THESIS ON POWER ENGINEERING,
ELECTRICAL ENGINEERING, MINING ENGINEERING D80

Residential Grids Power Quality Analyses Concerning Nonlinear Consumer Loads and PV Panels

JAAN NIITSOO

TUT
PRESS

TALLINN UNIVERSITY OF TECHNOLOGY
Faculty of Power Engineering
Department of Electrical Power Engineering

Dissertation was accepted for the defence of the degree of Doctor of Philosophy in Engineering on November 11th, 2016

Supervisors: Prof. Ivo Palu, Department of Electrical Power Engineering, Tallinn University of Technology

PhD Paul Taklaja, Department of Electrical Power Engineering, Tallinn University of Technology

Opponents: Prof. Saulius Gudžius, Department of Electric Power Systems, Kaunas University of Technology

Prof. Andres Annuk, Department of Energy Engineering, Estonian University of Life Sciences

Defence of the thesis: December 12th, 2016

Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for any academic degree.

Jaan Niitsoo ....

European Union
European Social Fund
Investing in your future

ISSN 1406-474X
ISBN 978-9949-83-038-1 (publication)
ISBN 978-9949-83-039-8 (PDF)

ENERGEETIKA. ELEKTROTEHNIKA. MÄENDUS D80

Madalpingevõrgu elektrikvaliteedi analüüs seoses ebalineaarsete elektrienergia tarbijate ja päikesepaneelidega

JAAN NIITSOO

TTÜ
KIRJASTUS

Table of Contents

Table of Contents 5
Acknowledgements 6
List of Abbreviations..7
Symbol Index 8
List of original papers..9
Introduction 11
1 An Overview of power quality issues in the distribution grid....................13
  1.1 Power Quality Issues Concerning Small Nonlinear Loads 16
  1.2 Power Quality Issues Concerning Electrical Vehicle Load................18
  1.3 Power Quality Issues Concerning Distributed Generation Units 19
2 The Characteristics of nonlinear loads and PV panels 22
  2.1 The Characteristics of Small Appliances 22
  2.2 The Characteristics of Electrical Vehicle Chargers............................24
  2.3 The Characteristics of PV Panel Systems 27
3 Modelling with Nonlinear Devices 31
  3.1 Modelling Residential Load with Electrical Vehicle 33
  3.2 Modelling Residential Load with Photo Voltaic 35
  3.3 Modelling Residential Load with Photo Voltaic and Electrical Vehicle Simultaneously 38
Conclusions 41
Future Work 44
References 45
Abstract 48
Kokkuvõte 49
Elulookirjeldus 50
Curriculum Vitae..53
AUTHOR’S PUBLICATIONS..56
APPENDIX / LISA 61

Acknowledgements

My research for the degree of PhD was conducted at Tallinn University of Technology, the Department of Electrical Power Engineering during six years of study, starting already at Master's level. Therefore, there are a large number of people and organizations to whom I owe my thanks and gratitude.

First of all, I would like to express my appreciation to my supervisor Prof. Ivo Palu for his help and encouragement during the years of my studies.

Special thanks to my long time office roommate and my co-supervisor PhD Paul Taklaja for his help, fresh ideas and conversations on professional and as well on casual topics which has inspired me.

All my colleagues and fellow students from Tallinn University of Technology have earned my gratitude for productive discussions and exchange of ideas that have helped to finalize this thesis. PhD Toomas Vaimann, PhD Ants Kallaste, PhD Heigo Mõlder, PhD Lauri Kütt, PhD Reeli Kuhi-Thalfeldt, PhD Jako Kilter, PhD Viktor Beldjajev, Tarmo Rähmonen, Kalle Klandorf, Edgar Dubbelmann, Erki Rannak, Tanel Laasma, thank you all!

For financial support I would like to show my gratitude towards the Doctoral School of Energy and Geotechnology II and the Archimedes Foundation for DoRa Doctoral Studies Programmes.

For revising and editing English texts in my articles and the thesis, I would like to thank Prof. Joni Klüss and colleague Ivar Kiitam.

I would like to express my greatest thanks to my family and especially my wonderful wife Olga, our son Karl Jaan and daughter Lenna Liis, for the support and joy in rough times.

Last, but not least, I would like to thank all others who have helped me during the years but are not mentioned in this list.

Jaan Niitsoo

List of Abbreviations

AC	Alternating Current
AMe	Arithmetical Mean
BEV	Battery Electric Vehicles
CFL	Compact Fluorescence Lamp
CSI	Current Source Inverter
DC	Direct Current
DG	Distributed Generation
DPF	Displacement Power Factor
EU	European Union
EV	Electric Vehicle
GMe	Geometrical Mean
IEEE	Institute of Electrical and Electronics Engineers
MP	Measurement Point
OHL	Overhead Line
PCC	Place of Common Coupling
PFC	Power Factor Correction
PHEV	Plug-in Hybrid Electric Vehicle
PQI	Power Quality Index
PV	Photo Voltaic
rms	root mean square
TUT	Tallinn University of Technology
WT	Wind Turbine

Symbol Index

I	Electric Current
I_1	Fundamental Component of Current
HD	Harmonic Distortion
HD_I	Harmonic Distortion of Current
HD_U	Harmonic Distortion of Voltage
P	Total Active Power
P_1	Fundamental Component of Active Power
Q	Total Reactive Power
S	Total Apparent Power
S_1	Fundamental Component of Apparent Power
PF	Power Factor
t	Time
THD	Total Harmonic Distortion
THD_I	Total Harmonic Distortion of Current
THD_U	Total Harmonic Distortion of Voltage
U	Voltage
U_1	Fundamental Component of Voltage
W	Energy

LIST OF ORIGINAL PAPERS

This doctoral thesis is based on the following publications by the author. These publications are referred to in the text as [PAPER – I] – [PAPER – IX]:

[PAPER - I] **Niitsoo, J.** (2011). An overview of the impacts of CFLs implementation. *Proceedings of the 10th International Symposium "Topical Problems in the Field of Electrical and Power Engineering"* Pärnu, Estonia, January 10-15, 2011. Estonian Society of Moritz Hermann Jacobi, pp. 242 – 245

[PAPER - II] **Niitsoo, J.**; Palu, I. (2012). Investigation of Undesirable Consumption and Distorted Current. *Proceedings of the 13th International Scientific Conference Electric Power Engineering 2012.* Brno, Czech Republic, IEEE, pp. 287 – 291

[PAPER - III] **Niitsoo, J.**; Palu, I. (2011). Distorted load impacts on distribution grid. *Proceedings of the 12th International Scientific Conference Electric Power Engineering 2011*, Kouty nad Desnou, Czech Republic, May 17-19, 2011: IEEE, pp. 37 – 40

[PAPER - IV] Kütt, L.; Saarijärvi, E.; Lehtonen, M.; Mõlder, H.; **Niitsoo, J.** (2013). Current Harmonics of EV Chargers and Effects of Diversity to Charging Load Current Distortions in Distribution Networks. *Proceedings of 2013 International Conference on Connected Vehicles & Expo: (ICCVE 2013)*, Las Vegas, 2-6 Dec 2013. IEEE, pp. 1 – 6

[PAPER - V] Vaimann, T.; **Niitsoo, J.**; Kivipõld, T.; Lehtla, T. (2012). Power Quality Issues in Dispersed Generation and Smart Grids. *Electronics and Electrical Engineering,* vol. 10, no, 8, pp. 23 – 26

[PAPER - VI] **Niitsoo, J.**; Kütt, L.; Taklaja, P. (2013). Consequences of Distributed Generation on Power Quality. In: Proceedings of 14th International Scientific Conference Electric Power Engineering 2013: EPE 2013, May 28-30, 2013, Kouty nad Desnou, Czech Republic. IEEE, pp. 163 – 167

[PAPER - VII] **Niitsoo, J.**; Taklaja, P.; Palu, I.; Kiitam, I. (2015) Modelling EVs in residential distribution grid with other nonlinear loads. *Proceedings of the 15th International Conference on Environment and Electrical Engineering,* 10-13 June 2015, Rome, Italy, pp. 1543 - 1548.

[PAPER - VIII] **Niitsoo, J.**; Jarkovoi, M.; Taklaja, P.; Klüss, J.; Palu, I. (2015) Power quality issues concerning photovoltaic generation in distribution grids. *Smart Grid and Renewable Energy,* vol. 6, no. 6, pp. 148 – 163.

[PAPER - IX] **Niitsoo, J.**; Taklaja, P.; Palu, I.; Klüss, J. (2015) Power quality issues concerning photovoltaic generation and electrical vehicle loads in distribution grids. *Smart Grid and Renewable Energy,* vol. 6, no. 6, pp. 164 – 177.

Copies of listed publications are included in Appendix.

Author's Contribution per Paper

Contribution of author to the listed papers included in the thesis is as follows:

[PAPER - I] Jaan Niitsoo is the main author of the paper. He is responsible for gathering data, arranging measurements and writing the paper. Jaan Niitsoo made a presentation of the paper at the 10th International Symposium "Topical Problems in the Field of Electrical and Power Engineering", Pärnu, Estonia.

[PAPER - II] Jaan Niitsoo is the main author of the paper. He is responsible for gathering data, arranging measurements and writing the paper. Second author had the role of consulting. Jaan Niitsoo made a presentation of the paper at the 13th International Scientific Conference Electric Power Engineering 2012, Brno, Czech Republic.

[PAPER - III] Jaan Niitsoo is the main author of the paper. He is responsible for gathering data, arranging measurements and writing the paper. Second author had the role of consulting. Jaan Niitsoo made a presentation of the paper at the 12th International Scientific Conference of Electric Power Engineering 2011, Kouty nad Desnou, Czech Republic.

[PAPER - IV] Jaan Niitsoo is one of the authors of the paper. He is responsible for data input and consults. The main author is Lauri Kütt.

[PAPER - V] Jaan Niitsoo is one of the main authors of the paper. He is responsible for gathering data and partly responsible for writing the paper. Other main authors are Toomas Vaimann and Tanel Kivipõld.

[PAPER - VI] Jaan Niitsoo is the main author of the paper. He is responsible for gathering data, arranging measurements and writing the paper. Other authors had the role of consulting. Jaan Niitsoo made a presentation of the paper at the 14th International Scientific Conference Electric Power Engineering 2013, Kouty nad Desnou, Czech Republic.

[PAPER - VII] Jaan Niitsoo is the main author of the paper. He is responsible for gathering data, arranging measurements and writing the paper. Other authors had the role of consulting.

[PAPER - VIII] Jaan Niitsoo is the main author of the paper. He is responsible for gathering data, arranging measurements and writing the paper. Other authors had the role of consulting.

[PAPER - IX] Jaan Niitsoo is the main author of the paper. He is responsible for gathering data, arranging measurements and writing the paper. Other authors had the role of consulting.

INTRODUCTION

This thesis provides a comprehensive analysis of power quality issues related to connecting nonlinear loads and generation units into the existing grid. The thesis identifies and describes key research in this topic and complements it with field measurements. Averaged values of loads and PV panels are provided and results of integrating nonlinear loads and PV panels into existing grid are introduced based on measurements and modelling.

Background and Motivation

The appliances and electric devices connected to the public low-voltage network can generate linear and nonlinear loads. Linear loads are designed to operate with a sinusoidal current; meanwhile nonlinear loads are operating with non-sinusoidal current. Presently, nonlinear loads make up large percentage of electrical demand and their popularity is growing rapidly worldwide.

New technologies and consumer trends reduce traditional linear loads and linear generation units connected to the grid. Increase in popularity of electrical vehicles (EV), small wind turbines (WT) and photovoltaic (PV) panels and restrictions on sale of incandescent lamps in European Union (EU) prove such developments. Present thesis is motivated to introduce possible technical challenges due to those changes.

The idea for this thesis formed out of the author's Master's thesis analysing the impacts of compact fluorescent lamps (CFL) on the electricity grid. The goal of the present PhD work was to present an overview of nonlinear loads and nonlinear generation units and investigate their interactions in the grid. The research required basic models of nonlinear loads and nonlinear generation units that were constructed in the thesis.

Overall meaning of the thesis was to bring attention to power quality issues, which may appear if new loads and generations are connected thoughtlessly. Special attention is needed by distribution grid specialist because it all comes together into the grid.

Shortcomings in Earlier Research

Numerous researches have been conducted on power quality. Comprehensive studies on harmonic spectres of loads and generation units and modelling them together in different scenarios has been insufficient before compiling the papers for this thesis. Limited data has been available for specific loads such as CFLs and EVs, and usually only total harmonic distortion (THD) has been examined and no information for individual harmonics has been given.

Current curve of load depends on supply voltage, but at the same time voltage depends on the current. There is lack of information about how supply voltage affects harmonic current spectre of individual appliances. Also, studies about how different current curves influence system voltage have not been comprehensive at the time when the papers for the thesis were compiled. Furthermore, single harmonic current and phase angle values for majority of nonlinear loads and nonlinear generating units had not been researched in-depth.

Main Objectives and Tasks of the Thesis

The main objective of this thesis is to analyse power quality issues related to nonlinear loads and nonlinear generation units, focused on PVs. The thesis consists of investigation of prior research by other authors, field measurements and modelling. In addition, measurements data and averaged values for diverse devices for further modelling and analysis are presented in the second paragraph.

For the correct estimation of harmonic levels, magnitudes and phase angle, values of individual harmonics up to 50th order for all devices are measured and taken into account. All results were published for further analysis and modelling.

The broad objective of this research is to create grounds for comprehensive power quality studies in Estonia regarding nonlinear loads and nonlinear generation units. So far no remarkable research has been published assessing what happens when large numbers of nonlinear loads and nonlinear generation units are implemented together into the distribution network.

Subject of the Research and Dissemination of the Results

The research was performed throughout 2009-2015. It was conducted in different parts which resulted in several Bachelors' thesis and Masters' thesis supervised by the author of the present thesis, as well as scientific papers and presentations at conferences. Many field and laboratory measurements were conducted for this work and final conclusions were made based on modelling results.

The results of the doctoral thesis have been presented by the author at seven international conferences. The author has published 32 international scientific papers, nine of which are directly associated with the thesis. In addition, three papers were published in local scientific conferences and four papers were published in non-scientific journals or newspapers.

Thesis Outline

Chapter 1 gives an overview of various aspects related to power quality issues in the distribution grid. Attention is paid to power quality issues concerning small nonlinear loads, nonlinear electric vehicle loads and distributed generation units.

Chapter 2 provides an overview of characteristics of small appliances, electrical vehicles and PV panels. Measurement data and averaged values are presented for further modelling.

Chapter 3 presents modelling results of altered scenarios. Situations with and without nonlinear loads, electrical vehicles and PV panels are handled. Aim of the chapter is to use the knowledge gathered in the first chapter and measurement results from the second chapter in models for potential real life situations.

1 AN OVERVIEW OF POWER QUALITY ISSUES IN THE DISTRIBUTION GRID

This thesis focuses on current and voltage harmonics that are produced by nonlinear loads and nonlinear generation units, as such information and data has been lacking in existing research before compiling the thesis. Reactive power, voltage unbalance and neutral current issues are included, as these are the most hazardous matters that relate to individual appliances. All such factors may lead to extensive financial costs being incurred if there is no awareness of their presence.

Firstly, the consequences of poor power quality levels and parameters such as harmonics, reactive power, voltage unbalance, and neutral current are explained. Subsequently, power quality issues concerning precise loads and nonlinear generation units are handled.

The Consequences of Poor Power Quality Levels

The connection of nonlinear loads and nonlinear generation units to distribution networks should be observed in terms of power quality, reliability, network control and stability. For such operational aspects, a number of problems could arise when connecting nonlinear loads, such as:

- a malfunction of harmonics-sensitive equipment
- voltage unbalance
- DC injection
- exceeding the thermal limits of conductors
- power losses
- a rise of voltage harmonics distortion
- resonance
- a decrease in the lifetime of components
- voltage flicker
- abnormal operation of the protection system
- a decrease of power factor
- high current in neutral conductor
- under- or over-voltage of the network
- mechanical stress
- reactive power generation
- non-reception of the tariff signal
- islanding
- increase of the network outages

The above-mentioned effects are not limited, but one of the most affected components are the distribution transformers, cables, and fuses [1]. The most direct effect can be seen in the distribution transformers, which could encounter great stress and heating due to increased harmonic losses and voltage unbalance, but also an increased load due to nonlinear loads.

Harmonics

Harmonic currents are caused by non-linear loads, *i.e.* loads which draw a current with an unlike waveform comparison to the supply voltage. A distorted sine wave can be observed, dividing it into numerous components, each having an integer-multiple frequency of the main frequency. For different waveforms, there is a diverse harmonic content present, referring to individual harmonic magnitudes and phase shift when compared to the main frequency component.

The distortions can be observed individually by comparing harmonic components as a harmonic distortion (HD). A more general approach to quantify the distortions is the use of THD. THD can be expressed separately for total current harmonic distortion as $\mathrm{THD_I}$ and for total voltage distortion as $\mathrm{THD_U}$. The harmonic distortion indicators can be calculated using corresponding equations (1), (2), (3), and (4),

$$HD_I = \frac{I_i}{I_1} \tag{1}$$

$$HD_U = \frac{U_i}{U_1} \tag{2}$$

$$THD_I = \frac{1}{I_1} \times \sqrt{I_{rms}^2 - I_1^2} \times 100 \tag{3}$$

$$THD_U = \frac{1}{U_1} \times \sqrt{U_{rms}^2 - U_1^2} \times 100 \tag{4}$$

It has to be pointed out that $\mathrm{THD_I}$ does not reveal the magnitudes of individual harmonics, which could still exceed the limits for specific harmonics regardless of $\mathrm{THD_I}$ value. For the correct estimation of the harmonic levels, phase angle values of individual harmonics are required in addition to magnitudes. For example, the attenuation effect is dependent only upon the phase angle, but the effect's severity is dependent upon the magnitude of the harmonic voltage [2].

Harmonic angle diversity is relevant when multiple appliances are operating simultaneously, creating either the reinforcement or cancellation of harmonic magnitudes [3]. It is reported that smaller harmonic current magnitudes with a 10% reduction can be seen when phase angle information is included when compared to the simple summing up of magnitudes without phase angles [4].

Harmonic currents that are produced by nonlinear loads are injected back into the supply systems and distortion affects all customers who are fed through this place of common coupling (PCC). Some loads draw a current with a THD over 100%, but their active power consumption is not as significant when compared to other harmonic generating devices as stated in [PAPER - I]. In such cases, harmonic distortion may increase when numerous harmonic-emitting devices are utilised in bulk. The total level of impact depends on the number of appliances, their power ratings, and their harmonic diversity.

Reactive Power

It must be considered that most electronic devices investigated for this research generate more reactive power to the grid than they consume active power as stated in [PAPER - II]. A respectable indicator for estimating the amount of reactive power is the power factor (PF) calculated as (5).

$$\mathrm{PF} = \frac{\mathrm{P}}{\mathrm{S}}, \tag{5}$$

where P is real power and S is apparent power. In the sinusoidal case there is only one phase angle between the voltage and the current (since only the fundamental frequency is present) and therefore the power factor can be computed as the cosine of the phase angle (φ) and is commonly referred to as the displacement power factor (DPF), calculated as (6).

$$\mathrm{DPF} = \cos \varphi \tag{6}$$

Some devices have DPF near unity, but the true PF rating is around 0.5-0.6. Using only the displacement power factor would provide a false sense of security in those cases.

Voltage Unbalance

Voltage unbalance in the three-phase system is a condition in which voltages differ from each other to notable levels. In public electricity networks the allowed level in Europe is 2% (EN 50160:2010). The voltage unbalance is commonly observed as a relation of maximum deviation from three phase average voltage (ΔU) to three phase average voltage (U_{avg}) and is described with an unbalance factor (k_a) as given in (7) or as a relation of negative sequence voltage (U_2) to positive sequence voltage (U_1) as given in (8). Positive and negative sequence values can be computed with method of symmetrical components.

$$k_a = \frac{\Delta U}{U_{avg}} \times 100\% \tag{7}$$

$$k_a = \frac{U_2}{U_1} \times 100\% \tag{8}$$

Three phase motors are mostly affected by the negative sequence. Another problem that emerges from the presence of harmonics and voltage unbalance is the increase in neutral wire current [5], which can increase noticeably and can pose risks if overloaded.

Neutral Wire Current

The neutral point of a low-voltage power system is commonly earthed, and single phase devices operate on a voltage between neutral and phase. In a single phase system, currents in the neutral and in the phase are equal, and in a three phase system the current rates at zero in neutral for a balanced load.

A special situation occurs in the case of a balanced three phase load that consists of identical nonlinear loads. Since the triplen harmonics total up in neutral, the three phase supply system neutral conductor's total current can be higher than the individual phase current [6], [7]. For example, in analyses made in the Denmark and Netherlands has shown that the fifteenth harmonic current, which is one of the triplen harmonics, has exceeded tolerable limits in several cases [7], [8].

1.1 Power Quality Issues Concerning Small Nonlinear Loads

Those appliances and electric devices that are connected to the public low-voltage network are designed to operate with a sinusoidal voltage at rated power. Many of the connected loads are the nonlinear type, meaning that they draw current with a distorted sine waveform. This causes distorted sine voltage drop, thereby resulting in a distorted network voltage waveform. The share of worldwide nonlinear loads is growing rapidly. It has been estimated that already in 2012, a total of 60% of loads in the USA were nonlinear loads [3].

The total impact depends upon the number of appliances, their power ratings, and their harmonic diversity. Harmonic angle diversity is relevant when multiple appliances are operating simultaneously, creating either a reinforcement or cancellation of harmonic magnitudes [3]. The attenuation effect is dependent only on the phase angle, but the effect's severity is dependent upon the magnitude of the harmonic voltage [2].

The most investigated nonlinear loads in the world are probably CFLs. Therefore power quality issues concerning nonlinear loads here are handled in terms of CFLs. CFLs consume less energy with the same luminous efficiency when compared to incandescent lamps, but their current curve is not a perfect sinusoid. For example analysis [9] was carried out in which all bulbs were replaced with CFLs in one household. After the replacement has been carried out, CFLs constituted 26.3% of overall load - PF decreased to 0.65, voltage distortion increased to 4.4%, and current THD increased to an unacceptable 23.5%. Also studies [10], [11], [12] have shown that the current THD of CFLs increases as the supply harmonic level increases. The ratio is not linear and it is particularly evident in the case of CFLs with electronic ballast.

The widespread use of CFLs have implications for significant reactive power in a grid [9]. If the cos φ of the CFLs is usually about 0.9 the PF is not the same which was proved with measurements presented in [PAPER - I]. Average PF is around 0.5-0.6 which means that a lamp generates much more reactive power to the grid than it consumes active power. In [PAPER - I], a number of test series with CFLs were carried out. Part of the results is described in Table 1.1.

Table 1.1. Measured Parameters for CFLs

Parameter	**Set 1**	**Set 2**
cos φ	0.89	0.92
PF	0.61	0.57
Reactive power [var]	18.0	20.0
Current THD [%]	104	120

For assessing the harmonics, in [PAPER - I], CFLs were installed symmetrically in three phases. The test started with two lamps for one phase, then three and finally four. Results were almost as poor as theoretically they could be. When changing the number of lamps, the current in the neutral wire was always 70% higher than the phase current. Fig. 1.1 shows how the third, ninth, fifteenth and twenty-first harmonics aggregate in the neutral conductor. Other harmonics cancel each other out.

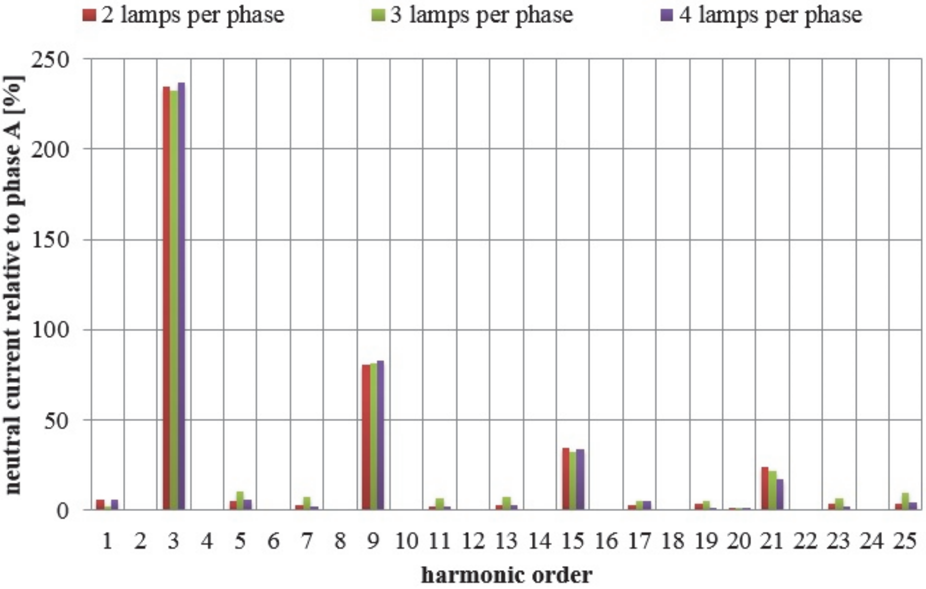


Fig. 1.1. Triplen Harmonics Aggregation in Neutral Conductor.

All nonlinear loads cause losses and distribution transformers, which are one of the most important devices in supply system and can mitigate or worsen the situation of harmonic emission, are affected in two ways. First, the eddy current losses increase with the square of the harmonic number. The second effect concerns the triple harmonics (third, ninth, fifteenth, *etc*), which circulate in the delta winding of the transformer and may damage it due to increased thermal losses [13]. For example, the results of experiment [14] showed 33% active loss increase of a transformer when incandescent lamps where replaced with CFLs.

Above described effects are dependent on power as being more severe when nonlinear loading is increasing. For that reason, next sections are describing electrical vehicle and distributed generation which are more powerful than CFLs.

1.2 Power Quality Issues Concerning Electrical Vehicle Load

Electrical vehicles are considered as being every-day-use commuter vehicles with significant on-board energy storage which can use the low-voltage power supply for charging the energy storage cells. An EV battery requires a direct current (DC) for charging and for the conversion from alternating current (AC), and charging control is provided by the power electronics converters, presenting a non-linear load.

The harmonics associated with the EV charging are closely related to the charger circuit topology that is providing an interface with the AC network. The simplest single-phase full-bridge rectifier or and for higher power ratings three-phase diode rectifier (similar to all uncontrolled rectifiers), provide the high current harmonics to the AC power network. The circuits and control strategies have evolved rapidly to include more network-friendly features, such as power factor correction (PFC) and current waveform shaping.

The EV chargers that are most likely to be deployed on board of the EVs would be the single-phase chargers. It is likely that for a large number of customers in a three-phase system, the charging current would be distributed uniformly among the phases.

The task of charging up EVs is expected to impose a noticeable additional load on distribution networks. Residential networks in which EV owners will charge their vehicles after returning from their daily activities will be especially subjected to high load increases. As an EV charger is a powerful non-linear load, large harmonic currents can be present during EV charging. In [PAPER - IV], EVs are analysed for the current harmonics that may be present during slow rate home charging.

Distribution networks suffer from limitations when it comes to support for EV charging [15], even for low EV penetration levels. It is assumed, that an EV penetration rate of between 20% and 25% will be tolerable for the present distribution networks [16]. This figure is aimed at being applicable both for overload as well as for power quality issues. Considering the power of EV chargers and the characteristics of the EV charging load, analysis is required if public low-voltage network standards are still to be met if numerous EVs are being charged simultaneously.

In [PAPER - IV] the EV charging scenarios are presented by including or excluding EV charging of the four EVs. The sum total of charging currents and THD_I are presented in Table 1.2. The lowest THD_I value can be observed when

EV1 and EV3 are present as their individual THD_I values are the lowest. However, when all of the EVs are connected for charging, the level of distortion is still low, at 4.9%, which is significantly lower than the average THD_I of all the EVs (7.5%). The lowest THD_I value is observed when EV1 and EV3 are present, with a decrease in the third harmonic by 83% (phase angle difference 195 degrees) and in the fifth harmonic by 59% (phase angle difference 186 degrees). In all the observed cases, when there is more than one different EV connected to the grid for charging, harmonic cancellation is observed and the level of harmonic current will be smaller than the arithmetic sum total of the currents.

