physical behavior of devices.

Experiments show that devices' active power consumption varies between -23% to +26% in the worst case of high intensity discharge lamp and between 0% to +1% in the best case of electronically ballasted fluorescent lamp. In case of the most common domestic load – resistive one, the power consumption varies between -19% up to +19%, which can easily be proved theoretically. The modeled household power consumption varies between -15.7% and +17%, that leads to quite huge economical impacts. For example, according to HELEN general distribution tariff [9] 3.11c/kWh, thus for one hour of constant operation at 1.1 p.u. supply voltage, investigated customer has to pay 8.07c in addition to 47.47c. Lower voltage leads to savings, but there are different factors causing losses.

Moving further and adding estimated cost of harm caused to electric devices considered for domestic load ends up in up to 12% of electricity price taken as penalty from electricity distribution company, while for commercial customer it would be up to 18%. If that kind of penalty would be introduced it will motivate electricity distribution companies to put more effort into providing voltage of better quality and lead to more efficient energy usage.

Huge amount of work was done to update data on ZIP coefficients and point out main consequences of voltage variations, but further research is necessary to find the way to convert lack of comfort in monetary value, as well as investigate ageing of power electronics devices due to voltage variations. In addition, future plans should include research of influence of voltage sags on electrical equipment.

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