Table 1.2. THD_I Values for EV Charging Configurations

	EV2	**Absent**		**Present**	
	EV1	**Absent**	**Present**	**Absent**	**Present**
EV4	**EV3**				
Absent	**Absent**	0	4.0%	12.2%	6.4%
	Present	3.3%	2.0%	5.7%	3.9%
Present	**Absent**	10.5%	4.6%	10.1%	6.5%
	Present	5.9%	3.6%	6.7%	4.9%

On the other hand, a typical distribution network has a large number of non-linear loads connected to it. Adding the EV chargers of various manufacturers to this grid, it is likely that there will be a variety of harmonic patterns present. The diversity of the patterns may lead to some harmonic cancellation. This effect occurs when harmonics with diverse phase angles provide a sum total to a magnitude that is smaller than the individual harmonics magnitudes.

1.3 Power Quality Issues Concerning Distributed Generation Units

Investigations [PAPER - V] and [PAPER - VI] provide an overview of power quality issues that concern distributed generation units. Distributed generation (DG) is the production of electricity at or near the point of consumption. Most of the consumed energy is produced at the point of consumption and the rest of the electricity is transferred into the distribution grid.

In most cases it is assumed that the electrical current and voltage have a sinusoidal waveform. But if hundreds or thousands of minor power production plants are connected to the grid, this could result in a distortion of the sinusoidal current and voltage waveform. Small generators are usually combined with frequency converters in order to drive them and synchronise them with the grid. When a large number of DGs are connected to the distribution network, power electronics become one of the main sources of harmonics [17].

As it is seen in Fig. 1.2, the number of new producers in the Estonian national distribution grid as operated by Elektrilevi OÜ is increasing every year. An especially increasing trend is adding new generation units that are at a low-voltage level (more than 500 in four years).

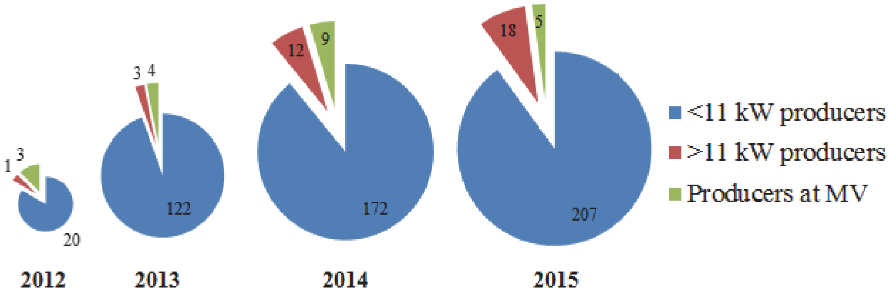


Fig. 1.2. New Producers in the Elektrilevi OÜ Grid

Small producers can have an effect on all aspects of power quality. The possible effects depend mainly on the power of the generation units when compared to the short-circuit capacity of the grid. Effects are more serious as power of generation unit increases and grid's short-circuit capacity decreases. DG units have a larger effect on local phenomena, such as supply voltage variation events, flicker *etc*. DG units are usually not large enough to have a significant effect on system frequency, but with larger units and a higher ratio of DG units, problems may occur [18].

The varying power density of renewable energy resources (*ie*. irradiance level and temperature in PV conversion and wind speed) potentially causes voltage and frequency variations or sag/swell patterns in the grid. The application of power converters as interfaces between energy sources and the grid, as well as their interaction with other system components, may cause high levels of harmonic distortion [19], [20].

For example, the performance of PV plants in terms of power quality levels depends upon the inverter structure, external conditions such as solar irradiance and temperature, the type and volume of loads, and the characteristics of the supply system [21], [22], [23], [24]. The harmonics produced by DG in the distribution network are influenced mainly by the factor of the equivalent impedance in the PCC [23].

Although the quality of a network supply is conventionally assessed in terms of voltage harmonics, the grid impedance determines how these relate to the output current [25]. Power quality levels from inverters are significantly influenced by minor distortions of the voltage waveform in the network into which power is being directed. For example, in [25] a case analysis is presented for connecting the DG unit into an ideal grid with resistive load. A voltage distortion of about 3.2% was indicated, whereas connecting the DG unit to the low voltage network produced a voltage distortion of about 5.7% with all other conditions remaining the same. Similar ranges were observed when the distortion was measured for an inverter that was connected to the real grid and afterwards in an islanded operation. The values of voltage THD were at 6.2% and 3.3% respectively [25].

The aim of the study [26] which was one part of research done for the thesis was to use measurement data that had been obtained from eleven producers to analyse the present situation of power quality levels and the effects of the DG units in order to determine whether they have an effect on local power quality levels. The research focused on small producers with an installed capacity of between 200 kW to 5 MW.

The research concludes that DG units can cause problems with supply voltages due to complications in voltage regulation [27] or due to producing only active power, which can cause over-voltages in nearby substations [18]. The effect is more prominent if the DG unit is high-powered and/or is installed farther from main substations in the grid [28].

Measurement results for continuous phenomena (Table 1.3) are presented using the PQI (Power Quality Index) method [29]. The PQI method uses a relative value that indicates the real value subject to the EN 50160 limit. For example, THD_U values of 3.8% and 10% correspond to PQI values of 47.5% and 125%.

Table 1.3. Measurement Results for DGs [26]

Parameter	**Avg PQI [%]**	**Max PQI [%]**
Supply voltage variations (100% of time)	18.5	66.7
Flicker	43.6	150.0
Asymmetry	22.2	50.5
THD_U	17.4	46.2
Harmonics	5.4	57.0

According to the measurement results from 11 measurement points, the overall degree of power quality levels was good with an average PQI value of 44%. It could be concluded that the supply voltage variation is not very high in those places– the average PQI value was 18.5% and the maximum was less than 67%. The variations were somewhat higher in measurement points with asynchronous generators. The average harmonic levels were low, with an average PQI value of 17.4% for THD and 5.4% for individual harmonics. Maximum values were under 47% and 57% respectively.

Problems to Be Solved in the Thesis

The present levels of distortions in some distribution networks are already significant. Monitoring of a hundred distribution network feeders in the USA revealed that the average voltage THD at the PCC was 4.73% [30]. It can be presumed that the stated percentage is quite common for many distribution grids. More severe cases have been revealed distortion higher than 17% [31].

Due to this progressive phenomenon the present thesis concentrate its investigations mainly on the harmonics of nonlinear loads and nonlinear generation units. And as it is evident from previous that problems with nonlinear loads and nonlinear generation units do exist, the following part of the thesis will investigate their characteristics in detail. In the final part, models based on characteristics of small appliances, electrical vehicles, and distributed generation units will be examined by modelling them together in different perspective real life scenarios.

2 THE CHARACTERISTICS OF NONLINEAR LOADS AND PV PANELS

In this part of the thesis, the characteristics of nonlinear loads and PV panels are presented. The characteristics of specific devices help to provide an understanding of how distortions arise when they are used in real situation models. Relevant data is collected from scientific researches and measurements that have been carried out for the present thesis.

2.1 The Characteristics of Small Appliances

Some loads have a current THD over 100%, but their active power consumption is not significant compared to other harmonic-generating apparatuses. Therefore, their quality requirements are not precisely regulated, but total harmonic load increases when numerous harmonic emitting devices are utilised in bulk.

Table 2.1. Power and Harmonic Current Values for Measured Devices

device	**harmonic order [n]**			**1**	**3**	**5**	**7**	**9**	**11**	**13**	**15**
air purifier	**P [W]**	11.9	**I [%]**	100	29	22	5	6	4	2	2
	Q [VAr]	10.3	**φ [°]**	0	110	118	57	66	95	48	51
desk lamp	**P [W]**	30.7	**I [%]**	100	6	2	1	0	0	0	0
	Q [VAr]	67.4	**φ [°]**	0	305	104	298	136	322	143	276
refrigerator 1	**P [W]**	119	**I [%]**	100	14	6	4	1	2	1	1
	Q [VAr]	77.9	**φ [°]**	0	314	42	139	324	341	168	264
refrigerator 2	**P [W]**	80.7	**I [%]**	100	16	7	7	6	2	2	0
	Q [VAr]	19.3	**φ [°]**	0	246	224	157	156	161	206	294
lamp set 1	**P [W]**	82.7	**I [%]**	100	83	59	35	18	11	9	9
	Q [VAr]	-106.6	**φ [°]**	0	358	355	8	37	88	124	201
lamp set 2	**P [W]**	91.4	**I [%]**	100	78	52	27	13	11	11	14
	Q [VAr]	-122.1	**φ [°]**	0	358	343	11	52	105	130	156
laptop 1	**P [W]**	47.8	**I [%]**	100	42	5	7	2	2	2	2
	Q [VAr]	-29.3	**φ [°]**	0	301	148	57	120	308	247	102
laptop 2	**P [W]**	69.9	**I [%]**	100	90	76	62	53	49	45	39
	Q [VAr]	-130.4	**φ [°]**	0	346	339	338	341	344	344	344
monitor	**P [W]**	29.9	**I [%]**	100	85	64	41	21	17	20	17
	Q [VAr]	-40.3	**φ [°]**	0	318	292	272	269	294	292	277
printer	**P [W]**	42.3	**I [%]**	100	17	13	10	6	3	1	2
	Q [VAr]	-31.6	**φ [°]**	0	290	243	198	147	100	208	183
TV 1	**P [W]**	58.6	**I [%]**	100	83	60	33	12	6	11	10
	Q [VAr]	-66.6	**φ [°]**	0	342	328	313	281	149	115	90
TV 2	**P [W]**	80.3	**I [%]**	100	70	31	13	10	4	3	2
	Q [VAr]	68.5	**φ [°]**	0	339	310	236	176	117	14	291
TV-tuner 1	**P [W]**	6.6	**I [%]**	100	81	65	49	31	20	16	15
	Q [VAr]	-10.1	**φ [°]**	0	294	252	215	181	164	151	128
TV-tuner 2	**P [W]**	3.9	**I [%]**	100	82	70	54	37	23	13	11
	Q [VAr]	-5.4	**φ [°]**	0	347	327	249	50	29	75	106

In order to estimate the total magnitude of harmonics it is important to know the harmonic components and their magnitudes when it comes to designing harmonic mitigation devices. For this purpose, the active and reactive power level values, harmonic current magnitudes and harmonic current phase shift angle values of different home appliances were measured. The results for a fourteen devices are presented in Table 2.1, where active (P) and reactive (Q) power values for each device are given and complemented with harmonic current and phase shift angles up to 15th order. In further modelling process, described in last chapter of the thesis, values up to 50th harmonic have been used, but due to their low values are not presented at this point.

From the Table 2.1 it can be seen that a number of devices used in housekeeping have a moderate active power consumption around 100 W or less. As comparing harmonic current values, it can be said that there are very different current curves. All those devices together can reach up to one or two kW-s and show very varying harmonic spectres.

In study [32] which was a part of research done for the thesis, average values for devices, *eg*. laptops, printers, monitors, *etc* were presented. For example, third harmonics for laptops in this analysis are presented in Fig. 2.1, where 'X' and 'Y' are standing for active and reactive current components ('+' if consuming, '-' if producing) calculated using formulas (9) and (10). The arithmetic mean (AMe) of amplitudes and geometric mean (GMe) of phase angles were calculated respectively according to (11) and (12). The results show that same type of appliances can be modelled with one universal model. All values are presented as percentage of fundamental current which itself is taken 100%.

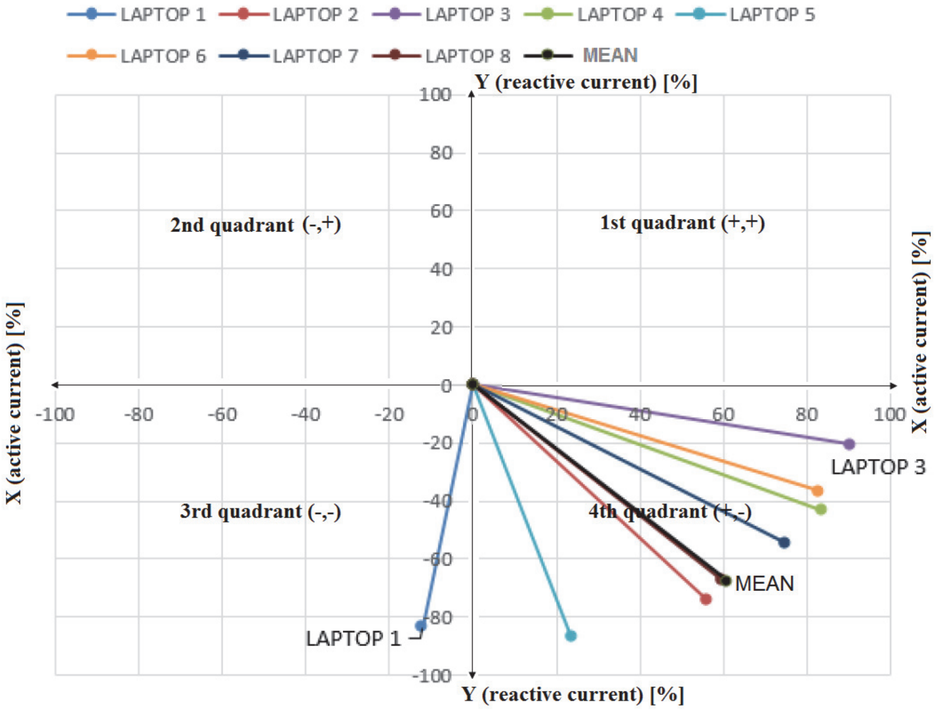


Fig. 2.1. Quadrant of Third Harmonic Current Vectors of Different Laptops. [32]

By the research [32] it can conclude that same type appliances from different manufactures have similar current curves. For example measured laptops and monitors all have odd harmonic currents up to 11th order with reactive generating nature as seen in Fig. 2.1.

$$Y_i = I_i \times \sin \varphi_i \tag{9}$$

$$X_i = I_i \times \sin \varphi_i \tag{10}$$

$$AMe = \frac{1}{n} \times (i_1 + i_2 + \cdots + i_n) \tag{11}$$

$$GMe = \sqrt[n]{i_1 \times i_2 \times \ldots \times i_n}, \tag{12}$$

where I_i is current amplitude of the order i, φ_i is phase angle between fundamental voltage and current of order i, i_i is current rms of order i.

Same type averaged values as in Fig. 2.1 calculated with upper mentioned equations (9-12) are worked out also for electrical vehicles and PV panels. Those results are presented in following sections and are used in modelling which is covered in the last chapter.

2.2 The Characteristics of Electrical Vehicle Chargers

Study [PAPER - IV] introduces the EV battery charger load, which is a powerful nonlinear load. Chargers for modern EVs that are intended for charging at home are actually operating close to the load levels that the average residential customers already consume without the EV. EVs draw between 10 A to 15 A of current, which means that adding an EV essentially means load doubling in many homes [33].

An EV battery requires a DC supply for charging, and the simplest approach is to use a single-phase full-bridge rectifier in the circuit. Another option for higher power ratings is to use a three-phase diode rectifier.

A disadvantage inherent in all of the uncontrolled rectifiers is the high content of current harmonics that are injected to AC power networks. Based on the available literature, it can be concluded that over the years the volume of distortion from EV charging has decreased. Measurements in the 1990s indicated that the use of uncontrolled or low-control rectifiers results in an average THD_I of 50% [34]. Measurements of modern commercial EVs have indicated a charging THD_I around 11% or 12% [35], [36], and levels as low as 4.5% [37]. When using more advanced power electronic circuits and controls, a variety of topologies results in a THD_I below 5% at a load level between 50% and 100% of rated power [38].

Investigation [PAPER - VI] focuses on the identification of the properties of EV chargers. The EV chargers that are being produced by EV manufacturers and the types available are very likely to have different harmonic patterns, *ie.* individual current harmonic magnitude levels and phase angle values. A comparison of the measured EVs in steady state current charging mode is presented in Table 2.2.

Table 2.2. Measured Characteristics for Charging EVs.

EV	**Charging current [A]**	**Charging power [kW]**	**THD$_I$ during steady state charging [%]**
1	9.7	2.2	4.2
2	10.3	2.4	12.3
3	12.7	2.9	3.4
4	10.3	2.4	10.5

In Fig. 2.2. the charging time has been presented with the relative scale of zero to 100% of charging time. Distinguishable modes of charging are observable and during the steady state mode, the current harmonic magnitudes and phase angles remain at constant values.

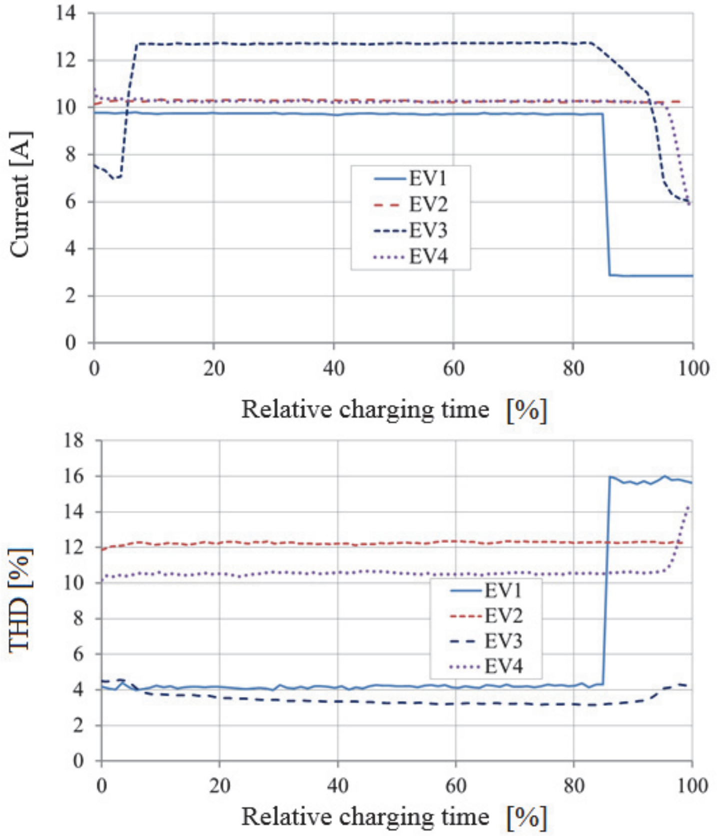


Fig. 2.2. Charging Current and THD Levels During Full Charging.

The harmonic amplitudes and phase angles are different for the various EVs. Therefore two simulations with EVs can lead to entirely dissimilar results. For this purpose, general values for further modelling of average EVs has been presented in [PAPER - VII]. The averaged values based on five EVs were calculated similarly as described for small appliances in section 2.1 by using formulas 8 to 11. A graphical illustration for the third harmonic as the most significant individual harmonic is presented in Fig. 2.3.

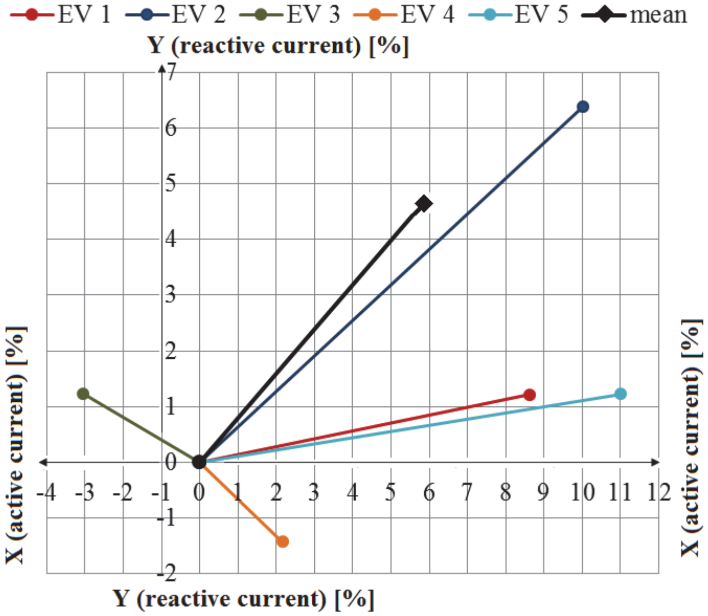


Fig. 2.3. Quadrant of Third Current Harmonic Vectors of Different EVs.

In Table 2.3, averaged harmonic currents of measured EVs for all orders up to the 50th are given for modelling the mean EV. Different values are given for distinguishable harmonic orders and groups with similar dimension.

Table 2.3. Current Harmonic Amplitudes of Mean EV

Order	Amplitude
2	0,4
3	7,5
4; 6; 8; 10	0,2
5	1,9
7	1,4
9; 11; 13; 15	0,65
12...50 even	0,06
17...49 odd	0,25

Phase angles of current harmonics for the mean EV are presented in Table 2.4. 3^{rd} and 33rd harmonic phase shift values are given separately due to their discrepancy.

Table 2.4. Current Harmonic Phase Shift Angles of Mean EV

Order	Angle
2; 4; 8; 12; 14; 18; 22; 28; 32; 36; 40; 42; 46	200
3	40
5; 7; 17; 21; 31; 35; 37; 41; 45	210
6; 10; 16; 20; 24; 26; 30; 34; 38; 44; 48; 50	150
9; 11; 13; 15; 19; 23; 25; 27; 29; 39; 43; 47; 49	140
33	90

Values presented in Table 2.3 and Table 2.4 are used to model the mean EV. The modelling process and results are described in the last chapter of the thesis.

2.3 The Characteristics of PV Panel Systems

PV system has been chosen as an example for distributed generation units. The harmonic generation of a PV system depends on the inverter technology, solar irradiance, temperature, loads, and the supply system characteristics.

Both the current THD and the output reactive power are related to the output active power levels, which in turn are strongly dependent upon solar irradiance levels.

Most of the inverters consume or feed reactive power into the network depending on their output active power and their technology. During operation at low solar irradiance levels (*eg.* sunrise, sunset, and on cloudy days), current THD values can increase rapidly because the THD factor is inversely proportional to the output active power of the PV inverters. THD is notably reduced as the output active power of the PV inverters increases and reaches its nominal value [39], [40].

The magnitude and order of harmonic currents that are injected by converters depends upon the technology and topology of the inverter [41], and its mode of operation [42]. The current harmonic content of most modern sine wave inverters is typically less than 3% [43].

The harmonic current emission of the converters depends on power output, this being comparatively high during low power generation and comparatively low if generated power exceeds an approximate figure between 15% and 20% of the rated power [21], [22], [24]. Most commercial inverters for connecting low power generators into the grid are designed to operate at unity power factor, but the inverter fails to maintain unity power factor at low power outputs [25].

Some inverters combine the reference source and the synchronisation in the grid voltage, by using the shape of the grid voltage as a reference source. In the case of distorted grid voltage, the reference source will be distorted and the current control loop of the inverter influence its output current accordingly [44]. A distorted voltage acts like a disturbance in the inverter control system, causing a distortion of the current waveform generated by the inverter [39].

Investigation [PAPER - VIII] introduces the measurement results for three PV systems and offers averaged values for a single phase PV system for the purpose of further modelling. The measurement results for a single phase PV inverter for three power levels are presented in Table 2.5. Power levels are describing situations where PV output power is approximately 30%, 60% and 100% accordingly. From the data presented in the tables, it is apparent that current distortion decreases with increasing current. The same conclusion can be drawn by observing the power factor (PF) value which approaches unity with increasing current.

Table 2.5. Measured Power and Power Quality Values for a Single Phase PV Inverter

Power level	U_{rms} [V]	I_{rms} [A]	P [W]	Q [var]	S [VA]	cos φ	PF	THD_U [%]	THD_I [%]
30%	233.6	3.45	739	322	807	1	0.92	1.01	4.27
60%	238.8	9.08	2125	-425	2168	1	0.98	0.82	1.98
100%	239.1	11.73	2783	-257	2805	1	0.99	1	1.67

Voltage and current distortion over a fifteen hour measurement period of the single phase PV are presented in Fig. 2.4. Voltage distortion at the MP was notably low (approximately 1%) throughout the observed time period and current distortions are not greatly affected by grid disturbances thereby.

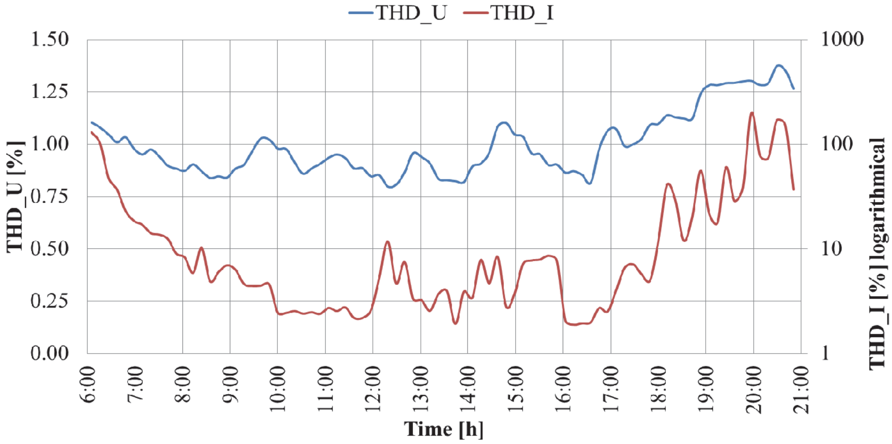


Fig. 2.4. The Measured Voltage THD and Current THD for a Single Phase PV Inverter.

Active power (P), reactive power (Q), and apparent power (S) are displayed in Fig. 2.5. The results are coherent in terms of the previous conclusion for reactive power in which reactive power is mainly capacitive throughout the measurement period. It can be confirmed that reactive power is not dependent upon current (compared to active and apparent power).

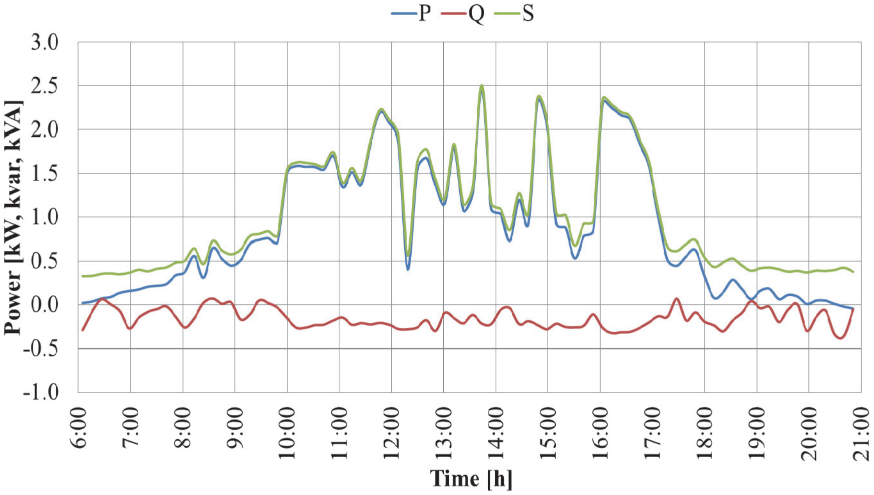


Fig. 2.5. The Measured Power Values for a Single Phase PV Inverter.

It can be concluded from Fig. 2.6, that cos φ remained near unity throughout the measurement period, whereas PF varied considerably. The observed fluctuations in PF are a result of current harmonics. It is seen when comparing the current THD and PF curves in Fig. 2.4 (THD_I) and Fig. 2.6 (PF) where strong correlation comes evident between them.

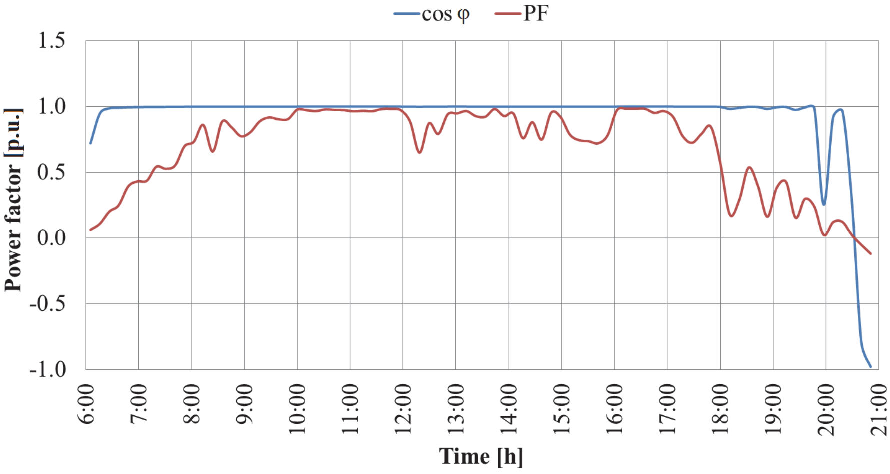


Fig. 2.6. The Measured Power Factors Values for the Single Phase PV Inverter.

For modelling mean PV generation, the average values of the current harmonic amplitudes and angles were calculated from this described measurement. Fundamental frequency current phase angles were defined as zero as in the ideal case and other angles were calculated in relation to the fundamental voltage. Fig. 2.7 is a graphical representation of the calculated average harmonics.

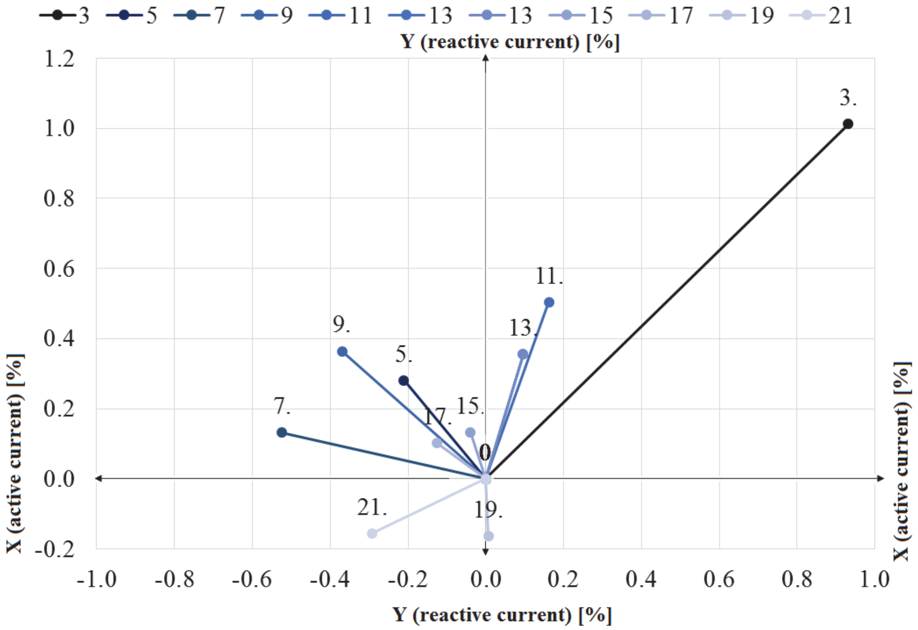


Fig. 2.7. Quadrant of Mean Harmonic Current Values of the Single Phase PV Inverter.

It can be concluded that the current harmonic distortion of the PV device output is correlated against current. Distortion is decreased when the PV operates at a higher load level. Due to unstable energy availability (ie. variable solar radiation), continuous variation in power quality parameters are expected. In the research that was conducted for this thesis, two PV devices also exhibited considerable harmonic current distortion at full power (with an average THD that was over 5%). Only one PV had an average current THD under 2%, which is considered to be satisfactory.

3 MODELLING WITH NONLINEAR DEVICES

After investigating the power quality issues and characteristics of nonlinear loads and nonlinear generation units, the next step is to use this knowledge and data in models. For this investigation modelling was carried out using DIgSILENT Power Factory software.

Goal of the modelling was to use the averaged values presented in chapter two and evaluate distortion values at residential bus bar. Due to various non-technical obstacles averaged values of small appliances are not included in the modelling process and real measurement data for all implemented appliances is used. For EV and PV averaged values as described in chapter two are used in the modelling process.

Description of Modelling Method

The 50 Hz residential distribution network at 0.4 kV with loads for assessing load flow were modelled using DIgSILENT Power Factory software. The model consisted of a three-phase residential load at 0.4 kV voltage level composed of different single phase loads. The schematic of the residential load model is presented in Fig. 3.1. Modelled devices were arranged in a manner where similar active power consumption was seen in every phase. In the model, all nonlinear devices are in operation and coincidence factors are not taken into account, thus representing the presumed worst case scenario.

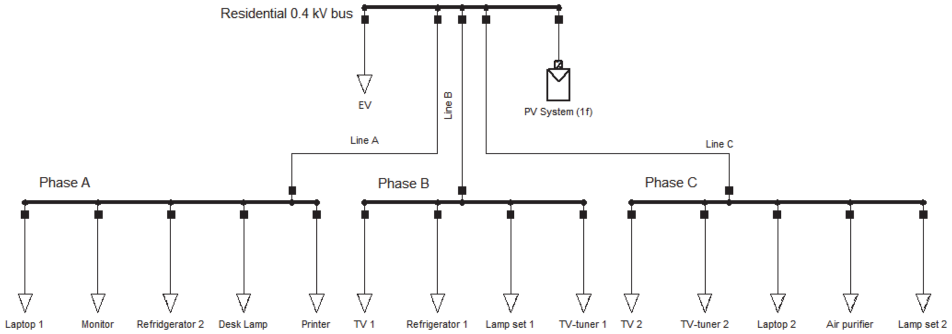


Fig. 3.1. Schematic of Residential Load Model

For assessing the influence of the residential load, the active and reactive power level values, harmonic current magnitudes and harmonic current phase shift angle values of fourteen home appliances were used in modelling process. Part of the measurement results were presented in Table 2.1 in section 2.1. For modelling PV generation and EV load averaged values described in chapter 2 were used.

The compiled residential load was connected to the distribution network substation via a 1.4 km long 4x95 mm overhead line (OHL) as depicted on Fig.

3.2 and it is the only consumer of this substation. The distribution network substation was connected to a 10 kV network with short-circuit power of 200 MVA and short-circuit current 11.5 kA, which represents grid strength below average if compared to other distribution grids. The high voltage (HV) busbar is modelled as a slack bus. The transformer used in the distribution substation was modelled with the following parameters:

- nominal power 25 kVA;
- relative short circuit voltage 4.5%;
- zero sequence impedances r0=0.02 pu and x0=0.04 pu
- magnetizing impedance/short circuit impedance ratio 3;
- vector group Yyn.

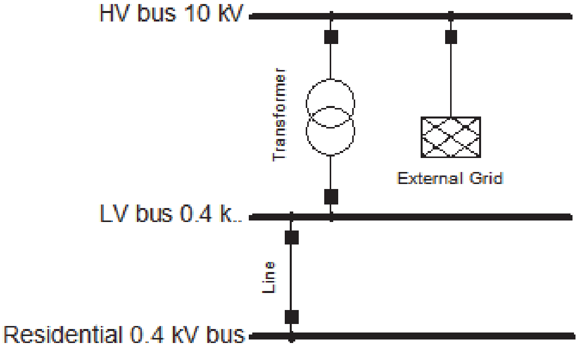


Fig. 3.2. Schematic of Distribution Grid Model

Implemented parameters in the simulation were selected based on power quality problematic issues identified in Elektrilevi's network (Estonia's main distribution grid operator) for July 1, 2013. The length of the OHL between substation and customer's PCC was defined as an average of all the lines between substations and customers with power quality problems. Similarly, the selected diameter of the line and nominal power of the transformer are the most common values for the identified problematic components.

Harmonic voltage amplitudes and phase angles up to the 50th order were obtained from measurements conducted by Elektrilevi at one of the sites where power quality issues were identified. Harmonic voltage distortion at the 10 kV bus was measured and modelled around 2%, which is a common value for this grid.

Initial Conditions of Modelling

Initial conditions represent the loads common to present day households.

- First case: one EV charging load connected to the PCC in addition to the initial load.
- Second case: one single-phase PV unit connected to the PCC in addition to the initial load.

- Third case: EV charging load and PV inverter are connected to the PCC in addition to the initial load.

Initial values of current, voltage, power and THD in the grid before adding the mean PV generations or the mean EV load are presented in Table 3.1.

Table 3.1. Initial Modelled Current, Voltage, Power and THD Values

I	I_a	I_b	I_c	I_n
	1.0	1.3	1.3	0.7
U	U_a	U_b	U_c	
	230	230	231	
P	P_a	P_b	P_c	
	0.23	0.28	0.25	
Q	Q_a	Q_b	Q_c	
	-0.01	-0.12	-0.16	
PF	PF_a	PF_b	PF_c	
	1.00	0.92	0.84	
THD	THD_a	THD_b	THD_c	
	2.9	2.1	3.2	

3.1 Modelling Residential Load with Electrical Vehicle

In [PAPER - IX], mean EV was added to the grid at the residential busbar and a phase of connection was altered to see the influence of connection point. The EV load causes voltage drop in phase where it is connected more than 5% in each case as see in Fig. 3.3. This was expected due to the relatively weak grid.

In all following figures blue colour stands for phase A, red colour stands for phase B, green colour stands for phase C and purple colour stands for neutral conductor.

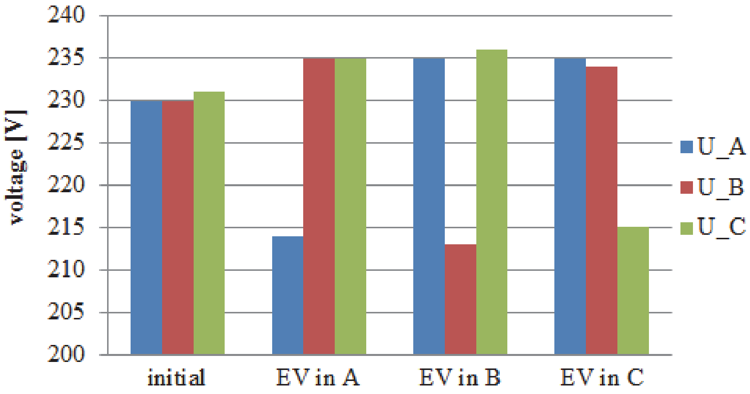


Fig. 3.3. Modelled Voltage Values with EV Load

Currents are changing accordingly to added EV load as seen in Fig. 3.4 as rising in the phase where the EV is connected. Changes around one ampere in neutral conductor are caused by different reinforcement or cancellation of harmonic magnitudes.

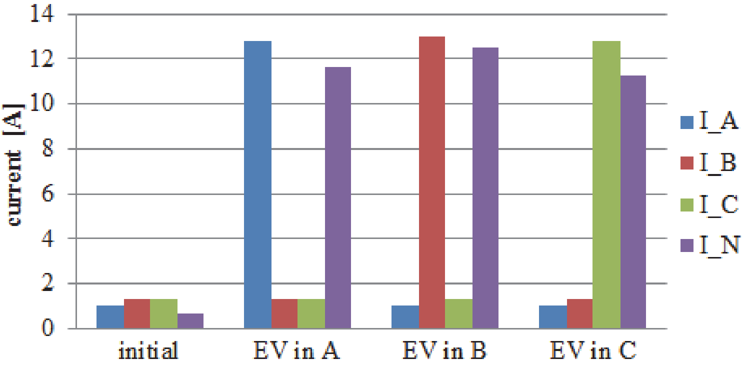


Fig. 3.4. Modelled Current Values with EV Load

Voltage THD was observed to increase up to 0.5% in two cases, but remained at same level when EV was connected to phase C as evident from Fig. 3.5. Slight increase in every phase with EV was expected, but expectation did not realized in phase C due to a harmonic cancellation.

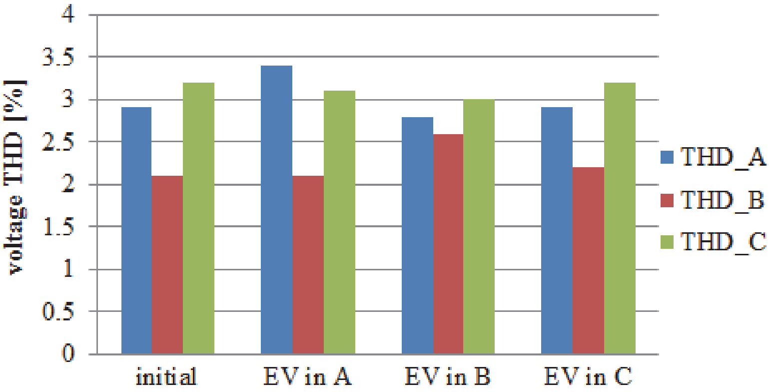


Fig. 3.5. Modelled Voltage THD Values with EV Load

Power factor changed slightly due to additional EV load and slightly improved in the phase where it was connected as seen in Fig. 3.6. Nothing odd was discovered in those values.

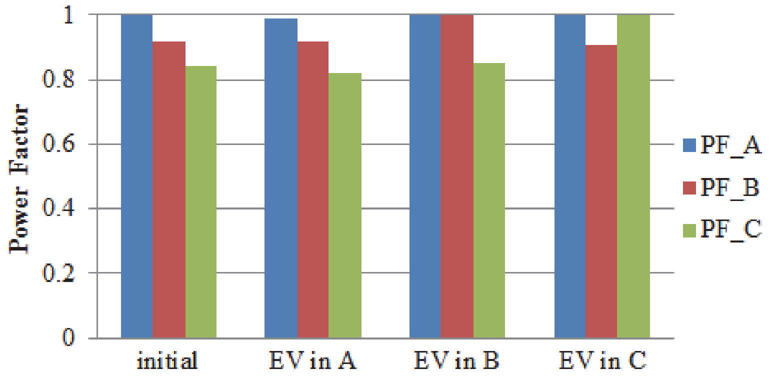


Fig. 3.6. Modelled PF Values with EV Load

Nothing critical can be observed from power changes which are described in Fig. 3.7. Added EV load increased active and reactive power values in the same amount as the EV power values were and in the same phase where they were added.

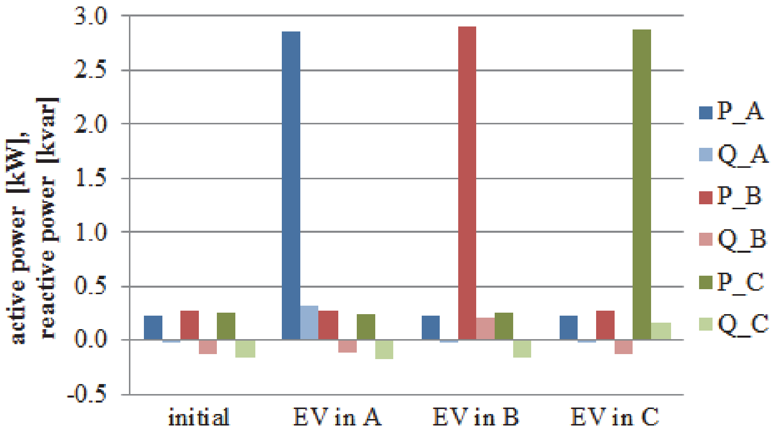


Fig. 3.7. Modelled Active and Reactive Power Values with EV Load

3.2 Modelling Residential Load with Photo Voltaic

In research [PAPER - IX], a single phase PV inverter was connected to the residential busbar and a phase of connection was altered. As it can be seen from Fig. 3.8 voltage in the phase where the PV is connected rises more than 5%. This was expected due to the relatively weak grid.

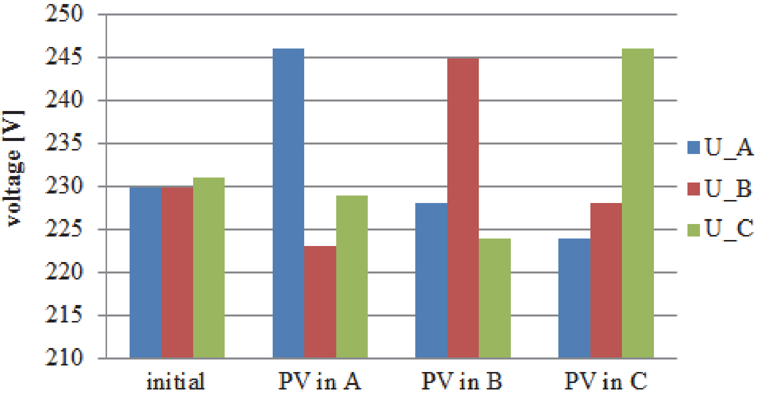


Fig. 3.8. Modelled Voltage Values with PV Load

Currents are changing accordingly to added PV load as seen in Fig. 3.9. Changes around one ampere in neutral conductor are caused by different reinforcement or cancellation of harmonic magnitudes.

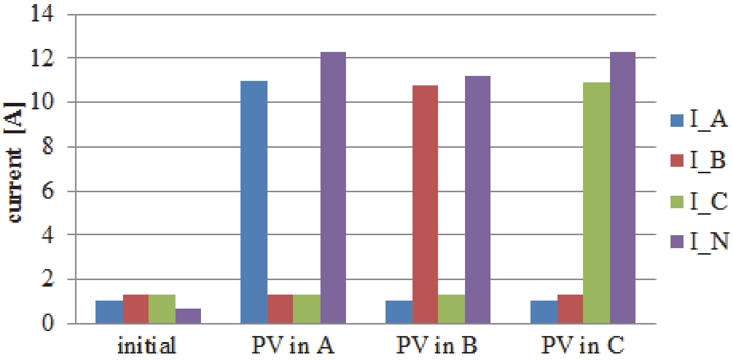


Fig. 3.9. Modelled Current Values with PV Load

Significant voltage THD rise due to the connected PV could not be seen as it was predicted. Instead, THD decreased slightly in cases where PV was connected to phase A and C as evident in Fig. 3.10.

Due to the change in reactive power, seen in Fig. 3.12, the PF value changed in the phase where the PV was installed, seen in Fig. 3.11. As PV was generating a power to the grid, PF values were negative. Added PV load increased active and reactive power values in the same amount as the PV power values were and in the same phase where they were added.

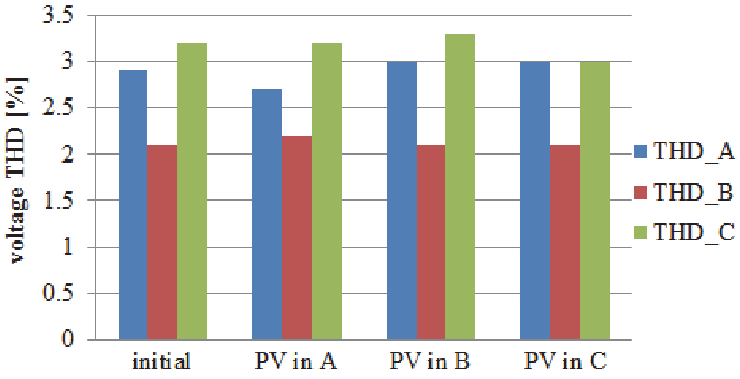


Fig. 3.10. Modelled THD Values with PV Load

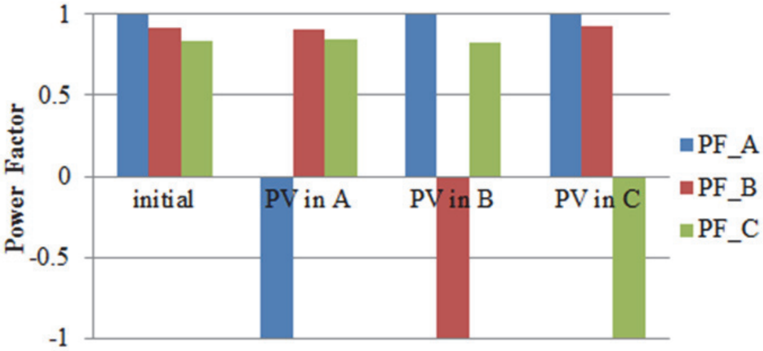


Fig. 3.11. Modelled PF Values with PV Load

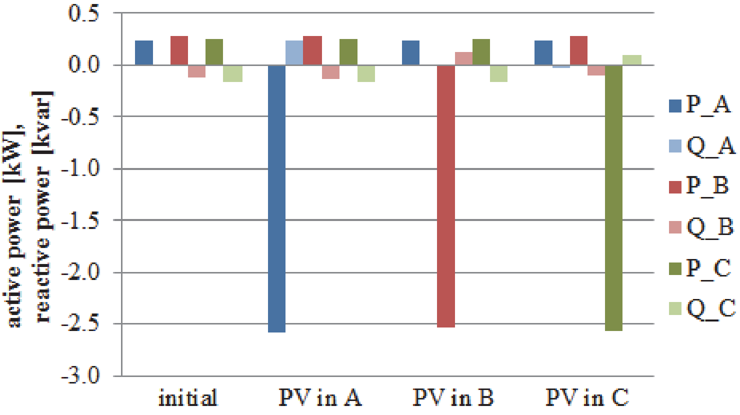


Fig. 3.12. Modelled Active and Reactive Power Values with PV Load

3.3 Modelling Residential Load with Photo Voltaic and Electrical Vehicle Simultaneously

PV and EV were modelled together from one residential busbar in [PAPER - IX]. In order to investigate differences in harmonic cancellation, the mean PV and mean EV were both installed in the same phases as well as in separate phases. Voltages and currents are presented in Fig. 3.13 and Fig. 3.14 accordingly.

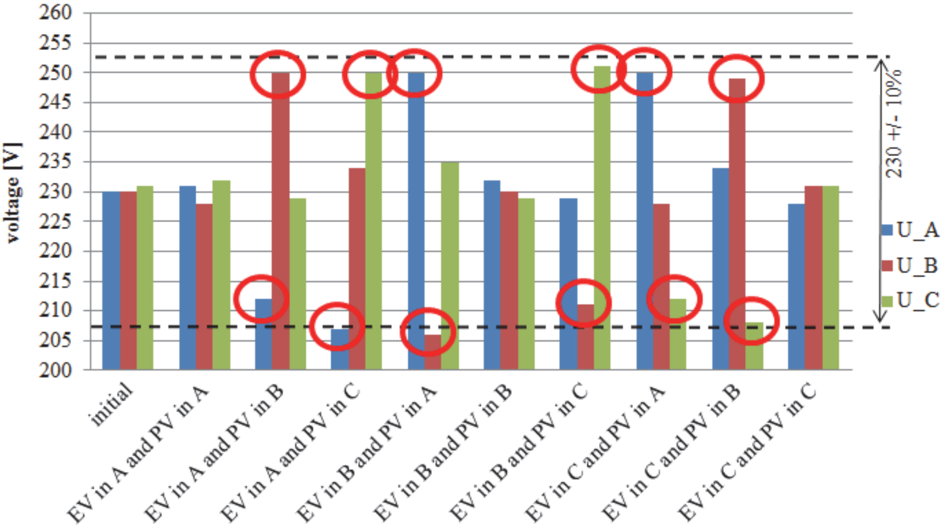


Fig. 3.13. Modelled Voltage Values with EV and PV Load

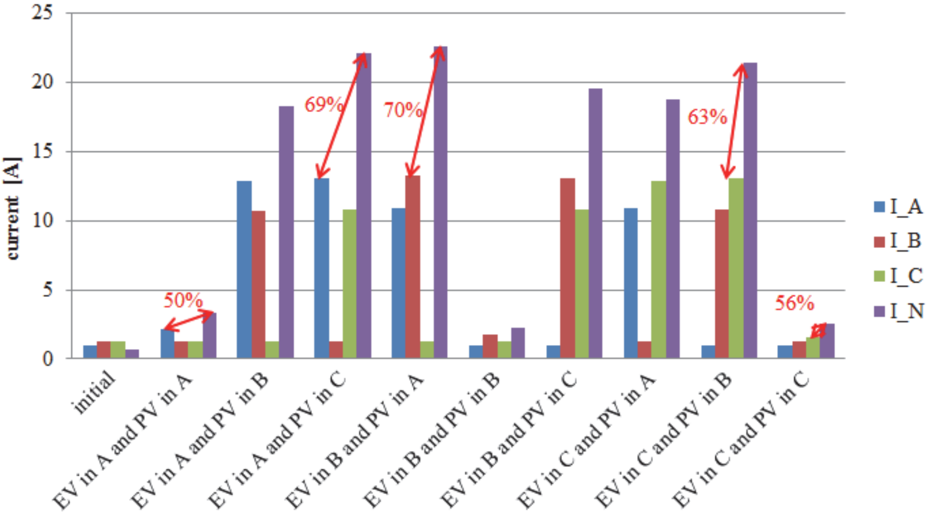


Fig. 3.14. Modelled Current Values with EV and PV Load

It was observed that in arrangements in which PV and EV are in different phases, voltages will change drastically. Voltage unbalance is more than 10% in some of those cases. A neutral current rise can be observed in several cases. Voltages near the +/- 10% limit are marked with red circles in Fig. 3.13 and high neutral currents are marked red arrows in Fig. 3.14.

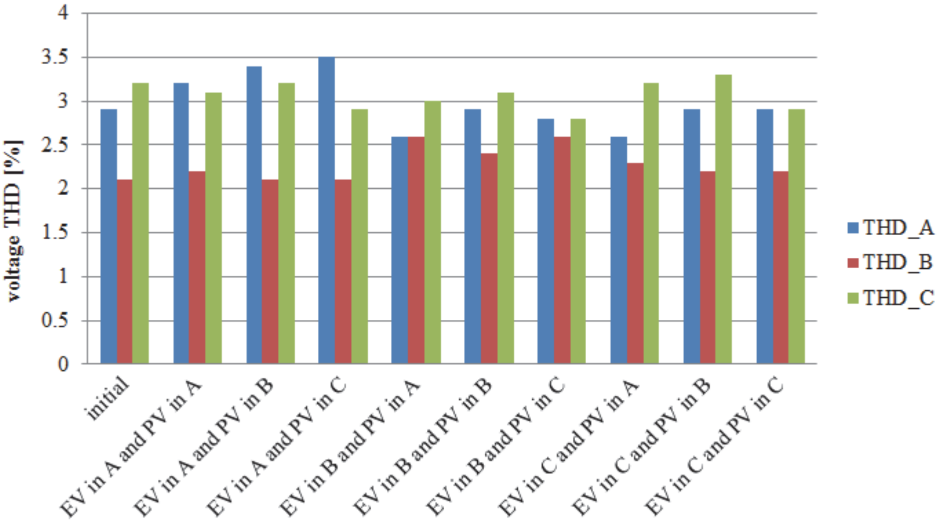


Fig. 3.15.Modelled Voltage THD Values with EV and PV Load

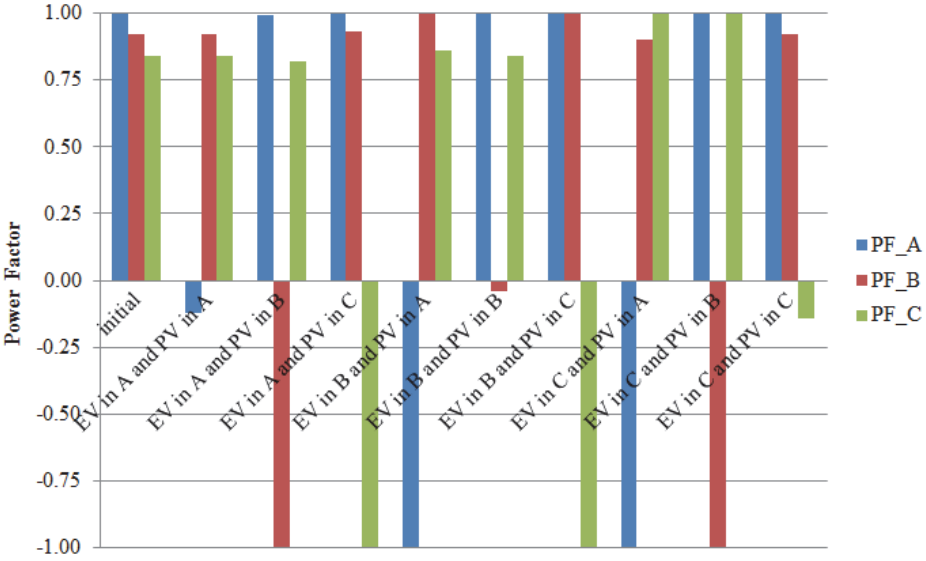


Fig. 3.16. Modelled PF Values with EV and PV Load

In the worst case, voltage THD increases in one phase by up to 0.6%, but placing the EV and PV together in the same phase can lead to slightly decreased voltage THD in several situations. Voltage THD and PF values are presented in Fig. 3.15 and Fig. 3.16 respectively.

Devices that are in the same phase lead to a slight growth of reactive power in the same phase as evident in Fig. 3.17. Active power is compensated due to opposite direction of power flow of the EV and PV.

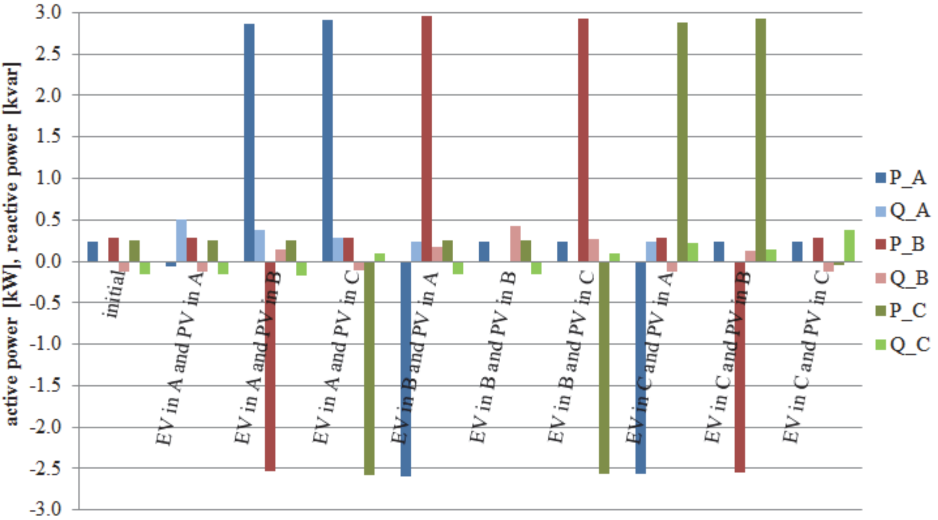


Fig. 3.17. Modelled Active and Reactive Power Values with EV and PV Load

Voltage distortion increases when PVs and EVs are connected to a residential load. The rise is dependent upon grid strength, and a less attractive situation occurs in cases in which less powerful transformers and thinner cables are utilised. The present study showed that the most reasonable option is to connect both the PV and EV into the same phase. Installing the EVs and PVs separately or installing them in separate phases results in a notable increase in voltage distortion.

The situation is more severe in terms of voltage drops and rises and neutral currents. In cases in which the PV and EV were both installed in different phases, the voltage in those phases in which the PV was connected rose near the 10% limit, and decreased close to 10% in the phase in which the EV was connected. When the PV and EV were connected in different phases, the neutral currents were up to 1.8 times higher than phase currents. It can be concluded that modelling with different transformer power ratings, power cable lengths and cross sections, should be conducted before installing any nonlinear devices.

CONCLUSIONS

The findings of this thesis are important when distributed generation units, electrical vehicles, and other nonlinear loads are going to be connected into low-voltage networks in great numbers. When grid strengthening and load connecting are arranged wisely, the need to make investments could be postponed or reduced.

In Estonia, such distribution grids with residential loads as described in the thesis with predictable new nonlinear loads and EVs and DG units are common. Estonia's potential for dispersed generation units is extensive and the impacts for power quality may be massive even if the majority of that potential is not even installed. On the load side, the number of EVs is growing and, besides this, a vast number of heat-pumps with extensive power consumption are connected to residential houses. Heat pumps were not considered in this thesis.

In the situation in which generation as well as consumption results in decreased power quality levels in the grid, it is essential to analyse both generation and consumption in a comprehensive way. If comprehensive research proves to be necessary, it may make sense to limit the usage of new power generating units and appliances or to use other methods in order to decrease their negative effect upon power quality levels.

Detailed predictions on the possible harmonic distortion levels of distribution networks in future are complex. Many nonlinear loads have low power consumption and, for low power levels, their quality requirements are not strictly regulated by any standards. The effect of such nonlinear loads can be hazardous to network operation if the number of such devices is extensive. The total impact depends upon the number of appliances, their power ratings, and the characteristics of their current waveforms. A lack of enforceable standards has not encouraged the utility companies to implement wide-ranging monitoring, but it is becoming steadily more important as the number of power electronic devices in the grid is growing.

The characteristics of electric vehicles and distributed generation units have been presented before now; however, the measurement results have not revealed the individual harmonic magnitude and phase angle values in a detailed enough manners so that, for example, an evaluation can be drawn up of the way the harmonic patterns total together. In order to determine the impact of current harmonics on both, the network and voltage harmonics, the actual harmonic current values will have to be used.

Several aspects of how to avoid possible power quality issues are handled in the thesis. One measure for reducing the distortion is to arrange the loads between phases more wisely. This is something that can be carried out when the harmonic content of these loads are known. In the case of similarly loaded feeders, transposing the phases in substations may be considered beneficial in the future. Generally, powerful new loads and generation units should be modelled in the existing network before any installation work is carried out. Therefore, many field and laboratory measurements were carried out during the process of PhD studies. Averaged values were suggested and all of the results were published in order to help this process in the future.

Concluding Results

Based on the doctoral thesis it can be concluded that:

- small appliances in vast numbers affect power quality levels in several aspects
- the unregulated charging of powerful loads such as EVs may have a negative effect on power quality indices
- unregulated installation of distributed generation units such as PVs and WTs have a negative effect on power quality indices
- the neutral current may rise to dangerous levels when nonlinear loads and nonlinear generation units are implemented unwisely
- due to the existence of nonlinear loads with significantly distorted currents the entire residential load is severely distorted
- due to unbalanced nonlinear loads a high current in a neutral conductor can occur
- more severe situations with a reinforcement of current harmonics rise as more of the same appliances are installed together
- harmonic cancellation can be observed when a wider range of appliance types are installed together
- for a precise evaluation of harmonics, phase angle values are needed as well as magnitude values

Scientific and Practical Novelty

The scientific and practical novelty of the doctoral thesis includes:

- bring overall attention in Estonia to the power quality topic
- bring attention to possible severe future trends in power quality to the distribution grid specialist in Estonia
- analysing field measurements results up to fiftieth harmonic order
- analysing harmonic angles in addition to amplitudes
- modelling nonlinear loads together with nonlinear generation units
- proposing more precise models for specific nonlinear loads and nonlinear generation units
- gathering vast amounts of measurement data for nonlinear loads and nonlinear generation units
- publishing characteristics of various nonlinear loads and nonlinear generation units
- mapping different power quality issues due to nonlinear loads and nonlinear generation units

Suggestions

Based on the doctoral thesis clear following suggestions can be made:

- distribution network companies should map all the possible risks concerning new nonlinear loads and nonlinear generation units
- distribution network companies should monitor changes in power quality over time in areas where possible new generation units may be installed
- distribution network companies should set limits for next generation unit installations if there have been already remarkable changes due to nonlinear generation units
- distribution network companies should utilise their monitoring resource in maximum possible manner (remote meter reading devices)
- small producers should be informed and share the responsibility of all possible negative effects (including changing power quality parameters) of utilising small generation units

FUTURE WORK

Those studies that have been conducted for this thesis only examine one household and one PV or EV at a time. The effects described may escalate when a larger number of devices are considered. Special attention is required in situations in which devices have similar harmonic patterns, the harmonic cancellation effect is minimal, and the grid is weak. It has been shown that different network configurations, transformer sizes, and network strength are relevant in this type of study. Therefore, comprehensive measurements taken from the distribution grid are aimed at clarifying the present power quality situation.

General values for further modelling of PVs and EVs were presented in this thesis, but additional measurements should be carried out in order to obtain more accurate values for modelling PV generators and EV loads. It will be necessary to have measurement data that extend over entire years in order to acquire results that are independent of any disturbance. Furthermore, flicker and voltage level issues should be accounted for as they may have a significant influence on real life applications.

Beside DGs and EVs, field and laboratory measurements for all other significant nonlinear loads such as, for example, heating pump loads, are planned with the goal of presenting more precise models for further modelling. Current harmonic profile changes for those loads and generation units due to voltage profile are one of the main objectives.

Upon completion of all the aforementioned measurements and models, everything needs to be modelled together in various scenarios and in diverse grids. Comprehensive data then helps in carrying out various analyses for specific situations.

Undergoing the replacement of old induction meters with new digital meters in Estonia has raised interest when it comes to investigating more widely the accuracy of energy meters under the conditions of distorted power quality levels.

References

[1] J. C. Gomez and M. M. Morcos, “Impact of EV battery chargers on the power quality of distribution systems,” *IEEE Trans. Power Deliv.*, vol. 18, no. 3, pp. 975–981, Jul. 2003.

[2] J. Yong, L. Chen, and S. Chen, “Modeling of Home Appliances for Power Distribution System Harmonic Analysis,” *IEEE Trans. Power Deliv.*, vol. 25, no. 4, pp. 3147–3155, Oct. 2010.

[3] M. J. H. Rawa, D. W. P. Thomas, and M. Sumner, “Simulation of non-linear loads for harmonic studies,” in *11th International Conference on Electrical Power Quality and Utilisation*, 2011, pp. 1–6.

[4] L. Kütt, E. Saarijärvi, M. Lehtonen, H. Mõlder, and J. Niitsoo, “A review of the harmonic and unbalance effects in electrical distribution networks due to EV charging,” in *2013 12th International Conference on Environment and Electrical Engineering*, 2013, pp. 556–561.

[5] J. J. M. Desmet, I. Sweertvaegher, G. Vanalme, K. Stockman, and R. J. M. Belmans, “Analysis of the neutral conductor current in a three-phase supplied network with nonlinear single-phase loads,” *IEEE Trans. Ind. Appl.*, vol. 39, no. 3, pp. 587–593, May 2003.

[6] J. Desmet, C. Debruyne, J. Vanalme, and L. Vandevelde, “Power injection by distributed generation and the influence of harmonic load conditions,” in *IEEE PES General Meeting*, 2010, pp. 1–6.

[7] M. M. Jensen and H. Hansen, “Triplen Harmonic Voltage Distortion in the Low-Voltage Network,” in *Proceedings of the NORDAC 2014*, 2014.

[8] S. Bhattacharyya, S. Cobben, P. Ribeiro, and W. Kling, “Harmonic emission limits and responsibilities at a point of connection,” *IET Gener. Transm. Distrib.*, vol. 6, no. 3, p. 256, 2012.

[9] N. Watson and S. Hirsch, “THE EFFECTS OF COMPACT FLUORESCENT LAMPS ON POWER QUALITY,” in *EU-Asia Power Quality Initiative*, 1994.

[10] A. B. Nassif and W. Xu, “Characterizing the Harmonic Attenuation Effect of Compact Fluorescent Lamps,” *IEEE Trans. Power Deliv.*, vol. 24, no. 3, pp. 1748–1749, 2009.

[11] Z. Radakovic, F. V. Topalis, and M. Kostic, “The voltage distortion in low-voltage networks caused by compact fluorescent lamps with electronic gear,” *Electr. Power Syst. Res.*, vol. 73, no. 2, pp. 129–136, 2005.

[12] M. Kontturi and J. Alander, “Energiansäästölamppujen verkkovaikutukset,” Joensuu, Finland, 2008.

[13] R. A. Jabbar, M. Al-Dabbagh, A. Muhammad, R. H. Khawaja, M. Akmal, and M. R. Arif, “Impact of compact fluorescent lamp on power quality,” in *Proceedings of the Australasian Universities Power Engineering Conference (AUPEC ’08)*, 2008, pp. 1–5.

[14] H. Mõlder, M. Lellsaar, and L. Kütt, “Compact fluorescent lamp harmonic disruption effect of transformer losses,” in *Proceedings of the 8th International Symposium „Topical Problems in the Field of Electrical and Power Engineering“*, 2010, pp. 277–280.

[15] V. Tikka, J. Lassila, J. Haakana, and J. Partanen, “Case study of the effects of electric vehicle charging on grid loads in an urban area,” in *2011 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies*, 2011, pp. 1–7.

[16] L. Kütt, E. Saarijärvi, M. Lehtonen, H. Mõlder, and J. Niitsoo, “A Review of the Effects of Electric Vehicle Charging on Distribution Network Operation and Power Quality,” in *Proceedings of the 8th International Conference on Electrical and Control Technologies ECT-2013*, 2013, pp. 162–167.

[17] W. Zhou, H. Xie, and Y. Tong, “Propagation mechanisms research of harmonics produced by distributed generations in distribution network,” in *2012 IEEE 15th International Conference on Harmonics and Quality of Power*, 2012, pp. 774–777.

[18] M. Farhoodnea, A. Mohamed, H. Shareef, and H. Zayandehroodi, “Power quality impacts of high-penetration electric vehicle stations and renewable energy-based generators on power distribution systems,” *Measurement*, vol. 46, no. 8, pp. 2423–2434, Oct. 2013.

[19] A. Makbul and M. I. Hamid, “Power quality behavior of single phase fed adjustable speed drive supplied from grid of PV generation,” in *2008 IEEE 2nd International Power and Energy Conference*, 2008, pp. 1098–1102.

[20] M. Van Lumig, S. Bhattacharyya, J. F. G. Cobben, and W. L. Kling, “Power Quality measurements near DER and disturbing loads Key words,” in *Proceedings of the International Conference on Renewable Energies and Power Quality (ICREPQ’11)*, 2010, pp. 11–16.

[21] F. Batrinu, G. Chicco, J. Schlabbach, and F. Spertino, “Impacts of grid-connected photovoltaic plant operation on the harmonic distortion,” in *MELECON 2006 - 2006 IEEE Mediterranean Electrotechnical Conference*, 2006, pp. 861–864.

[22] G. Chicco, J. Schlabbach, and F. Spertino, “Characterisation and assessment of the harmonic emission of grid-connected photovoltaic systems,” in *2005 IEEE Russia Power Tech*, 2005, pp. 1–7.

[23] T. Ackermann and V. Knyazkin, “Interaction between distributed generation and the distribution network: operation aspects,” in *IEEE/PES Transmission and Distribution Conference and Exhibition*, 2002, vol. 2, pp. 1357–1362.

[24] A. D. Simmons and D. G. Infield, “Current waveform quality from grid-connected photovoltaic inverters and its dependence on operating conditions,” *Prog. Photovoltaics Res. Appl.*, vol. 8, no. 4, pp. 411–420, Jul. 2000.

[25] D. G. Infield, P. Onions, A. D. Simmons, and G. A. Smith, “Power Quality From Multiple Grid-Connected Single-Phase Inverters,” *IEEE Trans. Power Deliv.*, vol. 19, no. 4, pp. 1983–1989, Oct. 2004.

[26] R. Armas, “Väiketootja mõju pingekvaliteedile jaotusvõrgus Elektrilevi OÜ näitel,” Tallinn University of Technology, 2014.

[27] J. Driesen and R. Belmans, “Distributed generation: challenges and possible solutions,” in *2006 IEEE Power Engineering Society General Meeting*, 2006, p. 8 pp.

[28] S. Quaia, “Distributed Generation and under load transformers operation: Voltage quality problems and possible improvements,” in *SPEEDAM 2010*, 2010, pp. 890–894.

[29] R. Armas, “Impact of small producers on power quality in distribution grids based on Elektrilevi OÜ grid,” in *Proceedings of the 23rd International Conference on Electricity Distribution (CIRED 2015)*, 2015, no. June, pp. 15–18.

[30] K. D. McBee and M. G. Simoes, “Evaluating the long-term impact of a continuously increasing harmonic load demand on feeder level voltage

distortion," in *2012 IEEE Industry Applications Society Annual Meeting*, 2012, pp. 1–8.

[31] M. T. Au, J. S. Navamany, and E. C. Yeoh, "Impact of medium power inverter-based residential harmonic loads and PFCs on low voltage lines," in *2010 IEEE International Conference on Power and Energy*, 2010, pp. 695–699.

[32] T. Kilgi, "Elektritarvitite voolukarakteristikud," Tallinn University of Technology, 2015.

[33] S. Shao, M. Pipattanasomporn, and S. Rahman, "Demand Response as a Load Shaping Tool in an Intelligent Grid With Electric Vehicles," *IEEE Trans. Smart Grid*, vol. 2, no. 4, pp. 624–631, Dec. 2011.

[34] S. H. Berisha, G. G. Karady, R. Ahmad, R. Hobbs, and D. Karner, "Current harmonics generated by electric vehicle battery chargers," in *Proceedings of International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth*, 1996, vol. 1, pp. 584–589.

[35] M. Wanik, M. Siam FadzilMohd, A. Ayob, S. Yanto, A. Mohamed, A. HanifahAzit, S. Sulaiman, M. A. M. Ali, Z. F. Hussein, and A. K. MatHussin, "Harmonic Measurement and Analysis during Electric Vehicle Charging," *Engineering*, vol. 5, no. 1, pp. 215–220, Jan. 2013.

[36] N. Melo, F. Mira, A. de Almeida, and J. Delgado, "Integration of PEV in Portuguese distribution grid: Analysis of harmonic current emissions in charging points," in *11th International Conference on Electrical Power Quality and Utilisation*, 2011, pp. 1–6.

[37] C. Wenge, T. Winkler, M. Stotzer, and P. Komarnicki, "Power quality measurements of electric vehicles in the low voltage power grid," in *11th International Conference on Electrical Power Quality and Utilisation*, 2011, pp. 1–5.

[38] P. S. Moses, S. Deilami, A. S. Masoum, and M. A. S. Masoum, "Power quality of smart grids with Plug-in Electric Vehicles considering battery charging profile," in *2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*, 2010, pp. 1–7.

[39] P. A. B. Block, H. L. L. Salamanca, M. D. Teixeira, D. B. Dahlke, O. M. Shiono, A. R. Donadon, and J. C. Camargo, "Power quality analyses of a large scale photovoltaic system," in *2014 5th International Renewable Energy Congress (IREC)*, 2014, pp. 1–6.

[40] K. P. Kontogiannis, G. A. Vokas, S. Nanou, and S. Papathanassiou, "Power Quality Field Measurements on PV Inverters," *Int. J. Adv. Res. Electr. Electron. Instrum. Eng.*, vol. 2, no. 11, Nov. 2013.

[41] J. H. R. Enslin and P. J. M. Heskes, "Harmonic Interaction Between a Large Number of Distributed Power Inverters and the Distribution Network," *IEEE Trans. Power Electron.*, vol. 19, no. 6, pp. 1586–1593, Nov. 2004.

[42] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications, and Design*. John Wiley & Sons, 2002.

[43] M. A. Eltawil and Z. Zhao, "Grid-connected photovoltaic power systems: Technical and potential problems—A review," *Renew. Sustain. Energy Rev.*, vol. 14, no. 1, pp. 112–129, Jan. 2010.

[44] P. J. M. Heskes and J. H. R. Enslin, "Power Quality Behaviour of Different Photovoltaic Inverter Topologies," in *Proceedings of the 24th International Conference PCIM-2003*, 2003.

Abstract

The world is heading rapidly towards the more intensive employment of renewable energy sources, which will increasingly affect traditional electricity grids. This is especially critical in terms of power quality levels, because power plants have traditionally produced electricity with a sinusoidal voltage and all appliances are designed to work with a sinusoidal voltage. Presently we have reached a situation in which an increasing number of generating units are implemented with output voltages that are produced using power electronics. These devices do not produce a perfect sinusoid waveform. On the other side of the grid, traditional loads that consume a sinusoidal current are on the decrease, and these are being substituted with devices that are full of electronics, and their current waveform may not resemble a sinusoid.

Finding a grand total for the new generating units and new loads in the electrical networks which are built upon the assumption of there being a sinusoidal voltage may lead to various challenges. Issues of operational viability may occur when it comes to aforementioned devices, but at the same time all other traditional apparatuses and grid components will be in danger. Moreover, the lifespan of devices and components decreases, power losses increase and other effects which were previously under control may now rise.

Various power quality issues that may occur are covered in the first chapter of the present thesis. Over separate sections, the influence of small appliances, electrical vehicles and distributed generation units are presented.

In section two, the characteristics of low power appliances, electrical vehicles, and distributed generation units are described. Precise measurement data and averaged values for further modelling are presented.

The third section includes the modelling results. In most cases, a simple proportion of the electrical distribution network with one to three loads is modelled and small appliances, electrical vehicles, and photovoltaic panels are integrated into the model. The numbers of devices were altered at different power levels in various scenarios.

The overall conclusion of the thesis is one in which the diverse devices that are presently being used have different technical characteristics, and comprehensive research should be carried out before widely implementing them into the electrical grid. All characteristics of the devices, the possibility of integration, and the level of compatibility have to be clarified. It is evident that nonlinear loads and appliances influence power quality levels quite significantly.

The present thesis lays the foundations for this kind of research and proves that more comprehensive measurements have to be carried out and simplified models for modelling characteristic situations have to be composed.

Kokkuvõte

Maailm liigub jõuliselt üha mahukama taastuvenergia kasutamise suunas, mis aina enam hakkab mõjutama traditsioonilisi elektrivõrke. Seda just paljuski elektrikvaliteedi seisukohast, kuna elektritootmisüksused on tavapäraselt genereerinud elektrienergiat siinuspingel ning kõik võrku ühendatavad tarvitid on ettenähtud talitlema samuti siinuspingel. Tänapäeval on aga jõutud olukorda, kus võrku ühendatakse aina enam elektrit genereerivaid seadmeid, mille väljundpinge kuju moduleeritakse jõuelektroonika abil ning mille kuju ei vasta enam siinuslainele. Teisest küljest on kadumas kasutusest traditsioonilised tarvitid, mis talitlevad siinuselise kujuga voolu tarbides, ning need asenduvad aina enam elektroonikat sisalduvate seadmetega, mille tarbimisvool ei pruugi võrgusageduslikku siinuslaine kuju meenutada.

Ühelt poolt uute tootjate ja teiselt poolt uute tarbijate lisandumine endistel põhimõtetel ehitatud elektrivõrku toob tulevikus kaasa erinevaid väljakutseid. Probleeme võib tekkida nii nende seadmete endaga kui ka kõikide allesjäänud traditsiooniliste seadmetega ja sealhulgas elektrivõrgu komponentidega. Peale võimalike tõrgete lisandumisega seadmete talitlusele võivad oluliselt väheneda nende planeeritud eluead, suureneda elektrikaod ning võimenduda nähtused, mis varasemalt ei ole probleemiks olnud.

Erinevatest probleemidest, mis võivad elektrijaotusvõrgus ilmneda, antakse ülevaade töö esimeses osas. Eraldi peatükkidena on välja toodud väikese võimsusega tarvitite, elektriautode ning hajatootmisüksuste mõju.

Töö teises osas on kirjeldatud väikese võimsusega tarvitite, elektriautode ja hajatootmisüksuste karakteristikuid. Välja on toodud on mõõtetulemused ning esitatud keskmistatud väärtused edaspidiseks modelleerimiseks.

Töö kolmas osa võtab kokku modelleerimistulemused. Enamikel juhtudel on modelleeritud võrku alates väikese võimsusega toitetrafost kuni pika liini lõpus olevate tarbijateni. Tarbijatena on kujutatudelektriautosid, päikesepaneele ning erinevaid väikese võimsusega tarviteid.

Käesoleva töö järeldus on, et tänapäevased elektroonikat sisaldavad seadmed on väga erinevate tehniliste näitajatega ning enne nende massilist elektrivõrku ühendamist tuleks teha mahukad uurimused. Selgeks tuleb teha nii seadmete karakteristikud kui nende võrku ühendamise võimalikkus ning võimalikkuse piir. Selge on, et ebalineaarsed seadmed mõjutavad elektrikvaliteedi näitajaid märgatavalt.

Antud doktoritöö on aluseks tulevaste mahukamate uurimuste tegemisel ning tõestab, et vaja on teostada veelgi laiaulatuslikumaid mõõtmisi ning iga konkreetse olukorda modelleerimiseks tuleks välja töötada võimalikult täpsed mudelid erinevate seadmetüüpide ning nende koosseisu kohta võrgus.

Elulookirjeldus

1. Isikuandmed

Ees- ja perekonnanimi: Jaan Niitsoo
Sünniaeg ja -koht: 24.02.1987, Rapla
Kodakondsus: Eesti
E-posti aadress: jaan.niitsoo@ttu.ee
Aadress: Vesiniku tee 1, Vääna-Jõesuu

2. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool	2010	Elektroenergeetika/ Tehnikateaduse magister
Tallinna Tehnikaülikool	2009	Elektroenergeetika/ Tehnikateaduse bakalaureus
Rapla Vesiroosi Gümnaasium	2006	Keskharidus

3. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Eesti keel	Kõrgtase
Inglise keel	Kõrgtase
Vene keel	Algtase
Soome keel	Algtase

4. Täiendusõpe

Õppimise aeg	Täiendusõppe nimetus	Täiendusõppe läbiviija
2016 (5 päeva)	Assessorite koolitus	Eesti Akrediteerimiskeskus
2015 (3 päeva)	Substation Earthing koolitus	EA Technology, Inglismaa

2014 (5 päeva)	A-pädevuse eksamiks ettevalmistav loengusari	Inspecta OÜ, Eesti
2012 (3 päeva)	Harmonics in Power Electronics and Power Systems koolitus	Aalborgi Ülikool, Taani
2011 (3 päeva)	Post-Graduate Course on Power Quality	Aalto Ülikool, Soome
2011 – 2012	Erinevad DIgSILENT tarkvara koolitused	DIgSILENT GmbH, Gomaringen, Saksaamaa
2011 (3 päeva)	Overvoltages, overvoltage protection and insulation coordination in high voltage power systems	Lappenranta Tehnikaülikool, Soome
2010 – 2013	Erinevad täienduskoolitused	Energia- ja geotehnika doktorikool II
2010 (14 päeva)	Suvekool „Power“	Aarhuse ülikool, Taani
2010 (14 päeva)	Kevadkool „Automation and Modelling of Fuel Cell and Hydrogen based Energy Systems“	Stralsundi Rakendusteaduste Ülikool, Saksamaa

5. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2014 - …	Elektrilevi OÜ	Sektorijuhataja
2010 - …	Tallinna Tehnikaülikool; Elektroenergeetika instituut	Assistent
2010 – 2011	Kehtna Majandus- ja Tehnoloogiakool	Õpetaja
2008	OÜ Jaotusvõrk	Spetsialist
2005	AS Eltel Networks	Elektrik

6. Teadustöö põhisuunad

- Loodusteadused ja tehnika, Energeetikaalased uuringud, Energeetika

7. Jooksvad projektid

- Uute elektritootmismustrite mõju kõrgepingeseadmete ja kaablite isolatsioonile

8. Teaduspreemiad ja -tunnustused

2014 Elektriala A-pädevus
2013 Mati Jostovi nimeline doktoriõppe stipendium
2013 Volitatud elektriinsener V kutse
2013 Talveakadeemia 2013 teadustööde konkursi II astme 3. koht
2012 Jaan Poska nimeline stipendium
2012 Talveakadeemia 2012 parim ettekanne
2012 Talveakadeemia 2012 teadustööde konkursi II astme 1. koht
2011 Olev Liigi nimeline doktoriõppe stipendium
2011 Talveakadeemia 2011 teadustööde konkursi II astme 1. koht
2010 Ülemaailmse Eesti Kesknõukogu (ÜEKN) Margot ja Herbert Linna nimeline stipendium
2010 Tallinna Tehnikaülikooli Elektroenergeetika magistriõppe lõpetamine *cum laude*

9. Juhendatud väitekirjad

2015 Alo Toom, magistrikraad, Elektrilevi OÜ KP/MP alajaamade lahendused ülitihedalt asustatud piirkondades, Tallinna Tehnikaülikool
2015 Roland Murakas, bakalaureusekraad, Kõrgemate harmoonikute mõju elektrienergia arvestite täpsusele, Tallinna Tehnikaülikool
2015 Toomas Kilgi, bakalaureusekraad, Elektritarvitite voolukarakteristikud, Tallinna Tehnikaülikool
2014 Rasmus Armas, magistrikraad, Väiketootja mõju pingekvaliteedile jaotusvõrgus Elektrilevi OÜ näitel, Tallinna Tehnikaülikool
2013 Henri Külm, bakalaureusekraad, Väiketuulikute mõju elektrikvaliteedile, Tallinna Tehnikaülikool
2013 Erik Arro, bakalaureusekraad, Elektriauto laadimise mõju elektrikvaliteedile, Tallinna Tehnikaülikool
2013 Allar Keerme, bakalaureusekraad, Päikesepaneelide mõju elektrikvaliteedile, Tallinna Tehnikaülikool
2012 Madis Leinakse, bakalaureusekraad, Elektrienergia kvaliteedi mõõtmine analüsaatoriga Chauvin Arnoux C.A 8352, Tallinna Tehnikaülikool
2012 Ats Haas, bakalaureusekraad, Elektrikvaliteedi mõju elektrienergia arvestite täpsusele, Tallinna Tehnikaülikool
2012 Jaan Jakobson, magistrikraad, Soome, Eesti, Läti ja Leedu ühine maagaasi järelturg, Tallinna Tehnikaülikool
2011 Edgar Dubbelmann, magistrikraad, Tuuleelektrijaama modelleerimine ning mudeli verifitseerimine, Tallinna Tehnikaülikool

Curriculum Vitae

1. Personal data

Name: Jaan Niitsoo

Date and place of birth: 24.02.1987, Rapla, Estonia

E-mail: jaan.niitsoo@ttu.ee

Address: Vesiniku tee 1, Vääna-Jõesuu, Estonia

2. Education

Educational institution	Graduation year	Education (field of study/degree)
Tallinn University of Technology	2010	Electric Power Engineering/ Master of Science
Tallinn University of Technology	2009	Electrical Power Engineering/ Bachelor of Science
Rapla Vesiroosi Gymnasium	2006	Secondary education

3. Language competence/skills (fluent; average, basic skills)

Language	Level
Estonian	Fluent
English	Fluent
Russian	Basic skills
Finnish	Basic skills

4. Special Courses

Period	Course name	Organization
2016 (5 days)	Assessors Training	Estonian Accreditation Centre
2015 (3 days)	Substation Earthing course	EA Technology, UK

2014 (5 days)	Lectures for preparing “A” competency level exam in field of electricity	Inspecta OÜ, Estonia
2012 (3 days)	Harmonics in Power Electronics and Power Systems	Aalborg University, Denmark
2011 (3 days)	Post-Graduate Course on Power Quality	Aalto University, Finland
2011 – 2012	Different DIgSILENT software courses	DIgSILENT GmbH, Gomaringen, Germany
2011 (3 days)	Overvoltages, overvoltage protection and insulation coordination in high voltage power systems	Lappenranta University of Technology, Finland
2010 – 2013	Different intensive courses	Doctoral School of Energy and Geotechnology II
2010 (14 days)	Summer School „Power“	Aarhus University, Denmark
2010 (14 days)	Spring School „Automation and Modelling of Fuel Cell and Hydrogen based Energy Systems“	Stralsund University of Applied Sciences, Germany

5. Professional Employment

Period	Organisation	Position
2014 - …	Elektrilevi OÜ	Department manager
2010 - …	Tallinn University of Technology, Department of Electrical Power Engineering	Assistant
2010 - 2011	Kehtna Economics and Technology School	Teacher
2008	OÜ Jaotusvõrk	Specialist
2007	AS Eltel Networks	Electrician

6. Field of research

- Natural Sciences and Engineering, Energetic Research, Energy research

7. Current grants & projects

- Impact of new types of electricity generating patterns to high voltage equipment and cable insulations

8. Honours & Awards

2014 “A” competency level in field of electricity
2013 Mati Jostov named scholarship for doctoral studies
2013 Accredited Electrical Engineer level V
2013 3rd place on Talveakadeemia 2013 competition of scientific papers
2012 Jaan Poska named scholarship
2012 Best presentation at Talveakadeemia 2012
2012 1st place at Talveakadeemia 2012 competition of scientific papers
2011 Olev Liigi named scholarship for doctoral studies
2011 1st place at Talveakadeemia 2011 competition of scientific papers
2010 Margot ja Herbert Linna named scholarship
2010 Cum Laude for Master’s studies at Tallinn University of Technology

9. Dissertations supervised

2015 Alo Toom, Master’s Degree, Solutions for Elektrilevi OÜ MV/LV substations in urban core areas, Tallinn University of Technology
2015 Roland Murakas, Bachelor’s Degree, Effect of higher harmonics on the accuracy of electricity meters, Tallinn University of Technology
2015 Toomas Kilgi, Bachelor’s Degree, Current Harmonics of Various Devices, Tallinn University of Technology
2014 Rasmus Armas, Master’s Degree, Impact of Small Producers on Power Quality in Distribution Grids Based on Elektrilevi OÜ Grid, Tallinn University of Technology
2013 Henri Külm, Bachelor’s Degree, Impacts of Small Wind Turbines on Power Quality, Tallinn University of Technology
2013 Erik Arro, Bachelor’s Degree, Electric Vehicle Charging Impact on Power Quality, Tallinn University of Technology
2013 Allar Keerme, Bachelor’s Degree, Impacts of Photovoltaic Panels on Power Quality, Tallinn University of Technology
2012 Madis Leinakse, Bachelor’s Degree, Analysis of Electrical power quality with Electrical network analysis instrument Chauvin Arnoux C.A 8352, Tallinn University of Technology
2012 Ats Haas, Bachelor’s Degree, Power Quality Effects on Electrical Energy Meter’s Accuracy, Tallinn University of Technology
2012 Jaan Jakobson, Master’s Degree, Finland, Estonia, Latvia and Lithuania common natural gas secondary market, Tallinn University of Technology
2011 Edgar Dubbelmann, Master’s Degree, Wind Power Plant Modelling and Model Verification, Tallinn University of Technology

AUTHOR’S PUBLICATIONS

[A1] **Niitsoo, J.**; Taklaja, P.; Palu, I.; Klüss, J. (2015) Power quality issues concerning photovoltaic generation and electrical vehicle loads in distribution grids. *Smart Grid and Renewable Energy,* vol. 6, no. 6, pp. 164 – 177.

[A2] **Niitsoo, J.**; Jarkovoi, M.; Taklaja, P.; Klüss, J.; Palu, I. (2015) Power quality issues concerning photovoltaic generation in distribution grids. *Smart Grid and Renewable Energy,* vol. 6, no. 6, pp. 148 – 163.

[A3] **Niitsoo, J.**; Taklaja, P.; Palu, I.; Kiitam, I. Modelling EVs in residential distribution grid with other nonlinear loads. *Proceedings of the 15th International Conference on Environment and Electrical Engineering.* 10-13 June 2015, Rome, Italy. IEEE, pp. 1543 – 1548.

[A4] Taklaja, P.; Kiitam, I.; **Niitsoo, J.**; Hyvönen, P.; Klüss, J.V. (2015). Electric field distribution in glass and porcelain pin insulators. *Proceedings of the 15th International Conference on Environment and Electrical Engineering*, Rome, Italy, 10-13 June 2015. IEEE, pp. 367 - 371.

[A5] Kiitam, I.; Taklaja, P.; **Niitsoo, J.**; Hyvönen, P. (2015). Cable diagnostics methods for determining degradation caused by renewable energy production. *Proceedings of 5th the International Conference on Power Engineering, Energy and Electrical Drives*, Riga, Latvia, 11-13 May 2015. IEEE.

[A6] Kütt, L.; Saarijärvi, E.; Lehtonen, M.; Mõlder, H.; **Niitsoo, J.** (2014). Estimating the harmonic distortions in a distribution network supplying EV charging load using practical source data — case example. *Proceedings of the 2014 IEEE Power and Energy Society General Meeting*; National Harbor, MD, USA; 27-31 July 2014. IEEE.

[A7] Kütt, L.; Saarijärvi, E.; Lehtonen, M.; Mõlder, H.; **Niitsoo, J.** (2014). Electric vehicle charger load current harmonics variations due to supply voltage level differences — Case examples. *Proceedings of the 2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, 18-20 June 2014, Ischia, Italy. IEEE, pp. 917 - 922.

[A8] Taklaja, P.; Hyvönen, P.; Klüss, J.V.; **Niitsoo, J.**; Palu, I. (2014). Preventing Bird Streamer Outages Using Alternative Tower Configurations. *IEEE Transactions on Power Delivery,* vol. 29, no. 5, pp. 2402 - 2409

[A9] **Niitsoo, J.**; Palu, I.; Kilter, J.; Taklaja, P.; Vaimann, T. (2013). Residential load harmonics in distribution grid. *Proceedings of 3rd International Conference on Electric Power and Energy Conversion*

Systems 2013: EPECS 2013, October 2-4, 2013, Istanbul, Turkey. Istanbul: IEEE, pp. 1 - 6

[A10] Kütt, L.; Saarijärvi, E.; Lehtonen, M.; Mõlder, H.; **Niitsoo, J.** (2013). Current Harmonics of EV Chargers and Effects of Diversity to Charging Load Current Distortions in Distribution Networks. *Proceedings of 2013 International Conference on Connected Vehicles & Expo: (ICCVE 2013)*, Las Vegas, 2-6 Dec 2013. IEEE, pp. 1 - 6

[A11] **Niitsoo, J.**; Kilter, J.; Palu, I.; Taklaja, P.; Kütt, L. (2013). Harmonic Levels of Domestic and Electrical Vehicle Loads in Residential Distribution Networks. *Proceedings of IEEE AFRICON 2013 Conference*, 9-12 September 2013, Mauritius. IEEE, pp. 184 - 188

[A12] Taklaja, P.; Oidram, R.; **Niitsoo, J.**; Palu, I. (2013). Main Bird Excrement Contomination Type Causing Insulator Flashovers in 110 kV Overhead Power Lines in Estonia. *Oil Shale, 30(2S)*, pp. 211 - 224

[A13] Taklaja, P.; Oidram, R.; **Niitsoo, J.**; Palu, I. (2013). Causes of Indefinite Faults in Estonian 110 kV Overhead Power Grid. *Oil Shale, 30(2S)*, pp. 225 - 243

[A14] **Niitsoo, J.**; Kütt, L.; Taklaja, P. (2013). Consequences of Distributed Generation on Power Quality. In: Proceedings of 14th International Scientific Conference Electric Power Engineering 2013: EPE 2013, May 28-30, 2013, Kouty nad Desnou, Czech Republic. (Toim.) Rusek, S.; Goňo, R.. IEEE, pp. 163 - 167

[A15] Taklaja, P.; Hyvönen, P.; **Niitsoo, J.**; Palu, I.; Klüss, J.; Kütt, L. (2013). Volt-Time Characteristics of Medium Voltage Overhead Line Porcelain Pin Insulators. *Proceedings of the 14th International Scientific Conference Electric Power Engineering 2013: EPE 2013*, May 28-30, 2013, Kouty nad Desnou, Czech Republic. IEEE, pp. 423 - 427

[A16] Kütt, L.; Saarijärvi, E.; Lehtonen, M.; Mõlder, H.; **Niitsoo, J.** (2013). A Review of the Harmonic and Unbalance Effects in Electrical Distribution Networks due to EV Charging. *Proceedings of the 12th International Conference on Environmental and Electrical Engineering 2013*. IEEE, pp. 1 - 6

[A17] Kütt, L.; Saarijärvi, E.; Lehtonen, M.; Mõlder, H.; **Niitsoo, J.** (2013). A Review of the Effects of Electric Vehicle Charging on Distribution Network Operation and Power Quality. *Proceedings of the 8th International Conference on Electrical and Control Technologies ECT-2013*. Kaunas: Kaunas University of Technology, pp. 162 - 167

[A18] **Niitsoo, J.** (2013). Elektrienergiaarvestite analüüs moonutatud voolu korral. Kotkas, T. (Toim.). Talveakadeemia ajakiri 2013 (1).Tartu Ülikooli Kirjastus

[A19] Taklaja, P.; Hyvönen, P.; **Niitsoo, J.**; Palu, I.; Klüss, J. (2013). Impulse characteristics of 24 kV overhead line pin insulators. *Proceedings of 12th International Conference on Environment and Electrical Engineering*. Wroclaw, Poland, 5 - 8 May 2013. IEEE, pp. 641 - 645

[A20] **Niitsoo, J.**; Šuvalova, J.; Haas, A.; Palu, I.; Taklaja, P. (2013). Facing Distorted Current and Undesirable Consumption in Smart Grids. *The 13th International Symposium "Topical Problems in the Field of Electrical and Power Engineering- Doctoral School of Energy and Geotechnology II"*.Elektrijam, pp. 142 - 146

[A21] **Niitsoo, J.** (2012). Parasiitenergia kodumajapidamistes. *Värske Aju*

[A22] **Niitsoo, J.** (2012). Parasiitenergia kodumajapidamistes. *Talveakadeemia Teaduslikud lühiartiklid, Kogumik 10/2012*. Tartu Ülikooli Kirjastus, pp. 124 - 135

[A23] Koppel, T.; **Niitsoo, J.** (2012). Intermediate frequency noise in and from electrical power network in modern working places. *Proceedings of the 22nd International Conference Electromagnetic disturbances*. Vilnius: Vilnius Gediminas Technical University Press "Technika", pp. 47 - 51

[A24] Haas, A.; **Niitsoo, J.**; Taklaja, P.; Palu, I. (2012). Analysis of Electricity Meters under Distorted Load Conditions. *Proceedings of 8th International Conference 2012 Electric Power Quality and Supply Reliability*, Tartu, June 11 - 13, 2012. IEEE, pp. 281 - 284.

[A25] Drovtar, I.; **Niitsoo, J.**; Rosin, A.; Kilter, J.; Palu, I. (2012). Electricity Consumption Analysis and Power Quality Monitoring in Commercial Buildings. *Proceedings of 8th International Conference 2012 Electric Power Quality and Supply Reliability*. Tartu, June 11 - 13, 2012. IEEE, pp. 107 - 112

[A26] Taklaja, P.; **Niitsoo, J.**; Palu, I. (2012). Wet Test on Naturally Polluted Glass and Composite Insulators. *Proceedings of 8th International Conference 2012 Electric Power Quality and Supply Reliability*, Tartu, June 11 - 13, 2012. IEEE, pp. 261 - 266.

[A27] Vaimann, T.; **Niitsoo, J.**; Kivipõld, T.; Lehtla, T. (2012). Power Quality Issues in Dispersed Generation and Smart Grids. *Electronics and Electrical Engineering,* vol. 10, no, 8, pp. 23 - 26

[A28] Taklaja, P.; **Niitsoo, J.**; Palu, I. (2012). Determining the Unknown Faults of the HV Overhead Lines. *Proceedings of the 13th International Scientific Conference Electric Power Engineering*. IEEE, pp. 187 - 192

[A29] **Niitsoo, J.**; Palu, I. (2012). Investigation of Undesirable Consumption and Distorted Current. *Proceedings of the 13th International Scientific Conference Electric Power Engineering 2012.* Brno, Czech Republic, IEEE, pp. 287 - 291

[A30] Kilter, J.; Dubbelman, E.; Palu, I.; **Niitsoo, J.** (2012). Wind Park and Transmission Network Cooperation Considering Grid Code Requirements. *Proceedings of the 7th International Conference on Electrical and Control Technologies*. Kaunas Technologija, pp. 183 - 188

[A31] **Niitsoo, J.**; Taklaja, P.; Kütt, L.; Niilo, H.; Kallaste, A.; Mõlder, H.; Vaimann, T. (2012). Keskkonnamõjust hoolimata on põlevkivielekter möödapääsmatu. *Eesti Päevaleht*

[A32] **Niitsoo, J.**; Palu, I. (2012). Undesirable Usage of Energy in Residential House. J. Zakis (Toim.). *Proceedings of the 11th International Symposium "Topical Problems in the Field of Electrical and Power Engineering" and "Doctoral School of Energy and Geotechnology II"*. Tallinn: Elektriajam, pp. 126 - 128

[A33] **Niitsoo, J.** (2011). Kompaktluminofoorlampide kasutuselevõtu mõju elektrivõrgule. *Talveakadeemia Teaduslikud lühiartiklid 2011, kogumik 9/2011.*Tartu Ülikooli Kirjastus, pp. 40 - 47

[A34] **Niitsoo, J.** (2011). Säästulamp toob kaasa uued probleemid. *Inseneeria,* vol. 9, pp. 24 - 26

[A35] Vaimann, T.; **Niitsoo, J.**; Kivipõld, T. (2011). Dispersed Generation Accommodation Into Smart Grid. *Proceedings of the 52nd International Scientific Conference of Riga Technical University*. Riga, Latvia, October 13-14, 2011. Riga Technical University, ID - 42

[A36] **Niitsoo, J.** (2011). Euroliit on teinud hõõglambist poliitvangi. *Eesti Päevaleht*

[A37] **Niitsoo, J.**; Palu, I. (2011). Distorted load impacts on distribution grid. *Proceedings of the 12th International Scientific Conference Electric Power Engineering 2011*, Kouty nad Desnou, Czech Republic, May 17-19, 2011: IEEE, 37 - 40

[A38] Kivipõld, T.; **Niitsoo, J.** (2011). Overview of information and communication issues for smart grid solutions. *Proceedings of the 10th International Symposium "Topical Problems in the Field of Electrical and Power Engineering"* Pärnu, Estonia, January 10-15, 2011. Estonian Society of Moritz Hermann Jacobi, pp. 108 – 112

[A39] Niitsoo, J. (2011). An overview of the impacts of CFLs implementation. *Proceedings of the 10th International Symposium "Topical Problems in the Field of Electrical and Power Engineering"* Pärnu, Estonia, January 10-15, 2011. Estonian Society of Moritz Hermann Jacobi, pp. 242 - 245

APPENDIX / LISA

AUTHOR’S PUBLICATIONS RELATED TO THE STUDY

[PAPER - I] – [PAPER - IX]

PAPER - I

10th International Symposium
„Topical Problems in the Field of Electrical and Power Engineering“
Pärnu, Estonia, January 10-15, 2011

An overview of the impacts of compact fluorescent lamps implementation

Jaan Niitsoo
Tallinn University of Technology
jaan.niitsoo@ttu.ee

Abstract

European Union (EU) is continually promoting energy efficiency among electricity consumers. One of the latest EU activities that influence us all is to limit the use of traditional incandescent lamps by replacing them gradually with compact fluorescent lamps (CFL). By looking only on energy efficiency, the purpose seams to fulfill the target. On the same time it raises new questions so far not asked about lighting. These questions are higher harmonics, reactive power and neutral conductor current. In this paper common CFLs and their impact are investigated theoretically and supported with laboratory test results.

Keywords

CFL, harmonics, reactive power, neutral current

Introduction

In long term the energy consumption is growing and old generating units will drop off step by step. Therefore we constantly need new power plants or try to enhance our consumption. CFLs consume less energy with same luminous efficiency and last longer than usual bulbs, but their current curve is definitely not perfect sinusoid and it may be detrimental for power quality if they are used together in great numbers. So far the influence to the grid is ignored because the power of one lamp is marginal. Also the widespread use of CFLs may implicate significant reactive power and problems with higher harmonics in a grid. [1]

Higher harmonics, which CFLs generate to a grid and thereby affect the power quality, are the main issue using CFLs. Secondly what's important is the generated reactive power which definitely needs to be investigated.

1 Theoretical background

1.1 Requirements for higher harmonics in electricity grid

Current Total Harmonic Distortion (THD) of a signal is a measurement of the harmonic distortion present and is defined as the ratio of the sum of the currents of all harmonic components I_h to the current of the fundamental frequency I_1.

In this article THD is handled as follows:

$$THD = \sqrt{\sum_{h=2}^{50} \left(\frac{I_h}{I_1}\right)^2} \tag{1}$$

Some of the CFLs may have the THD over 100 %, but their active power use is not so significant compared to other harmonics generating devices. Therefore their quality requirements are not so precisely regulated. The current THD limit to the CFLs with electronic ballasts is 20 % according to IEEE (*Institute of Electrical and Electronics Engineers*) and IEC (*International Electrotechnical Commission*).

Harmonics generated by costumer´s appliances must not cause voltage rise in the connection point. [14] In this article current THD value which should not be exceeded when implementing CFLs has estimated on 5 %. Fixing limits may become important before using numerous harmonics emitting devices together.

1.2 Ratio of grid voltage harmonics and CFLs current harmonics

Studies have showed that current THD which CFLs emit increases as supply harmonics level increases. The ratio is not linear and it is particularly true in case of CFLs with electronic ballast. [2, 3, 4]

In field studies the influence of power grid´s higher harmonics to the CLS harmonics generation has not been notable. It is specially because there are not yet many grids with high harmonics penetration level. The problem may occur with the rising use of CFLs with electronic ballast and other harmonics emitting devices.

1.3 CFLs influence on harmonics level

Power Factor (PF) is defined as the ratio of the sum of all real power components P to the sum of all apparent power components S in the circuit. PF is dimensionless number between 0 and 1 and is here calculated with equation 2

$$PF = \frac{P}{S} \tag{2}$$

Implementation of CFLs brings up a problem with higher harmonics. Penetration of higher harmonics rises as number of installed CFLs increase.

Concrete example of increasing harmonics is a field study [4] where were installed 2500 CFLs. All harmonics increased, but not over the limit fixed for single harmonics. However the current THD 12.7 % crossed optimal 5 % level highly. 5 % THD was reached already at 920 lamps.

Other analysis [1] was done where all bulbs were replaced with CFLs in one household. After the replacement CFLs constituted to 26.3 % of overall load and PF fell down to 0.65 and voltage distortion rose up to 4.4 %. All those figures were within limits, only the current THD increased to unacceptable 23.5 %.

1.4 Reactive power of CFLs

Cos φ is defined as the ratio of the real power of the fundamental frequency P_1 to apparent power of the fundamental frequency S_1. Cos φ is dimensionless number between 0 and 1 and is here calculated with equation 3.

$$Cos\varphi = \frac{P_1}{S_1} \tag{3}$$

Considering losses in the transferring of reactive power in transformers and power lines it should be minimized. However the reactive power is inherent phenomenon of CFLs.

If the cos φ of the CFLs is usually about 0.9 the PF may be very different. Average PF is around 0.5-0.6 which means that lamp generates much more reactive power to the grid than it consumes active power.

For example in one test [5] thousand 60 W incandescent lamps were replaced with 7 W CFLs. The reactive power increased from 0 to 8848 var.

1.5 Neutral conductor current

In electrical schemes lamps are usually balanced with neutral and phases. In symmetrical situation with electronically ballasted CFLs triple harmonics (3rd, 9th, 15th *etc*) may aggregate and cause the overload in neutral conductor. In the worst case the neutral current may exceed phase current √3 times. [6]

Harmonics from single phase appliances spread over all three phases. The neutral current is equal to sum of currents from all three phase. In the case of symmetrical CFL load triple harmonics are in phase and are added arithmetically in neutral. Other harmonics cancel each other out. [7]

1.6 Losses caused by CFLs

Distribution transformers are affected in two ways. First, the eddy current losses increase with the square of the harmonic number. The second effect concerns the triple harmonics (3rd, 9th, 15th *etc*), which circulate in the delta winding of the transformer and may damage it due to increased thermal losses. [8]

In one experiment [9] results showed 33 % active loss increase when incandescent lamps where replaced with CFLs. Values of different losses are given in **Table 1**.

Transformer losses P_T are divided into no load losses P_{NL} and load losses P_{LL} as [10]:

$$P_T = P_{NL} + P_{LL} \tag{4}$$

P_{NL} are the losses due to the voltage excitation of the core. P_{LL} is expressed as [11, 12]:

$$P_{LL} = I^2R + P_{EC} + P_{OSL}, \tag{5}$$

where

I^2R losses due to load current and DC winding resistance, W;

P_{EC} winding eddy current losses, W;

P_{OSL} other stray losses are due to losses in structures other than windings, W.

Table 1. Losses in transformer [9]

Measured value, W	CFLs	Incandescent lamps
P_T	20.8	15.6
P_{NL}	7.7	7.7
P_{LL}	13.1	7.9
P_{EC}	4.1	1.5
P_{OSL}	3.8	1.2

Also the temperature of transformer was measured in the case [9]. In the case of common bulbs the transformer´s maximum temperature was 59.8 °C, but after the replacement the temperature was 67.6 °C. It makes impressive near 12 % growth.

2 Laboratory tests

All tests were done with two types of lamps which are sold in ordinary supermarkets. Lamps were divided in two:

- Set 1 – Osram brand lamps with price about 5 €;
- Set 2 – lamps without producer´s label and with price about 2 €.

Set 2 had poorer characteristics. With the same active power difference in reactive power consumption was 10 % and in apparent power 6.7 % accordingly. Other values of measured parameters are given in Table **2**.

Table 2. Measured parameters of CFLs.

	Set 1	Set 2
Cos φ	0.892	0.921
PF	0.607	0.569
Reactive power, var	18	20
Current THD, %	104	120

Set 2 had much higher harmonics content than set 1. The obvious differences were in all single harmonics up to 25th. It is clearly seen from Fig.1.

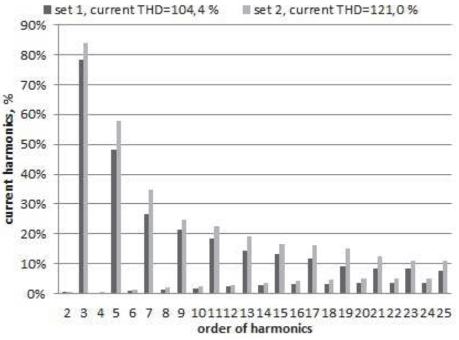


Fig.1. Current harmonics for different lamp sets

2.1 Adding the CFLs

Motive of this test was to see how power consumption changes when quantity of lamps were changed in scheme. Values were taken at points when 2, 4, 6, 8 and 10 lamps were in installed.

Fig. *2* shows apparent power, reactive power and active power values in situations of different number of CFLs in scheme. All power components rose linearly when lamps were added. No compensation was discovered.

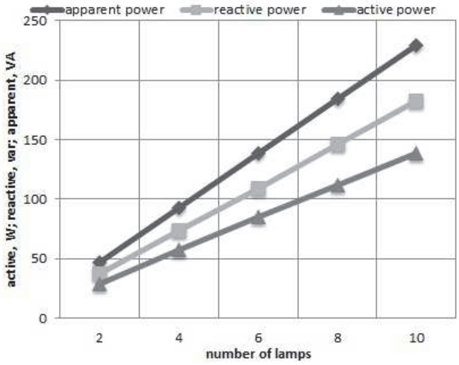


Fig. 2. Ratio of power and number of CFLs (reactive power is reversed)

Raising the number of CFLs in scheme without adding active load increased harmonic currents and distorted sinusoid. Harmonics did not cancel each other out. Thereby adding CFLs made the situation of power quality only worse.

2.2 Adding an active load

Goal of this experiment was to reach 5 % current THD level by adding active load to scheme. Number of CFLs in the scheme was constantly 10 and their aggregated active load 140 W.

Achieving the goal needed additional active load 280 more than CFLs own aggregated load. At beginning current THD decreased rapidly when load was added, but before achieving the fixed 5 % goal it slows down. Whole curve is shown in Fig.3.

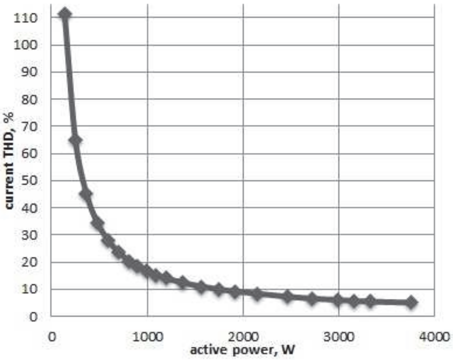


Fig.3. The ratio of current THD and active load

Fixed 5 % THD limit was achieved with active load about 4 kW. Without any active load the THD was over 110 %. It makes clear that only great active load beside CFLs keep harmonics at merest level in grid.

Increase of active load made cos φ and PF approaching to 1 bit quicker than current THD. Compering cos φ and PF, first one proceeded more sharply. It was because in calculation of cos φ only fundamental harmonics were considered and they were remarkably higher than all other harmonic components.

2.3 Three phase test

The idea of this test was to investigate the current neutral conductor. In this case CFLs were installed symmetrically in three phases. Test started with 2 lamps for one phase, then 3 and finally 4.

Results were almost the worst theoretically can be. With different number of lamps the neutral current was always 70 % higher than phase current.

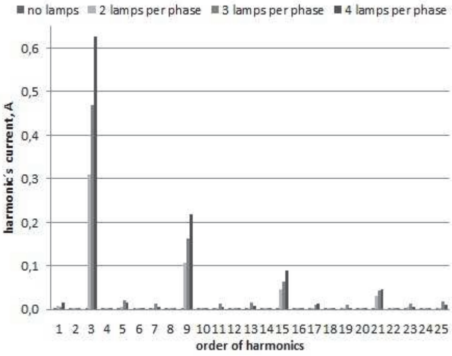


Fig. 4. Triple harmonics aggregation in neutral conductor

The increase of neutral current was caused by triple harmonics aggregation. Fig. *4* shows clearly how the 3rd, 9th, 15th and 21st harmonics aggregate in neutral conductor. Since the harmonics from CFLs do not compensate each other, adding the lamps to the scheme makes the current in neutral only higher.

This kind of difference in currents and aggregation of harmonics in neutral conductor makes grid engineering much more complicated compared to the case of incandescent bulbs. Placing all the CLFs symmetrically between phases the current in neutral conductor may raise unreasonably high. Installing all lamps in one phase makes the harmonics go up.

Conclusion

Higher harmonics cause energy losses, overheating of appliances, overvoltage, vibration and mechanical stress. Reactive power reduces overall power capacity of electricity transmission. High neutral current may cause malfunction of sensitive load.

Harmonics are inherent phenomenon of using CFLs, because average price level lamp generates current with 110 % THD. Great amount active power next to them hides the harmonics.

Average cos φ of the CFL is about 0.9 and PF 0,5...0,6 which means that remarkable reactive power is consumed even though the cos φ is high. So in the case of CFLs it should be considered that the reactive power generation is not clarified only by cos φ.

Lighting units are most commonly divided symmetrically between phases. If there is a great number of CFLs the triple harmonics aggregate and may cause high current in neutral conductor.

References

1. Watson N. and Hirsch S. The Effects of Compact Flourescent Lamps on Power Quality http://www.apqi.org/file/attachment/2009526/1693.pdf .
2. Nassif A. B. and Xu W. Characterizing the Harmonic Attenuation Effect of Compact Fluorescent Lamps [Conference] // Power Delivery, IEEE Transactions on. 24 (3). - [s.l.] : IEEE Xplore, 2009. - pp. 1748 – 1749.
3. Radakovic Z., Topalis F.V. and Kostic M. The voltage distortion in low-voltage networks caused by compact fluorescent lamps with electronic gear [Journal] // www.sciencedirect.com . - 2004.
4. Topalis F. V., Gonos I. F. and Vokas G. A. Arbitrary waveform generator for harmonic distortion tests on compact fluorescent lamps [Journal] // www.sciencedirect.com - 2001.
5. Kontturi M. and Ålander J. Energiasäästölamppunejen verkkovaikutukset. - 2008.
6. Schonek J. The singularities of the third harmonic. Cahier technique no. 202 [Report]. - [s.l.] : Schneider Electric, 2001.
7. Schonek J. and Vernay M. Power supply of lighting circuits. Cahier technique no. 205 [Report]. - [s.l.] : Schneider Electric, 2002.
8. Jabbar R. A. [et al.] Impact of Compact Fluorescent Lamp on Power Quality [Conference] // Power Engineering Conference, 2008. AUPEC '08. - Sydney, NSW : [s.n.], 2008.
9. Mõlder H., Lellsaar M. and Kütt L. Compact fluorescent lamp harmonic disruption effect of transformer losses [Conference] // 8th International Symposium „Topical Problems in the Field of Electrical and Power Engineering“ . - Pärnu : [s.n.], 2010.
10. IEEE IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents // IEEE Std C57.110-1198(R2004). - 2004.
11. Elmoudi A., Lehtonen M. and Nordman H. Effect of Harmonics on Transformers Loss of life [Conference] // Conference Record of the 2006 IEEE International Symposium on Electrical Insulation. - 2006.
12. Võrk V. and Mägi V. Elektrotehnika [Book]. - Tallinn : [s.n.], 1980.
13. Ashok S Harmonic Distortion of Fluorescent Lamps [Online] // Nalanda Digital Library. - http://www.nalanda.nitc.ac.in/nitcresources/ee/lectures/CFLdistort.pdf
14. Eesti Standardikeskus Voltage characteristics of electricity supplied by public distribution networks // EVS-EN 50160:2007. - 2007.
15. Watson N. R., Scot T. L. and Hirsch S. J. J. Implications for Distribution Networks of High Penetration of Compact Fluorescent Lamps [Conference] // IEEE Transactions on Power Delivery, VOL. 24, NO. 3, JULY 2009. - [s.l.] : IEEE, 2009. - pp. 1521-1528.

PAPER - II

Investigation of Undesirable Consumption and Distorted Current

Jaan Niitsoo[1], Ivo Palu[2]
Tallinn University of Technology, Faculty of Electrical Engineering, Department of Electrical Power Engineering,
Ehitajate tee 5, 19086 Tallinn, Estonia, www.tut.ee
[1] tel: +372 620 3754, email: jaan.niitsoo@ttu.ee,
[2] tel: +372 620 3769, email: ivo.palu@ttu.ee

ABSTRACT

Household appliances keep consuming energy even after they are turned to stand by regime or switched off. So far reactive component and current distortion of those devices are not investigated in detail. Within this paper the amount and the characteristics of this undesirable energy is examined for one specific household. All apparatus which are constantly working and which are turned off or at stand by for most of the time were examined one by one. Based on this research it can be concluded that despite the assumption that the device is switched off, the appliances still consume notable active and reactive power at standby or off condition. Also their consumed current is distorted by higher harmonics.

Keywords: Undesirable load, Standby, Harmonics, Reactive Power, Power Quality

1 INTRODUCTION

During the last decades the amount of electronic appliances used in households has raised tremendously. Most of this equipment maintains certain functionality even after turned off. For example the manual turn off switch has been replaced by a remote control mechanism or touch sensitive button, which need constant power to work [1]. Also devices are becoming more and more complex, but their performance regarding power quality is still rather improper.

Since present household appliances have extra features which require additional electrical energy, they use power constantly during a day, even when they are not in use or are turned off [2]. This consumed energy which does not serve primary purpose of device is called standby energy or leaking energy [3]. Because the increase of this undesirable usage of energy represents a noticeable component of residential electricity consumption, it has become a growing concern.

Studies [4-10] have been undertaken to measure parasitic consumption for different types of electrical appliances in different countries. Focus has been on measuring active power without considering accompanying power quality issues. So far the influence to the grid is ignored because the marginal power consumption of one item. In great numbers their distorted current curve may be detrimental for power quality and reactive power should be considered further.

Harmonic currents produced by nonlinear loads are injected back into the supply systems. These currents can interact adversely with a wide range of power systems equipment causing additional losses, overheating and overloading [11].

Aim of this article is to investigate power consumption of appliances at the regimes where no primary function is served. Additionally power quality and reactive power consumption of those devices are examined which has not been widely discussed in papers before. In this paper, overview of undesirable usage of energy in residential houses and field measurements for a range of electrical devices are presented.

2 UNDESIRABLE USAGE OF ENERGY IN RESIDENTIAL HOUSE

Undesirably used energy is here meant as the electrical energy consumed by household when they are turned off, or not in use. It is also referred as standby electricity use or leaking electricity. This undesirable usage is caused because many household devices have features such as remote control, memory, clock display which need energy and some devices which are working constantly (computer modems, digital cable and satellite TV receivers). Modern household contains a number of electrical entertainment appliances (TVs, VCRs etc), office equipment (computers, printers, monitors etc), clothes washers, dishwashers and adapters and chargers for those.

The actual power draw in standby mode is small, however standby power is consumed 24 hours per day. In fact the amount of new equipment consuming standby power is increasing as residential energy consumption is increasing and high growth in residential sector energy consumption is predicted [12]. Results indicate that standby and miscellaneous power consumption in the residential sector is increasing at approximately 8% per annum [8].

The information available is insufficient to determine trends, but all evidence points to a global increase in standby power consumption because efficiency improvements in some equipment (e.g., TVs) are outweighed by the increase in the numbers of appliances that consume power in standby mode [4]. In the UK, set-top decoder boxes for digital television, alone, will consume the electricity produced by an average sized power plant [10]. This fact is indicative of the alarming growth in electronics equipment. Beside of that it has also been reported that some appliances may use more energy in standby than in main operational mode [9].

International studies based on experimental campaigns performed at residential houses have indicated a standby power demand per household in the range 23-125 W [13] and even extensively varying results were found in [14]. Same number in developed countries varies between 20-60 W, and is responsible for about 2% of the total electricity consumption in OECD (Organisation for Economic Co-operation and Development) countries [9]. Average standby power of a device was calculated to be 3.8 watts by considering measured 605 housekeeping appliances in comprehensive research [6]. Therewith their standby power usually varies between 1 and 20 W or even more in some case [15].

Studies in Germany, Japan, the Netherlands, the United States and Australia have found that standby power accounts for as much as 10% of national residential electricity use [3,5,7,14]. The global energy consumption from standby has been estimated by the IEA (International Energy Agency) at between 200 TWh and 400 TWh per year [16].

3 POWER QUALITY ISSUES

The problem with nonlinear electronic apparatus is harmonic distortion caused by them. A nonlinear device is one in which the current is not proportional to the applied voltage and while the applied voltage is perfectly sinusoidal, the resulting current is distorted.

Harmonic currents injected from individual end users on the system should be limited, thus by limiting the amount of injected harmonic currents the voltage distortion can be limited as well. Example for illustrating nonlinear loads influence on distribution grid a study with compact fluorescence lamps (CFLs) is made [17,18].

The most commonly used indice for measuring the harmonic content of the waveform is the total harmonic distortion. Total harmonic distortion (THD) of a signal is a measurement of the harmonic distortion present and is defined as the ratio of the sum of all harmonic components M_h to the fundamental frequency component M_1. It is the potential heating value of the harmonics relative to the fundamental. This index can be calculated with formula 1 and for either voltage or current.

$$THD = \sqrt{\sum_{h=2}^{50}(\frac{M_h}{M_1})^2} \qquad (1)$$

Some devices may have the THD over 100 %, but their active power use is not so significant compared to other harmonics generating apparatus [17]. Therefore their quality requirements are not so precisely regulated, but fixing limits may become important when numerous harmonics emitting devices are utilized together. THD provides a good indication of the additional losses caused by the current flowing through a conductor.

Also most of electronic devices generate much more reactive power to the grid than they consume active power [15]. Respectable indice for estimating amount of reactive power is PF (Power Factor). PF is defined as the ratio of the sum of all real power components P to the sum of all apparent power components S in the circuit and is here calculated with equation 2.

$$PF = \frac{P}{S} \qquad (2)$$

4 FIELD MEASUREMENTS

There is a wide range of equipment types, which have various features and often more than one operational state. In performed study 16 different devices were investigated. All appliances are given in Tab. with indicative values of THD and PF at different states of operation. Different states of operation are defined in Tab. 1.

Tab. 1 Definitions of different modes

Mode	Definition
Disconnected	Appliance is not connected to grid
OFF	Appliance is switched off, but is connected to grid
Standby	Appliance is on, but is not providing a primary function
ON	Appliance is providing a primary function

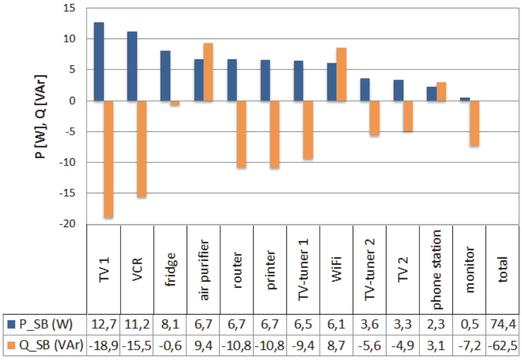
Tab. 2 Measured Appliances

Nr	Device	THD_ON	THD_OFF	THD_SB	PF_ON	PF_OFF	PF_SB
1	Phone charger 2	156	75	-	0,52	0,69	-
2	Router	150	-	-	0,52	-	-
3	VCR	136	144	138	0,59	0,53	0,57
4	TV-tuner 2	134	-	127	0,58	-	0,6
5	TV-tuner 1	125	-	126	0,55	-	0,55
6	Monitor	122	-	44	0,59	-	0,12
7	TV 2	111	-	64	0,66	-	0,56
8	TV 1	80	-	75	0,76	-	0,4
9	Printer	76	141	138	0,86	0,54	0,56
10	WiFi	52	-	-	0,48	-	-
11	Laptop	44	17	-	0,85	0,08	-
12	Air purifier	38	46	34	0,76	0,28	0,61
13	Phone Station	37	-	33	0,81	-	0,69
14	Phone charger 1	36	44	-	0,74	0,45	-
15	Radio	31	43	-	0,68	0,35	-
16	Fridge	17	-	5	0,84	-	1

Based on this measurement it can be concluded that practically all electronic appliances used in housekeeping have distorted current and their THD value is mostly near or over 100%. In case of a numerous of such devices together it results a distorted total current which may harm other system components.

4.1 Appliances at Standby Mode

Ten devices out of 16 in this study could be switched to standby mode and 3 out of ten could also be switched off. Total number of devices which could be turned off was 7. Investigated router and WiFi equipment could not be switched at all. Because those could not be switched their power can also be counted as standby power in this situation. Active and reactive power values of all those 12 appliances at standby regime are given at Fig. 1.



	TV 1	VCR	fridge	air purifier	router	printer	TV-tuner 1	WiFi	TV-tuner 2	TV 2	phone station	monitor	total
■ P_SB (W)	12,7	11,2	8,1	6,7	6,7	6,7	6,5	6,1	3,6	3,3	2,3	0,5	74,4
■ Q_SB (VAr)	-18,9	-15,5	-0,6	9,4	-10,8	-10,8	-9,4	8,7	-5,6	-4,9	3,1	-7,2	-62,5

Fig. 1 Active and reactive power of devices at standby mode

At standby mode smallest active power consumer was a monitor with 0.5 W. Total active power of measured apparatuses at standby state was 74.4 W. This makes nearly 20% of total active power when appliances would be providing their primary services.

Beside active power considerable reactive power was measured on all devices. Highest reactive power in this study was detected on CRT television and lowest on fridge with 18.9 and -0.6 VAr respectively.

Also it must be noticed that reactive power of apparatuses is whether inductive or capacitive. Inductive values are positive and are directed upwards and capacitive values are negative and are directed downwards.

At standby regime air purifier, WiFi and phone station had inductive reactive power value. Other devices showed capacitive values. Sum of reactive power of whole equipment was -62.5 VAr which makes about 45% of total when primary function is served.

By compering active and reactive power it is seen that power values of devices are positively correlated. In other words the higher active power means higher reactive power as well.

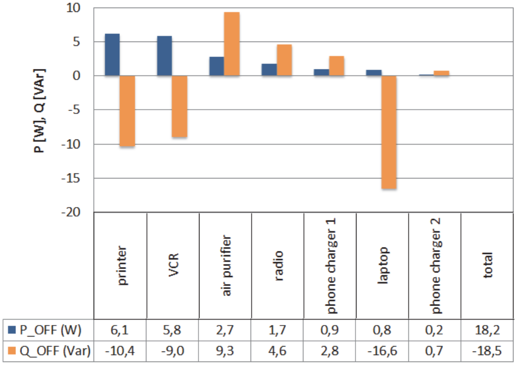
4.2 Comparing Standby and OFF Mode

Usually apparatus can be turned off, which in common sense means no power consumption after it. In this case only less of half of all measured 16 appliances had possibility to switch off. Those 7 devices at turned off mode are described with active and reactive values at Fig. 2.

Highest active power consumer at OFF mode was printer and lowest cell phone charger with 6.1 and 0.2 watts respectively. Total active power at this state was 18.2 watts which constitutes almost 5% of total active power compared to primary work regime.

Beside active power even higher reactive power values were identified when appliances were turned off. By comparing the results laptop had the highest value of reactive power (16.6 VAr) and cell phone charger had the lowest (0.7 VAr).

At off mode only air cleaner, radio and phone charger had inductive reactive power. All other apparatuses had capacitive values. Total reactive power of all devices was -18.5 VAr which makes about 13% of total reactive power of appliances at state where primary function is provided.



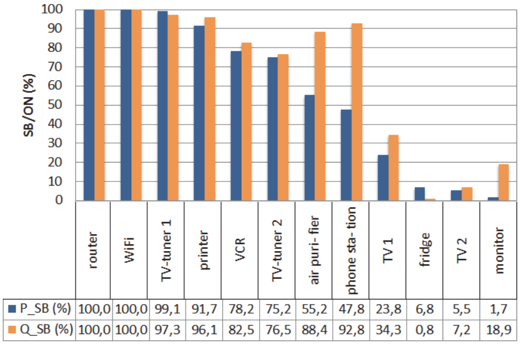
	printer	VCR	air purifier	radio	phone charger 1	laptop	phone charger 2	total
■ P_OFF (W)	6,1	5,8	2,7	1,7	0,9	0,8	0,2	18,2
■ Q_OFF (Var)	-10,4	-9,0	9,3	4,6	2,8	-16,6	0,7	-18,5

Fig. 2 Active and reactive power of devices at OFF mode

4.3 Comparing Standby and OFF Mode

Some of the apparatus cannot be turned off or switched to standby mode. In some cases the switching only means turning off the light on the apparatus or just changing the color of it. This kind of operation does not change the power consumption significantly [3].

When not considering the devices which could not be switched at all, it is still clearly seen from Fig. 3 that some of the appliances have standby active power over 90% compared to on regime power.

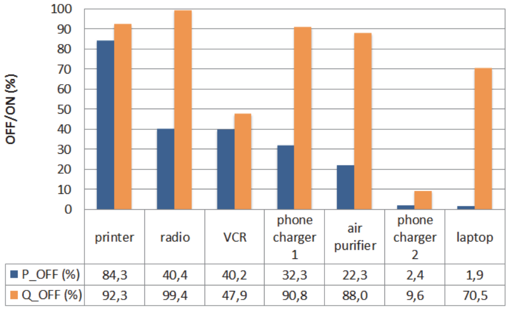


	router	WiFi	TV-tuner 1	printer	VCR	TV-tuner 2	air puri- fier	phone sta- tion	TV 1	fridge	TV 2	monitor
■ P_SB (%)	100,0	100,0	99,1	91,7	78,2	75,2	55,2	47,8	23,8	6,8	5,5	1,7
■ Q_SB (%)	100,0	100,0	97,3	96,1	82,5	76,5	88,4	92,8	34,3	0,8	7,2	18,9

Fig. 3 Standby mode active and reactive power proportions compared to ON mode value

More apparent is situation in case of reactive power. Standby and turned off mode reactive power values compared with primary function serving condition are higher than in case of active power. Most of devices had standby reactive power more than 70% compared with power when main functions are served.

Turned off regime power values compared to working condition values are shown at Fig. 4. In the case of printer the percentage was as high as 80%.



	printer	radio	VCR	phone charger 1	air purifier	phone charger 2	laptop
■ P_OFF (%)	84,3	40,4	40,2	32,3	22,3	2,4	1,9
■ Q_OFF (%)	92,3	99,4	47,9	90,8	88,0	9,6	70,5

Fig. 4 OFF mode active and reactive power proportions compared to ON mode value

When direction of reactive power maintained same at all three regimes the correlation between active and reactive power values disappeared at off state. Reactive power values were high even when active power values were low.

4.4 Power Quality of measured devices

Beside undesired energy consumption electronic appliances from housekeeping contribute also considerably to deterioration of power quality. Current curve of those devices in some cases even do not remind sinusoid common in AC power systems.

Results of investigated apparatus in this study are shown at Fig. 5, Fig. 6 and Fig. 7, where current curves of 10 devices at standby regime are presented. Also curve of router and WiFi equipment at primary working condition are shown. Voltage curve is added to every figure as indicative value.

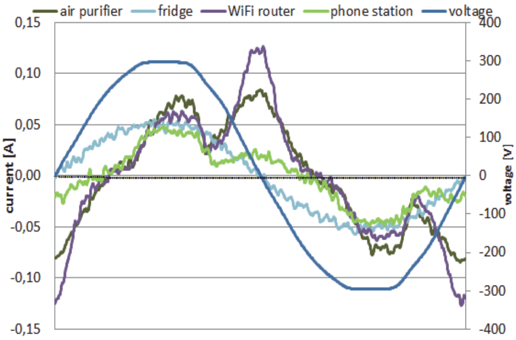


Fig. 5 Currents of measured appliances in set 1

At Fig. 5 a fridge has most similar current curve to sinusoid. Other devices have third and fifth harmonic more than 20% which deteriorate picture noticeably.

At Fig. 6 all devices have third harmonic over 90% and fifth over 60%. At Fig. 7 odd harmonics are dominant also for all appliances.

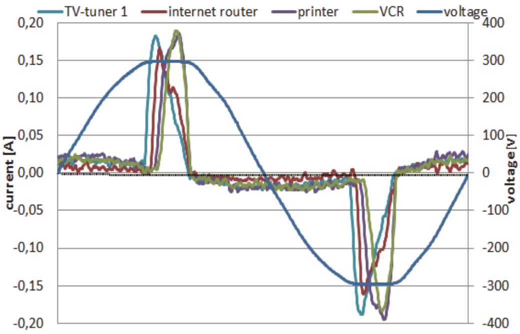


Fig. 6 Currents of measured appliances in set 2

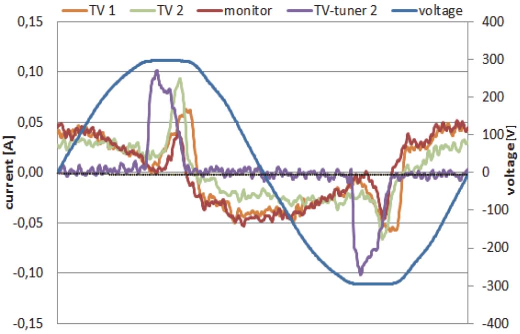


Fig. 7 Currents of measured appliances in set 3

In general VCR and TV 2 showed considerable even harmonics beside odd harmonics in their current. Other devices have mainly odd harmonic content.

In situation when most of the loads are with distorted load shape the total current in PCC is also heavily deteriorated. Only great amount of pure active load would hide the distortion.

5 CONCLUSION

Since modern household appliances have features which require electrical energy when not providing their main service, they use power constantly during a day despite they are not in use or are turned off.

Beside considerable amount of undesirable active power consumption apparatuses also consume or produce a noticeable amount of reactive power. It appears that parasitic reactive power of electronic devices in common household is even higher than active power.

Also power quality of those undesirable loads is poor. Odd harmonics content is dominant in current curve of those devices.

Great number of equipment with distorted current together worsens total current considerably and may lead to break down of elements of electricity system.

ACKNOWLEDGEMENTS

This research was supported by European Social Fund's Doctoral Studies and Internationalisation Programme DoRa.

REFERENCES

[1] M. Rayabhari, "Cutting Stand-By Power," *Power Engineer*, vol. 17, no. 2, 2003.

[2] A. S. Fung, A. Aulenback, A. Ferguson, and V. I. Ugursal, "Standby power requirements of household appliances in Canada," *Energy and Buildings*, vol. 35, no. 2, pp. 217-228, February 2003.

[3] A. Meier and K. Rosen. (2002) Leaking Electricity in Domestic Appliances.

[4] P. Bertoldi et al., "Standby power use: How big is the problem? What policies and technical solutions can address it?," Lawrence Berkeley National Laboratory, 2002.

[5] Energy efficiency strategies, "Standby power – current status, a report for the equipment energy efficiency (E3) committee," 2006.

[6] D. B. Floyd and C. Webber, "Leaking Electricity: Individual Field Measurement of Consumer Electronics," in *Proceedings of the 1998 ACEEE Summer Study on Energy Efficiency in Buildings*, Berkeley, US, 1998.

[7] L. Guan, T. Berrill, and R. J. Brown, "Measurement of standby power for selected electrical appliances in Australia," *Energy and Buildings*, vol. 43, pp. 485–490, 2011.

[8] L. Harrington and P. Kleverlaan, "Quantification of Residential Standby Power Consumption in Australia: Results of Recent Survey Work," National Appliance & Equipment Energy Efficiency Committee, 2001.

[9] B. Lebot, A. Meier, and A. Anglade, "Global implications of standby power use, ACEEE summer study on energy efficiency in buildings," 2000.

[10] L. Mcgarry, "Standby power challenge ," in *Asian Green Electronics, 2004. AGEC. Proceedings of 2004 International IEEE Conference on the Asian Green Electronics*, 2004, pp. 56 - 62.

[11] R. C. Dugan, M. F. McGranaghan, S. Santoso, and H. W. Beaty, *Electrical Power Systems*, 2nd ed. New York, USA: McGraw-Hill Professional Publishing, 2002.

[12] Department of the Environment, Water Heritage and the Arts (DEWHA), "Energy Use in the Australian Residential Sector 1986–2020," *Commonwealth of Australia*, 2008.

[13] A. Prudenzi et al., "Standby power end users and their demand management impact on household's load shape ," *Power and Energy Society General Meeting, 2011 IEEE* , pp. 1 - 6 , 2011.

[14] J. P. Ross and A. Meier, "Whole house measurements of standby power consumption," Berkeley, USA, 2000.

[15] J. Niitsoo and I. Palu, "Undesirable Usage of Energy in Residential House," in *11th International Symposium "Topical Problems in the Field of Electrical and Power Engineering" and "Doctoral School of Energy and Geotechnology II"*, Pärnu, Estonia, 2012, pp. 126-128.

[16] Equipment Energy Efficiency Committee, ""Order out of Chaos" summary paper for the international standby power conference," Canberra, Australia, 2006.

[17] J. Niitsoo and I. Palu, "Distorted load impacts on distribution grid," in *Proceedings of the 12th International Scientific Conference Electric Power Engineering 2011*, Kouty nad Desnou, Czech Republic, 2011, pp. 37 - 40.

[18] J. Niitsoo, "An overview of the impacts of CFLs implementation," in *10th International Symposium "Topical Problems in the Field of Electrical and Power Engineering"*, Pärnu, Estonia, 2011, pp. 242 - 245.

PAPER - III

ELECTRIC POWER ENGINEERING 2011

Distorted load impacts on distribution grid

Jaan Niitsoo[1], Ivo Palu[2]
Tallinn University of Technology, department of electrical power engineering, Ehitajate tee 5, 19086 Tallinn.
[1] tel: +372 620 3753 , email: jaan.niitsoo@ttu.ee ,
[2] tel: +372 620 3769, email: ivo.palu@ttu.ee

ABSTRACT

Electrical devices are becoming more and more complex, but their performance regarding power quality is still rather improper. One of those devices is compact fluorescent lamp (CFL). Recent European Union (EU) activities influence us all, as the purpose of new legislation is to limit the use of traditional incandescent lamps by replacing them gradually with compact fluorescent lamp. Considering the energy efficiency the purpose seams to fulfill the target. On another hand it raises new questions so far not associated with lighting. These issues are related to higher harmonics, reactive power consumption and higher currents in neutral conductor.

Focus within this paper is pointed on CFLs. There are other devices influencing power quality, but none of them are forced to be applied by lows and rules. Impacts of CFLs are described theoretically based on available literature and complemented with laboratory test.

Keywords: CFL, higher harmonics, reactive power, neutral current

1 INTRODUCTION

In long term the energy consumption is growing and as old generating units drop off the gap must be fulfilled with new units or reduce the consumption. CFLs consume less energy with same luminous efficiency and last longer than usual bulbs and it is seen as one possible solution to reduce overall consumption. There is also another point in the use of CFLs, but it is not so popular and is not commonly distributed. The problem is that their current curve is not perfect sinusoid and it may be detrimental for power quality if they are used together in great numbers. So far the influence to the grid is ignored because the power of one lamp is marginal. Also the widespread use of CFLs may implicate significant reactive power and problems with higher harmonics in a grid. [1]

Higher harmonics, which CFLs generate to a grid and thereby affect the power quality, are the main issue using CFLs. Secondly what's important is the generated reactive power that needs attention.

Harmonic currents produced by nonlinear loads are injected back into the supply systems. These currents can interact adversely with a wide range of power systems equipment, most notably capacitors, transformers and motors, causing additional losses, overheating and overloading. These harmonic currents can also cause interference with telecommunication lines and errors in power metering.

A major concern, especially for commercial buildings, is that power supplies for single-phase electronic equipment will produce too much harmonic current for the wiring. The percentage of load that contains electronic power supplies is increasing at a dramatic pace, with the increased utilization of personal computers in every commercial sector. [2]

2 THEORETICAL BACKGROUND

2.1 Harmonic distortion

Harmonic distortion is caused by nonlinear devices in the power system. A nonlinear device is one in which the current is not proportional to the applied voltage. Typical current curve of CFL is shown at Fig. 1. While the applied voltage is perfectly sinusoidal, the resulting current is distorted. Increasing the voltage by a few percent may cause the current to double and take on a different waveshape. [2]

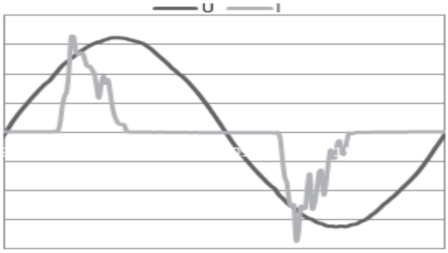


Fig. 1 Typical CFL current versus voltage curve

While the load current harmonics ultimately cause the voltage distortion, the load has no control over the voltage distortion. The same load put in two different locations on the power system will result in two different voltage distortion values. [2]

On radial utility distribution feeders and industrial plant power systems, the main tendency is for the harmonic currents to flow from the harmonic-producing load to the power system source.

2.2 Requirements for higher harmonics

The two most commonly used indices for measuring the harmonic content of the waveform are the total harmonic distortion and the total demand distortion. Both are measures of the effective value of a waveform and may be applied to either voltage or current. [2]

Total harmonic distortion (THD) of a signal is a measurement of the harmonic distortion present and is defined as the ratio of the sum of all harmonic components M_h to the fundamental frequency component M_1. It is the potential heating value of the harmonics relative to the fundamental. This index can be calculated with formula 1 and for either voltage or current.

$$THD = \sqrt{\sum_{h=2}^{50} (\frac{M_h}{M_1})^2} \quad (1)$$

Because fundamental voltage varies by only a few percent, the voltage THD is nearly always a meaningful number. THD can provide a good idea of how much extra heat will be realized when distorted voltage is applied across a resistive load. Likewise, it can give an indication of the additional losses caused by the current flowing through a conductor.

In situation when the magnitude of harmonic current is low, even though its relative current distortion is high, it may be wise to use peak load current I_L rather than the fundamental when referring THD. This is called total demand distortion (TDD) then. TDD is calculated as follows:

$$TDD = \frac{\sqrt{\sum_{h=2}^{50} (I_h)^2}}{I_L} \quad (2)$$

Some of the CFLs may have the THD over 100 %, but their active power use is not so significant compared to other harmonics generating devices. Therefore their quality requirements are not so precisely regulated.

Harmonics generated by costumer´s appliances must not cause voltage rise in the connection point. [3] In this article current THD value which should not be exceeded when implementing CFLs has estimated to be 5 %. Fixing limits may become important before using numerous harmonics emitting devices together.

Harmonic currents injected from individual end users on the system must be limited. These currents propagate toward the supply source through the system impedance, creating voltage distortion. Thus by limiting the amount of injected harmonic currents, the voltage distortion can be limited as well. This is the basic method of controlling the overall distortion levels proposed by IEEE standard 519-1992.

Depending on the diversity of the different load types small harmonic currents may add in phase or cancel each other. The voltage distortion levels depend on both the circuit impedances and the overall harmonic current distortion.

Generally studies have showed that current THD which CFLs emit increases as supply harmonics level increases. The ratio is not linear and it is particularly true in case of CFLs with electronic ballast. [3, 4, 5]

The upper mentioned standard divides the responsibility for limiting harmonics between both end users and the utility. End users will be responsible for limiting the harmonic current injections, while the utility will be primarily responsible for limiting voltage distortion in the supply system.

2.3 CFLs influence on harmonics level

Power Factor (PF) is defined as the ratio of the sum of all real power components P to the sum of all apparent power components S in the circuit. Because contribution of all power components is taken account it is known as the true power factor. PF is dimensionless number between 0 and 1 and is here calculated with equation 3:

$$PF = \frac{P}{S} \quad (3)$$

Implementation of CFLs brings up a problem with higher harmonics. Penetration of higher harmonics rises as number of installed CFLs increase.

Concrete example of increasing harmonics is described in [5], where 2500 CFLs were installed. All harmonics increased, but not over the limit fixed for single harmonics. However the current THD 12.7 % crossed optimal 5 % level highly. 5 % THD was reached already at 920 lamps.

Other analysis is described in [6] where in one household all bulbs were replaced with CFLs. After the replacement CFLs constituted to 26.3 % of overall load and PF fell down to 0.65 and voltage distortion rose up to 4.4 %. All those figures were within limits, only the current THD increased to unacceptable 23.5 %.

2.4 Reactive power of CFLs

In the sinusoidal case there is only one phase angle between the voltage and the current (since only the fundamental frequency is present) and therefor power factor can be computed as the cosine of the phase angle and is commonly referred as the displacement power factor. Cos φ is defined as the ratio of the real power of the fundamental frequency P_1 to apparent power of the fundamental frequency S_1. Cos φ is dimensionless number between 0 and 1 and is here calculated with equation 4:

$$Cos\ \varphi = \frac{P_1}{S_1} \quad (4)$$

Some devices have displacement power factor near unity, but the true power factor about 0,5-0,6. An ac-side capacitors in those devices do little to improve the true power factor because Q1 is zero. In fact, if it results in resonance, the distortion may increase, causing the power factor to degrade. Using only the displacement power factor would give a false sense of security. [2]

If the cos φ of the CFLs is usually about 0.9 the PF may be very different. Average PF is around 0.5-0.6 which means that lamp generates much more reactive power to the grid than it consumes active power.

For example in one test [7] thousand 60 W incandescent lamps were replaced with 7 W CFLs. The reactive power increased from 0 to 8848 var.

Considering losses in the transferring of reactive power in transformers and power lines it should be minimized. However the reactive power is inherent phenomenon of CFLs.

2.5 Current in neutral conductor

In electrical schemes lamps are usually balanced with neutral and phases. In symmetrical situation with electronically ballasted CFLs triple harmonics (3rd, 9th, 15th *etc*) may aggregate and cause the overload in neutral conductor. In the worst case the neutral current may exceed phase current √3 times. [8]

Triplen harmonics are the odd multiples of third harmonic. They deserve special consideration because the system response is often considerably different for triplens than for the rest of the harmonics. [2]

Harmonics from single phase appliances spread over all three phases. The neutral current is equal to sum of currents from all three phase. In the case of symmetrical CFL load triple harmonics are in phase and are added arithmetically in neutral. Other harmonics cancel each other out. [9]

Important implication is that transformers, particularly the neutral connections, are susceptible to overheating when serving single-phase loads on the wye side that have high third-harmonic content.

3 LABORATORY TESTS

To test and measure possible impact of CFLs the number of test series was carried out. Hereafter only fraction is described. All tests were done with two types of lamps which are sold in ordinary supermarkets. Lamps were divided in two:

- Set 1- brand lamps with producer’s name with the price about 5 €,
- Set 2- lamps without producer´s label and with price about 2 €.

Set number 2 had poorer characteristics. While the active power was same, the difference in reactive power consumption was 10 % and in apparent power 6.7 % accordingly. Set 2 had much higher harmonics content than set 1. The obvious differences were in all single harmonics up to 25th. Other values of measured parameters are given in Tab. 1.

Tab. 1 Measured parameters of CFLs.

	Set 1	Set 2
$\cos\varphi$	0.89	0.92
PF	0.61	0.57
Reactive power, var	18.0	20.0
Current THD, %	104	120

3.1 Adding the CFLs

Motive of this test was to see how power consumption changes when quantity of lamps were changed in scheme. Values were taken at points when 2, 4, 6, 8 and 10 lamps were installed.

Fig. 2 shows apparent power, reactive power and active power values in situations of different number of CFLs in scheme. All power components rose linearly when lamps were added. No compensation was discovered.

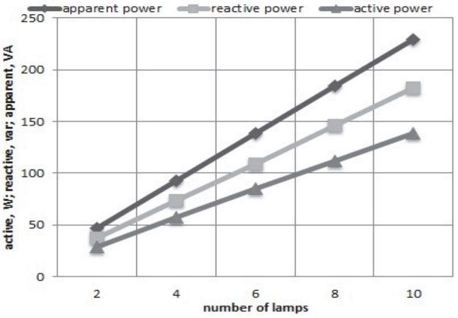


Fig. 2 Ratio of power and number of CFLs (reactive power is reversed)

Raising the number of CFLs in scheme without adding active load increased harmonic currents and distorted sinusoid. Harmonics did not cancel each other out. Thereby adding CFLs made the situation of power quality only worse.

3.2 Adding an active load

Goal of this experiment was to reach 5 % current THD level. Idea is that when adding pure active load to the scheme, the overall impact of CFLs is reduced. During the test, the number of CFLs was 10 with total aggregated active power 140 W.

Reducing the impact of CFLs down to 5% THD needed 280 times more power than were installed power of CFLs. At the beginning current THD decreased rapidly when load was added, but before achieving the fixed 5 % goal it slowed down. Whole curve is shown in Fig.3.

Fixed 5 % THD limit was achieved with active load about 4 kW. Without any active load the THD was over 110 %. It makes clear that only great active load beside CFLs keep harmonics at merest level in grid.

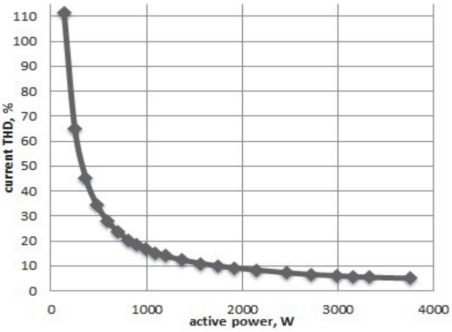


Fig. 3 The ratio of current THD and active load

Increase of active load made cos φ and PF approaching to 1 bit quicker than current THD. Compering cos φ and PF, first one approached more sharply to 1. It was because in calculation of cos φ only fundamental harmonics were considered and they were remarkably higher than all other harmonic components.

3.3 CFLs in three phase system

The idea of this test was to investigate the current in neutral conductor. In this case CFLs were installed symmetrically in three phases. Test started with two lamps in one phase, then three and four per phase.

Results were almost the worst theoretically can be. With different number of lamps the neutral current was always 70 % higher than phase current.

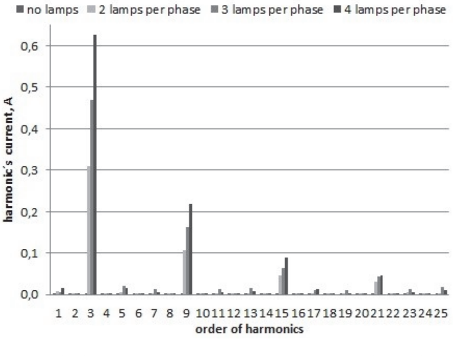


Fig. 4 Triple harmonics aggregation in neutral conductor

The increase of neutral current was caused by triple harmonics aggregation. Fig. 4 shows clearly how the 3rd, 9th, 15th and 21st harmonics aggregate in neutral conductor. Since the harmonics from CFLs do not compensate each other, adding the lamps to the scheme makes the current in neutral only higher.

This kind of difference in currents and aggregation of harmonics in neutral conductor makes grid engineering more complicated compared to the case of incandescent bulbs. Placing all the CLFs symmetrically between phases the current in neutral conductor may raise unreasonably high. Installing all lamps in one phase makes the harmonics go up.

4 CONCLUSION

Higher harmonics cause energy losses, overheating of appliances, overvoltage, vibration and mechanical stress. Reactive power reduces overall power capacity of electricity transmission. High neutral current may cause malfunction of sensitive load.

Harmonics are inherent phenomenon of using CFLs, because average price level lamp generates current with 110 % THD. Use of active power next to them hides the harmonics.

Average cos φ of the CFL is about 0.9 and PF 0,5-0,6 which means that remarkable reactive power is consumed even though the cos φ is high. So in the case of CFLs it should be considered that the reactive power generation is not clarified only by cos φ.

Lighting units are most commonly divided symmetrically between phases. If there is a great number of CFLs the triple harmonics aggregate and may cause high current in neutral conductor.

ACKNOWLEDGEMENTS

REFERENCES

[1] Watson, N. and Hirsch, S. The Effects of Compact Flourescent Lamps on Power Quality. [Online] http://www.apqi.org/file/attachment/2009526/1693.pdf.

[2] Dugan, R. C., et al., et al. Electrical Power Systems Quality. 2002.

[3] Eesti Standardikeskus. Voltage characteristics of electricity supplied by public distribution networks. EVS-EN 50160:2007. 2007.

[4] Characterizing the Harmonic Attenuation Effect of Compact Fluorescent Lamps . Nassif, A. B. and Xu, W. s.l. : IEEE Xplore, 2009. Power Delivery, IEEE Transactions on. 24 (3). pp. 1748 – 1749.

[5] The voltage distortion in low-voltage networks caused by compact fluorescent lamps with electronic gear. Radakovic, Z., Topalis, F.V. and Kostic, M. 2004, www.sciencedirect.com.

[6] 6. Arbitrary waveform generator for harmonic distortion tests on compact fluorescent lamps. Topalis, F. V., Gonos, I. F. and Vokas, G. A. 2001, www.sciencedirect.com.

[7] Ashok, S. Harmonic Distortion of Fluorescent Lamps. Nalanda Digital Library. [Online] http://www.nalanda.nitc.ac.in/nitcresources/ee/lectures/CFLdistort.pdf.

[8] Kontturi, M. and Ålander, J. Energiasäästölamppunejen verkkovaikutukset. 2008.

[9] Schonek, J. The singularities of the third harmonic. Cahier technique no. 202. s.l. : Schneider Electric, 2001.

[10] Schonek, J. and Vernay, M. Power supply of lighting circuits. Cahier technique no. 205. s.l. : Schneider Electric, 2002.

PAPER - IV

2013 International Conference on Connected Vehicles and Expo (ICCVE)

Current Harmonics of EV Chargers and Effects of Diversity to Charging Load Current Distortions in Distribution Networks

Lauri Kütt, Eero Saarijärvi, Matti Lehtonen
Department of Electrical Engineering
Aalto University, School of Electrical Engineering
Espoo, Finland
lauri.kutt@aalto.fi, matti.lehtonen@aalto.fi

Heigo Mõlder, Jaan Niitsoo
Department of Electrical Engineering
Tallinn University of Technology
Tallinn, Estonia

Abstract—**Charging of electric vehicles (EVs) is expected to bring a healthy addition of load for the distribution networks. The residential networks where the EV owners would charge their vehicles after returning from daily activities would especially be subjected to high load increase. As EV charger is a powerful non-linear load rather large harmonic currents can be present during the EV charging. This means a significant increase also to the current harmonics. Analysis of the quantities of the harmonic currents is necessary for guaranteeing the distribution network operation that would meet the power supply standards. In this paper, the EV charging measurement results are presented and analyzed with focus on the current waveform distortions. Different EVs are analyzed for the current harmonics present during the slow rate home charging. For the modeling of the EV charging loads in the networks, discussion is presented on the harmonic currents summing and cancellation effects. The results presented in the paper can be further used for modeling of the actual harmonic loads of the EVs in the distribution networks.**

Keywords-Electric vehicles, power system harmonics, energy storage, current measurements.

I. INTRODUCTION

Electrical vehicles are considered everyday use commuter vehicles with significant on-board energy storage and ability to use the mains power supply for charging the energy storage. Typical such vehicles are battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs). Due to similarity of the process of the on-board battery charging, there would be only slight differences in the impact for the power networks depending on the vehicle type. Therefore, within this paper, all such vehicles are referred to only as electric vehicles (EVs).

Typical EVs are provided with batteries having energy storage capacities from some kWh up to several tens of kWh [1]. High-capacity batteries are required for providing the electric driving range acceptable for the customer. The requirement to charge the batteries in a time-frame that does not provide serious compromise for the customer satisfaction means that the charging power has to be rather high. To accomplish this, expected power of the chargers is starting from 1.6 kW for single phase onboard chargers for home use [2] reaching into hundreds of kW for ultrafast charging [3]. The chargers of modern the EVs that are intended for charging at home are actually operating very close to the levels of the usual residential customers and drawing 10 – 15 A of current [2].

EV battery requires DC for charging and the conversion from AC as well as charging control is provided by the power electronics converters, which are non-linear loads. The non-linearity of the current consumed associated with the EV charging is closely related to the charger circuit topology that is providing an interface towards the AC network. The evolution of the EV chargers started with the simplest uncontrolled single-phase full-bridge rectifiers, having high levels of current harmonic distortions and low power factor. The circuits and control strategies have evolved rapidly to include more network friendly features [4] such as power factor correction (PFC) and current waveform shaping. Today the advanced charger topologies are employing switching mode operation and controllable power semiconductors, in ideal cases the current harmonic distortion level could be well below 5% at load levels from 50…100% of rated power. These functions are required to meet the criteria stated in the standards that set the operating conditions for public distribution networks such as the IEC61000 series [5]. The AC mains supply to the customers has to fulfill also requirements of low sinewave voltage distortions (for example set by IEC/EN50160 [6]). When conditions stated in these standards are met, devices connected to mains supply are expected to operate with full functionality. Considering the power of EV chargers and the characteristics of the EV charging load, analysis is required if the public mains network standards are still met if numerous EVs are charged simultaneously.

This paper will focus on the identification of properties of different EV chargers and the current distortions these EV chargers can provide for the distribution network. For evaluating this, charging measurement results of several commercially

978-1-4799-2491-2/13/$31.00 ©2013 IEEE

DOI 10.1109/ICCVE.2013.120

available modern EVs are provided. Furthermore the diversity of EVs connected to the distribution network will be discussed. It will be presented that during the measurements the EVs used rather constant current for the charging and every EV charger has its own pattern of drawing current from the supplying network. This means also different distortion patterns. It will be presented that due to diversity of the different EVs chargers characteristics, the total distortions to the network current are likely to remain relatively lower than the highest levels of individual chargers.

II. HARMONICS IN ELECTRIC DISTRIBUTION NETWORKS

The appliances and electric devices connected to the public mains network are designed to operate with a sinusoidal voltage at rated power. However, many of the connected loads are of nonlinear type, meaning that they draw current with a non-sinusoidal or distorted sine waveform. Nonlinear loads are most often based on power electronics and the share of such loads is growing rapidly worldwide. Also the modern EV chargers are power electronic units that have non-linear characteristics.

Total load current of a line or a substation is the sum of the currents of the appliances connected to this line or substation respectively. High non-linear loading causes non-linear voltage drop, leading to voltage waveform distortions for the customers associated. Distorted voltage and current in the distribution system may bring along negative effects, e.g. overloading, over-voltages, mechanical stress, malfunction of critical control and protection equipment and degradation of efficiency of appliances. Voltage distortions affect practically all customers fed through the point of common coupling (PCC).

Every non-linear load in the network produces non-sinusoidal current waveform which can be represented as a sum of different sinusoidal current components having different harmonic frequencies. The overall distortion level is usually described by total harmonic distortion (THD) index. The amount of harmonic current components, compared to the mains frequency sinusoidal component, is presented with the total current harmonic distortion THDi, calculated as

$$THDi,\% = \frac{\sqrt{\sum_{h=2}^{H} I_h^{\,2}}}{I_1} \cdot 100\% \,, \tag{1}$$

where h is the harmonic order number, H is the highest number of harmonic observed, I_h is the RMS-value of the current h-th harmonic component and I_1 is the mains frequency current component RMS value. Based on the limits in standard IEC 61000-3-4 [5] for individual harmonic emission levels, the highest current total harmonic distortion (THDi) level allowed for a charger connected to a public network would be 17.3% [7]. However, for evaluation of the total effect by EV chargers the approach should be more sophisticated and not rely on the THDi levels alone.

The EV chargers of different EV manufacturers and types are very likely to have different harmonic patterns meaning individual current harmonics magnitude levels and phase angle values. The diversity of the harmonic patterns has to be taken into account for estimating the total harmonic currents of the non-linear loads in the distribution networks. It is rather common, that only the harmonics levels are observed, as the utilities are required to keep the harmonics levels under a given limit. The harmonic magnitudes by themselves do not reveal the magnitude of the sum of the two harmonics. As the level of diversity of the harmonic patterns increases, a notable cancellation can occur [8]. This effect is seen when harmonics with different phase angles provide a sum in the magnitude that is smaller than the individual harmonics magnitudes.

III. EV CHARGING MEASUREMENTS

For the evaluation of the harmonic currents associated with the EV chargers, several different EV charger models have been presented in [9]. The downside of the models has been the lack of variety of the operation, as one of the most common models used for the harmonic currents modeling has been uncontrolled rectifier observed in the ideal operation. The chargers of the modern commercially available EVs use most often the active switching chargers employing power semiconductors. Due to the complex operation of such EV chargers, creating the model taking into account the circuit peculiarities is also very complex task.

Another option for obtaining the harmonic patterns of the EV chargers is to perform actual case measurements of the EV charging currents. The charging profiles of the EVs have been also presented before [10][11][12], however the measurement results however have not revealed the individual harmonic magnitude and phase angle values in a detailed enough manner to, for example, evaluate the summing of the harmonic patterns of the EV chargers.

In this paper the results of the actual measurements of the slow-rate EV charging are used. Subjects of the measurements have been 4 EV models, produced from the end of 2012 until mid 2013 that are commercially available from the internationally well-known car manufacturers. For the sake of discretion, the models of the cars will not be associated with particular results. The general data for the EVs charging are provided in Table I, if charging was carried out from a 230 V, 50 Hz mains supply.

TABLE I. CHARACTERISTICS OF THE CHARGING OF EVS MEASURED

EV	Charging current (A)	Charging power (kW)	THDi during the constant current charge %
1	9.7	2.2	4.2
2	10.3	2.4	12.3
3	12.7	2.9	3.4
4	10.3	2.4	10.5

Measurements of the EV charging were carried out using the Fluke Topas power quality recorder with measurement set-up presented in Fig 1. In order to obtain the most detailed data on the harmonics, the current waveforms were recorded and later processed using the Matlab software. The waveforms were recorded for 2.5 seconds after every minute (measurement series in later text) to leverage the amount of data obtained during the measurements. Validity of the data available from such recording was verified using comparisons of multiple measurement series of charging the same EV. Verification proved that using such recording mode was adequate for the analysis of the charging process.

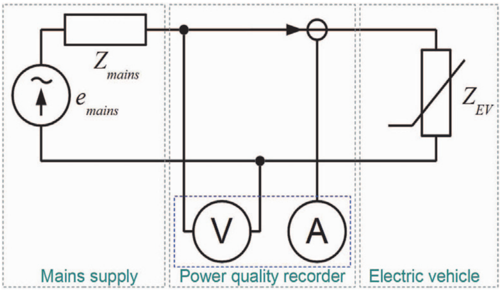


Figure 1. EV charging measurement set-up.

Charging and measurement was started when the EV was indicating 0 km electric range (battery state of charge (SOC) 0%) and the measurement was carried out until the EV completed and switched off the charging with the indication „battery full" (SOC 100%). The charging current measured during the charging has been presented in Fig. 2, in relation to the cumulative SOC determined by evaluating the total energy used for charging.

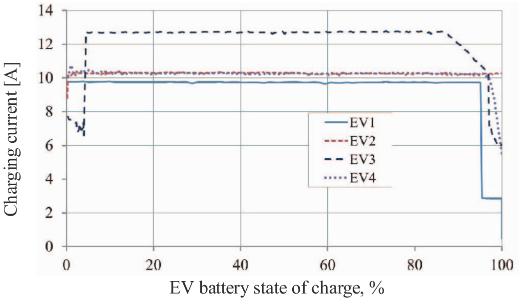


Figure 2. Charging current levels during charging span of 0% - 100% of the full charge.

It can be seen that the most significant portion of energy is transferred to the EV using constant current from the mains network. During the measurements, it was found that the charging current would follow the same pattern for the given SOC regardless of the SOC value other than 0% at the time the charging was initiated. An exception to this was only the vehicle that used current ramp in the start of charging. The highest current harmonic magnitudes were seen during the constant current charging mode, indicating this mode would be the highest harmonic burden for the distribution network.

For this selection of EVs the currents drawn from the mains network has proved to be relatively on the same levels. There are differences in distortion levels of the current waveforms, but it can be declared that the current waveform distortions would remain on rather low level. A comparison of the measured charging current waveforms, in a constant current charging mode, is presented in Fig. 3. The waveforms are indeed rather sinusoidal with power factors close to unity, referring to complex control of the power electronic circuits and special attention to the charging current waveforms.

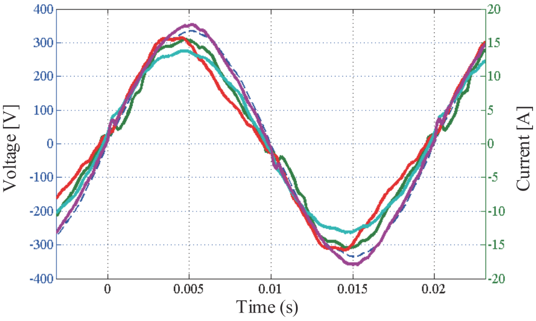


Figure 3. Comparison of the measured current waveforms. Mains voltage is provided as a reference as dotted line.

IV. EV CHARGING HARMONIC PATTERNS

The recorded waveforms provided the capability to analyze the current distortions for every mains cycle. This provided very useful information as for example, the cycle-to-cycle fluctuations of the magnitudes and phase angles of the harmonics could be closely observed. Analyzing the values within the different measurement series confirmed the results to have a distribution very close to the normal distribution and very low dispersion from the mean value. Thus, in the following the mean cycle values are presented.

In Fig. 4, the charging time has been presented with the relative scale 0…100% of charging time. Different modes of charging are clearly observable and during the constant current mode, the current harmonic magnitude and also phase angle are at rather constant values.

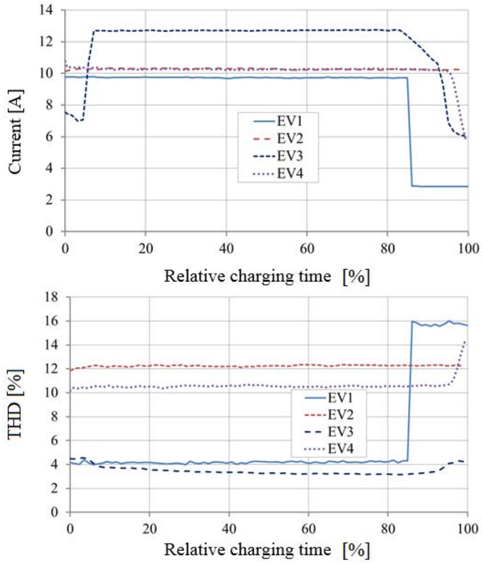


Figure 4. Charging current and THD levels during time span of 0% - 100% of the full charge.

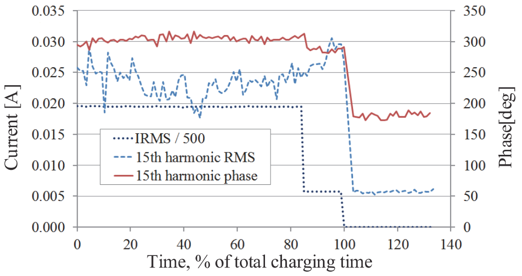


Figure 5. Current harmonics during the charging process, example of behavoir of 15th harmonic.

Similar constant trend can be also seen for the individual harmonic levels, even for higher harmonic orders. An example of the results of the statistical harmonic analysis has been presented in Fig. 4. This shows the 15th harmonic magnitude and phase angle throughout the charging process for EV1.

The current harmonics average magnitudes and phase angle values have been presented in Table II for all four measured EVs. It can clearly be seen that the harmonics phase angles are rather different for the different EVs.

TABLE II. CHARGING CURRENT HARMONICS MAGNITUDE AND PHASE VALUES FOR THE MEASURED EVS DURING CONSTANT CURRENT CHARGING MODES

		EV1: THDi = 4.0%		EV2: THDi = 12.2%		EV3: THDi = 3.3%		EV4: THDi = 10.4%	
Harmonic order	Harmonic frequency	Magnitude	Phase	Magnitude	Phase	Magnitude	Phase	Magnitude	Phase
	Hz	A	deg	A	deg	A	deg	A	deg
Main / 1	50	9.69	6	10.2	12	12.7	1	10.2	5
3	150	0.32	352	1.23	25	0.26	156	0.89	204
5	250	0.077	25	0.036	243	0.181	211	0.40	182
7	350	0.077	77	0.042	163	0.118	55	0.32	109
9	450	0.030	326	0.060	239	0.053	33	0.119	100
11	550	0.088	278	0.115	200	0.039	250	0.092	201
13	650	0.125	24	0.107	64	0.090	43	0.177	83
15	750	0.023	304	0.062	200	0.037	52	0.051	162
17	850	0.0109	94	0.040	210	0.034	30	0.040	297
19	950	0.0154	258	0.034	225	0.043	142	0.066	282
21	1050	0.040	300	0.045	242	0.068	345	0.076	259
23	1150	0.044	280	0.028	224	0.069	344	0.038	214
25	1250	0.034	284	0.025	181	0.065	334	0.024	190
27	1350	0.0089	204	0.041	111	0.054	311	0.012	181
29	1450	0.0181	269	0.021	160	0.061	318	0.075	285
31	1550	0.024	237	0.0185	159	0.061	316	0.075	247
33	1650	0.024	221	0.042	172	0.043	295	0.086	210
35	1750	0.0151	216	0.0072	88	0.054	302	0.0199	148
37	1850	0.0095	242	0.0067	114	0.048	282	0.0052	160
39	1950	0.0148	224	0.0114	285	0.052	269	0.024	289
41	2050	0.0129	220	0.0099	66	0.042	259	0.0185	207
43	2150	0.0157	190	0.0094	52	0.039	245	0.0166	157
45	2250	0.0089	179	0.0192	39	0.035	236	0.025	85
47	2350	0.0108	170	0.0089	130	0.036	221	0.0123	71
49	2450	0.0094	170	0.0096	288	0.034	215	0.0076	63

In Table II, the values during the constant power charging have been listed while the ramp-up and topping charging values have not been presented at this time. Although the THDi values can be higher for these modes, the actual harmonic currents magnitudes are lower than for the constant power mode charging. This means that the impact to the network during the ramp-up and topping charging stages is significantly lower. Thus the rougher estimates and worst-case scenarios for the distribution network harmonic levels can be evaluated using the constant power mode values.

V. TOTAL HARMONIC CURRENT DISTORTION OF THE EV CHARGERS

The load current in the electric distribution network is a sum of all the currents of individual loads connected to the network. Different loads in the AC network likely use current that is shifted by some phase angle towards the mains voltage waveform. When summing values of such currents the different phase angle should also be taken into account and the currents should be summed geometrically. This applies also to the harmonic currents, which were presented with individual amplitudes and phase angles in Table II previously.

Geometrical summing of the currents with the same phase angles provides the magnitude that is the arithmetical sum of the magnitudes of the harmonics that are added together. When the phase angles differ from each other, the result of adding the different magnitudes would provide the sum that is less than the arithmetical sum of the magnitudes. In the utmost case when the phase angles are at 180 degrees from each other the sum of the two harmonics provide most significant decrease in the value of the sum of the magnitudes. The decreasing effect is also shown in percentage of the arithmetic sum in the results for the 3rd and 5th harmonics (see Table IV, V).

The EV charging scenarios are presented in the following analysis by including or not including the EV charging of the 4 EVs presented above. Sum of charging currents is observed and THDi is used for the assessment of the level of distortions in the current waveform (see Table III). The lowest THDi value can be seen when EV1 and EV3 are present. It is quite expected, as the THDi values of these EVs is the lowest also by the results presented in Table II. However, when all the EVs are connected for charging, the level of distortions is still rather low, at 4.9%, which is significantly lower than the average THDi of all the EVs. The lowest THDi value is seen when EV1 and EV3 are present, with decrease in 3rd harmonic by 83% (phase angle difference 195 degrees) and 5th harmonic by 59% (phase angle difference 186 degrees). In all cases observed, when there is more than 1 different EV connected to the grid for charging, the harmonic cancellation is seen and the level of harmonic current will be less than the arithmetic sum of the currents. This is also visible from the THDi values of the different combinations of EVs.

TABLE III. THDI VALUES FOR DIFFERENT EV CHARGING CONFIGURATIONS

	EV2	Absent		Present	
	EV1	Absent	Present	Absent	Present
EV4	EV3				
Absent	Absent	0	4.0 %	12.2 %	6.4 %
	Present	3.3 %	2.0 %	5.7 %	3.9 %
Present	Absent	10.5 %	4.6 %	10.1 %	6.5 %
	Present	5.9 %	3.6 %	6.7 %	4.9 %

TABLE IV. 3RD HARMONIC EXPECTED MAGNITUDE DECREASE

	EV2	Absent		Present	
	EV1	Absent	Present	Absent	Present
EV4	EV3				
Absent	Absent	0	0	0	-21 %
	Present	0	-83 %	-18 %	-36 %
Present	Absent	0	-47 %	-9 %	-26 %
	Present	-6 %	-46 %	-16 %	-32 %

TABLE V. 5TH HARMONIC EXPECTED MAGNITUDE DECREASE

	EV2	Absent		Present	
	EV1	Absent	Present	Absent	Present
EV4	EV3				
Absent	Absent	0	0	0	-53 %
	Present	0	-59 %	-2 %	-53 %
Present	Absent	0	-31 %	-4 %	-32 %
	Present	-3 %	-25 %	-5 %	-26 %

VI. DISCUSSION AND CONCLUSIONS

The results provided above present quite clearly the occurrence of significant harmonic cancellation when multiple different types of EVs are connected for charging. This is good news for the distribution networks, as the EV charging will likely not provide extremely high addition of harmonic current to the network. In the present case, it is shown that the harmonic cancellation is expected also for the low-order harmonics, like 3rd and 5th that usually have the highest magnitudes. Previously, it has been suggested that the most significant harmonic cancellation would occur when the order of harmonics is higher [13].

It is still rather complicated to evaluate the overall level of harmonics in the residential distribution networks where the EVs are connected. The subject of harmonic cancellation in the distribution networks has been also referred to in several previous papers [14][15], however the clear analysis on the level of its effect during the numerous EV charging has not been discussed in detail. Moreover, the distribution network itself has numerous different types and makes of loads that similarly provide some harmonic cancellation. The authors of this paper will continue their work in these matters.

For the customers of distribution networks and the utilities, the current harmonics are not as critical as the voltage harmonics. The voltage harmonics are present due to harmonic voltage drop in the supplying transformer and lines. The voltage drop is dependent on the harmonic current values as well as the harmonic impedance values. Also, for the evaluation of the total harmonic currents to the supply transformer, the network normal load harmonics should be taken into account. Thus more sophisticated models are required [16].

In the present example, the EV charging was discussed in a rather straightforward manner by including or not including an EV for charging. For the real life cases the EV charging however is rather stochastic process. There are several probabilistic parameters required for this included such as distribution of charging start times, state of charge of the EV after arrival and many more. The scenarios using high number of variables and probabilistic data could be simulated, for example, using Monte Carlo methods [17] to evaluate the levels of the current harmonics taking into account the diversity of the load.

REFERENCES

[1] Yilmaz, M., Krein, P.T., Review of Charging Power Levels and Infrastructure for Plug-In Electric and Hybrid Vehicles, IEEE Electric Vehicle Conference (IEVC), 2012, 8 p.

[2] Shengnan Shao, Manisa Pipattanasomporn, Demand Response as a Load Shaping Tool in an Intelligent Grid With Electric Vehicles, IEEE Transactions on Smart Grid, Vol. 2, No. 4, Dec 2011, pp. 624-631.

[3] Hõimoja, H., Vasiladiotis, M., Grioni, S., Capezzali, M., Rufer, A., Püttgen, H.B., Toward Ultrafast Charging Solutions of Electric Vehicles, CIGRE 2012, paper C6-207, 8 p.

[4] Musavi, F., Edington, M., Eberle, W., Dunford, W.G., Evaluation and Efficiency Comparison of Front End AC-DC Plug-in Hybrid Charger Topologies, IEEE Transactions on Smart Grid, Vol. 3, No. 1, Mar 2012, pp. 413 – 421.

[5] IEC/TS 61000-3-4, Electromagnetic compatibility (EMC) - Part 3-4: Limits - Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A.

[6] IEC/EN 50160:2010, Voltage Characteristics in Public Distribution Systems. European standard.

[7] Bass, R., Harley, R., Lambert, F., Rajasekaran, V., Pierce, J., Residential Harmonic Loads and EV Charging, IEEE Power Engineering Society Winter Meeting, 2001, Vol.2, pp. 803 – 808.

[8] Staats, P.T., Grady, W.M., Arapostathis, A., Thallam, R.S., A Statistical Method for Predicting the Net Harmonic Currents Generated by a Concentration of Electric Vehicle Battery Chargers, IEEE Transactions on Power Delivery, Vol. 12, No. 3, July 1997 , pp. 1258 – 1266.

[9] Collin, A.J., Djokic, S.Z., Thomas, H.F., Meyer, J., Modelling of Electric Vehicle Chargers for Power System Analysis, 2011 11th International Conference on Electrical Power Quality and Utilisation (EPQU), pp. 1-6.

[10] Meyer, J., Hahle, S., Schegner, P., Wald, C., Impact of electrical car charging on unbalance in public low voltage grids, 2011 11th International Conference on Electrical Power Quality and Utilisation (EPQU), pp. 1-6.

[11] Melo, N., Mira, F., de Almeida, A., Delgado, J., Integration of PEV in Portuguese Distribution Grid. Analysis of harmonic current emissions in charging points. 2011 11th International Conference on Electrical Power Quality and Utilisation (EPQU), pp. 1-6.

[12] Trovao, J.P., Pereirinha, P.G., Trovao, L., Jorge, H.M., Electric Vehicles Chargers Characterization: Load Demand and Harmonic Distortion, 2011 International Conference on Electrical Power Quality and Utilisation (EPQU) , pp. 1-7.

[13] Gomez, J.C., Morcos, M.M., Impact of EV Battery Chargers on the Power Quality of Distribution Systems, IEEE Transactions on Power Delivery, Vol. 18, No. 3, Jul 2003, pp. 975 - 981.

[14] Salles, D., Jiang, C., Xu, W., Freitas, W., Mazin, HE; Assessing the Collective Harmonic Impact of Modern Residential Loads-Part I: Methodology, IEEE Transactions on Power Delivery, Vol. 27, Iss. 4, Oct 2012, pp. 1937 - 1946.

[15] Lehtonen, M., A general solution to the harmonics summation problem, European Transactions on Electrical Power Engineering, Vol. 3, Iss. 4, Jul-Aug 1993, pp. 293 – 297.

[16] Staats P.T., Grady W.M., Arapostathis A., R. Thallam S., A Statistical Analysis of the Effect of Electric Vehicle Battery Charging on Distribution System Harmonic Voltages, IEEE Transactions on Power Delivery, Vol. 13, No. 2, Apr 1998, pp. 640 – 646.

[17] Chan, M.S.W., Chau, K.T., Chan, C.C., Modeling of electric vehicle chargers, Proceedings of the 24th Annual Conference of the IEEE Industrial Electronics Society, IECON 1998, Vol. 1, pp. 433 - 438.

PAPER - V

http://dx.doi.org/10.5755/j01.eee.18.8.2605 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, VOL. 18, NO. 8, 2012

Power Quality Issues in Dispersed Generation and Smart Grids

T. Vaimann[1], J. Niitsoo[2], T. Kivipold[2], T. Lehtla[3]
[1]Department of Fundamentals of Electrical Engineering and Electrical Machines, Tallinn University of Technology,
Ehitajate tee 5, 19086 Tallinn, Estonia, phone: +372 620 3800
[2]Department of Electrical Power Engineering, Tallinn University of Technology,
Ehitajate tee 5, 19086 Tallinn, Estonia, phone: +372 620 3754
[3]Department of Electrical Drives and Power Electronics, Tallinn University of Technology,
Ehitajate tee 5, 19086 Tallinn, Estonia, phone: +372 620 3704
toomas.vaimann@ttu.ee

***Abstract*—The world today is moving toward smart distribution grids and dispersed generation. Those tendencies are caused by different reasons. These include the decrease of fossil fuel consumption, EU directives of CO_2 emissions and climate objectives etc. Innovation and change in technology is a highly welcomed trend but one must not forget that there are drawbacks as well as benefits. One of the most important issues in future grids are the power quality and supply reliability issues. This paper describes how the change to dispersed generation and smart grids should look like and what are the main problems, that need quick and active solutions, so that future grids would be fully functional and reliable.**

***Index Terms*—Power distribution faults, smart grids, power system dynamics, harmonic distortion.**

I. INTRODUCTION

If centralized generation is characterizing factor for nowadays energy systems, then smart grids of the future mean also the spreading of dispersed generation. The cause of these changes is the strict environmental norms and liberalization of electricity markets [1].

Dispersed generation has been recommended as one of the environmentally friendly solutions for improving the energy system, decreasing the losses and increasing effectiveness [2]. In addition increasing the ratio of small producers in electricity generation has been proposed.

Connecting new producers and generators to the distribution network can drastically change the working parameters of the grid. This situation is extremely important when the new connected power plant is equal to or even greater than the load in this particular area. In such case the new power plant affects the voltage adjustment and power flux. It is important to evaluate the existing grid, capacity and loads in this certain area of the distribution network [2].

Dispersed units affect the current quality and through the grid also the voltage quality as experienced by other customers [2]. Power quality concerns the electrical interaction between the network and its customers. It consists of two parts: the voltage quality concerns the way in which the supply voltage impacts equipment; the current quality on the other hand concerns the way in which the equipment current impacts the system [3].

For these reasons it is important changing of the loads have to be observed in smart grids as well as the growth of dispersed generation. In addition loads are getting more and more nonlinear which means that the cooperation of untraditional generation and loads affect the grid in unpredictable ways.

One of the key aspects of electricity production and distribution is the power quality and supply reliability for the customers. Traditionally the problems have been solved but as the world is moving towards smart grids and dispersed generation, those problems need more active and precise control.

As it can be expected, a great number of small generation units will be connected to distribution grids in quite near future. Most probably it would require certain online diagnostic systems to secure the full functionality and reliability of those units.

As due to the rise of harmonics in the grid, the machines would become more vulnerable, their faults become even more difficult to detect, so one could expect a growing number of unexpected downtimes due to different faults of the generators. This is the issue why real time condition monitoring is of utmost importance in the dispersed generation situation.

II. DISPERSED GENERATION

Dispersed generation is the production of electricity at or near the point of use. Most or part of consumed energy is produced at point of use and rest of the electricity goes into the distribution grid [3].

In most cases it is assumed that the electrical current and voltage have a sinusoidal wave shape. But if hundreds or thousands of small power production plants are connected to

Manuscript received March 19, 2012; accepted May 12, 2012.
This paper is supported by SmartGrids ERA-Net project “Power Quality and Safety Requirements for People and Electrical Equipment in Smart Grid Customer Domain”.

a grid, it could mean that the sinusoidal current and voltage waveform are distorted and the waveform is no longer sinusoidal. Also, all small generators themselves produce harmonics. So the large-scale use of renewable energy sources for the production of electricity will bring major challenges for the electricity network.

Generators are typical electrical devices that are usually setup together with frequency converters to drive them and different inverters to synchronize their work with the grid. Not only generators themselves but also frequency converters and other electronic devices produce a vast number of harmonics that can be a problem to electrical machines they are set up with and also the grid they are working in. Due to financial benefits usually no additional filters are used to lessen the amount of induced harmonics. A typical harmonic distortion of a frequency converter is shown on Fig. 1.

As dispersed generation means also a growing number of small power plants such as small hydro and wind applications, this harmonic problem can become a serious issue for the power quality and supply reliability in smart grid or dispersed generation situation.

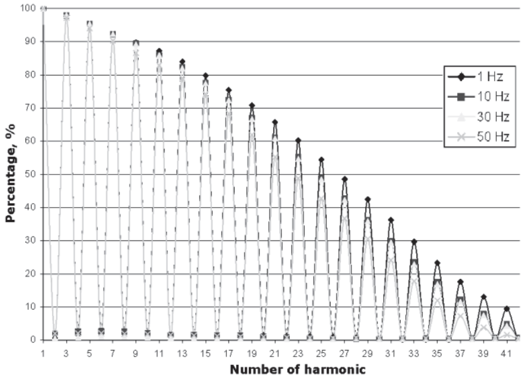


Fig. 1. Typical harmonic distortion of frequency converter.

For showing the probability of large extent of distributed generation in near future the potential is pointed out. The Estonian potential for dispersed generation, which currently is greater than the annual electricity consumption, is chosen as the example [3]. The potential of different energy sources in Estonia are shown in Table I.

TABLE I. ESTONIAN POTENTIAL OF DISPERSED GENERATION [3].

Name	Energy MWh/year	%
Wind energy	6 224 400,00	53
Litter oddments (biomass)	1 280 400,00	11
Wood (biomass)	1 279 800,00	11
Boiler plant reconstruction to CHP	1 179 000,00	10
Energy brush (biomass)	1 079 133,30	9
Solar Energy	224 000,00	2
Dung (biogas)	185 435,20	2
Hydropower	102 514,00	1
Reed (biomass)	50 000,00	0
Landfill gas (biogas)	25 974,40	0
Wastewater sludge (biogas)	21 201,60	0
Total:	11 651 858,50	100

III. POWER QUALITY

Connection of dispersed resources and changing dispersed generation to the distribution grid can affect the power quality in a great amount [2]. Smart distribution grid must secure the end users with power that has the demanded quality [4]–[6]. This is why the modern control systems, that are monitoring the important components of the distribution grid, must react precisely to the changes in power quality.

Power quality can be controlled and improved in whatever point of the electric system beginning from the means in the system or the grid and ending with single devices at the consumer level.

Connection of the dispersed generation of renewable energy to distribution grid can have both positive and negative effects to the power quality. It depends on possibilities of information and communication systems to control and maintain voltage in the feeders, turn the loads in or out and replace lost power with the reserves.

For example small amounts of wind power have negligible effects on electricity networks, but when electricity generation from wind power exceeds a certain threshold level, investments in the power system will be required. This threshold level is known as the hosting capacity [4].

The principle of hosting capacity is explained at Fig. 2. Hosting capacity does not say anything about how much generation from renewable energy sources that is connected to the grid, only how much can be connected without having to invest in measures to strengthen the grid.

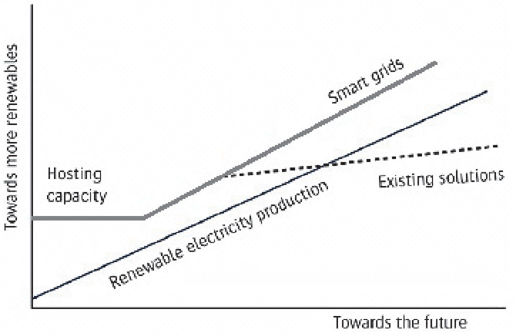


Fig. 2. The principle underlining hosting capacity [5].

IV. HARMONIC DISTORTION DUE TO DIFFERENT LOADS

Electrical devices, which are coming onto market, are becoming more and more complex. They may help to reduce energy consumption, but their performance regarding power quality is still rather improper.

The problem is that their current curve is not a perfect sinusoid. The widespread use of nonlinear loads may implicate significant reactive power and problems with higher harmonics in a grid [6].

Harmonic currents produced by nonlinear loads are injected back into the supply systems. These currents can interact adversely with a wide range of power systems equipment causing additional losses, overheating and overloading. These harmonic currents can also cause interference with telecommunication lines and errors in power metering [7]–[9]. That problem may come more important when smart grid solutions where communication is very important are adapted.

Typical current curves of nonlinear loads are shown at Fig. 2. While the applied voltage is almost perfectly sinusoidal, the resulting current is heavily distorted.

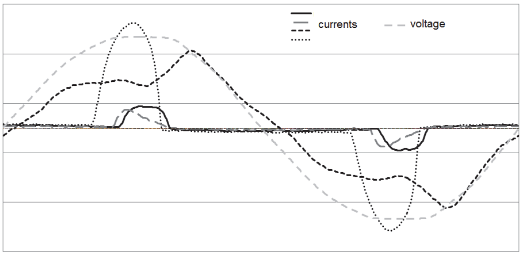


Fig. 3. Currents of typical nonlinear loads versus voltage.

Harmonics generated by consumer’s appliances must not cause voltage rise in the connection point [6]. Fixing limits may become important before using numerous harmonics emitting devices together. In some papers [8] measurements with nonlinear loads are done when 5% current´s total harmonic distortion value at connection point is followed. For example most of the common compact fluorescence lamps have the total harmonic distortion over 100% [9].

Harmonic currents injected from individual end users on the system should be limited. These currents propagate toward the supply source through the system impedance, creating voltage distortion. Thus by limiting the amount of injected harmonic currents, the voltage distortion can be limited as well. This is the basic method of controlling the overall distortion levels proposed by IEEE standard 519-1992. Example for illustrating nonlinear loads influence on distribution grid a study with compact fluorescence lamps (CFLs) is made [8], [9].

V. POSSIBLE SOLUTIONS FOR POWER QUALITY FALL IN SMART GRID

Equipment responds very differently to harmonic distortions, depending on their method of operation. For example incandescent lights and different household heaters are not affected by them. On the other hand, induction motor windings are overheated by harmonics, causing accelerated degradation of insulation and so the lifetime of the machine can shorten in an abrupt way. The problem is that harmonic voltages can give correspondingly higher currents than do 50 Hz voltages and one can easily underestimate the degree of additional heating in the motor [10].

It is a widely known fact that faults such as the broken rotor bars induce sideband harmonic components to the stator current spectrum of the induction machine. Those harmonics can be used for detecting the faults. As most of electrical machines today are used in hand with frequency converters, then those converters add additional variables to the problem. Frequency converter causes supply frequency to vary slightly in time and, as a result, some additional harmonics in the current spectrum are induced and sidebands are reduced [11] or even hindered. This phenomenon also raises the amount of noise in the test signals, which makes the faults more difficult to detect.

In that sense it could prove to be useful to use a certain on-line diagnostic system in the grids with dispersed generation and the wind generators that are integrated to this system. This could be a helpful tool to detect the faults at an early stage where the repairing of the machines is still possible and reasonable. Also it would help to differentiate the deviations and harmonic distortions in the grid from the faulty cases of the machines.

VI. CONCLUSIONS

Irrespective of how the term smart grid is defined, one can safely state that electricity networks will face new challenges in the future, and that current and future challenges can be solved by a set of technologies that either exist today, or are being actively developed.

If more and more dispersed generation is going to be installed all over the power networks like it seems to go then it is most important to find measures for guarantying quality and security of supply.

From the example of Estonia we can see that the potential of dispersed generation is extensive. The impacts of using distributed generation may be massive even if bulk of that potential will not be installed.

In the situation where generation as well as consumption produces decrease of power quality in the grid, it is essential to analyze both generation and consumption in a very thorough way. If it proves to be necessary it might make sense to limit the usage of new plants and appliances or use some other methods to decrease their negative effect to power quality.

Usage of nonlinear loads like compact fluorescent lamps has risen rapidly in the last decade, but their harmonic emission, reactive power consumption and other drawbacks have been ignored.

Beside the problem that harmonics are extremely dangerous to electrical motors, distorted supply makes the diagnostics of them more difficult. A growing number of machines are driven through frequency converters. This means that also diagnostic for appropriate setups with frequency converters should be investigated. Frequency converters add additional noise and harmonics to the traditional current spectrum of the machines and thus such drives need a slightly different approach in diagnostics than traditional grid supplied machines. Nevertheless, appropriate on-line diagnostics of dispersed generation units must be applied to guarantee sufficient power quality, supply reliability and overall safety of customers and different facilities connected to the grid.

REFERENCES

[1] Estonian Ministry of the Environment. Euroopa Liidu kliimapoliitika, 2012. [Online]. Available: http://www.envir.ee/1159209

[2] K.Purchala, R. Belmans, L. Exarchakos, A. D. Hawkes, "Distributed generation and the grid integration issue", KULeuven, Imperial College London.

[3] M. Bollen, *Understanding power quality problems: Voltage Sags and Interruptions,* 1st ed., Wiley-IEEE Press, 2000, p. 543.

[4] M.Bollen, M. Häger, "Power quality: interactions between distributed energy resources, the grid, and other customers", *Electric Power Quality and Utilisation Magazine,* vol. 1, no. 1, pp. 51–61, 2005.

[5] F. C. De La Rosa, *Harmonics and power systems*, CRC Press, 2006, pp. 1–184. [Online]. Available: http://dx.doi.org/10.1201/9781420004519.ch1

[6] T. Ackermann, G. Andersson, L. Söder, "Distributed generation: a definition", *Electric Power Systems Research,* vol. 57, pp. 195–204, 2001. [Online]. Available: http://dx.doi.org/10.1016/S0378-7796(01)00101-8

[7] T. Vaimann, J. Niitsoo, T. Kivipõld, "Dispersed generation accommodation into smart grid", in *Proc. of the 52nd International Scientific Conference of Riga Technical University. Section of Power and Electrical Engineering,* Riga Technical University Press, 2011, ID-42.

[8] European Standard, EN 50160:2011 Voltage characteristics of electricity, 2011.

[9] M. Bollen, *Adapting electricity networks to a sustainable– smart metering and smart grids*, Swedish Energy Markets Inspectorate, 2011, pp. 1–115.

[10] N. Watson, S. Hirsch, "The impact of compact flourescent lamps on power quality", in *Proc. of Conference of the Electric Power Supply Industry,* 1994, pp. 416–428.

[11] A. Miletic, M. Cettolo, "Frequency converter influence on induction motor rotor faults detection using motor current signature analysis – experimental research", *Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives,* 2003, pp. 124–128.

PAPER - VI

ELECTRIC POWER ENGINEERING 2013

Consequences of Distributed Generation on Power Quality

Jaan Niitsoo[1)], Lauri Kütt[2)], Paul Taklaja[1)]
[1)]Tallinn University of Technology, Department of Electrical Power Engineering,
Tallinn, Estonia, www.tut.ee, email: jaan.niitsoo@ttu.ee, paul.taklaja@ttu.ee
[2)]Aalto University School of Electrical Engineering, Department of Electrical Engineering,
Espoo, Finland, www.aalto.fi, email: lauri.kutt@aalto.fi

ABSTRACT

The small-power distributed generation units are often accompanied by high-power power electronic converters. The output of such converters is distorted sinewave which can cause harmful effects to the distribution network it is connected to. The goal of this paper is to give an overview of problems that may occur when increasing numbers of distributed generation (DG) units are accommodated into distribution grid. The investigation is based on findings from theory and possible challenges are listed and shortly described. More important ones are explained in details. Focus is put on issues of voltage distortion due to higher harmonics produced by power electronics used in DG units. All distribution network operators should be aware of the likely problems and be ready for the appropriate measures to leverage these as the amount of DG installations is increasing rapidly.

Keywords: Distributed power generation, power electronic inverters, power quality, power system harmonics

1 INTRODUCTION

Since the penetration of DG systems in the distribution network is increasing, the need to monitor and model the contribution of these systems to the harmonic distortion of current and voltage waveforms is becoming an up-to-date issue [1]. When a large number of DGs are connected to distribution network, power electronics become one of the main harmonic sources [2]. If possible, this should be taken into account along with the new power flow situation [3] in planning and analysis stages.

Furthermore international standards are incomplete and controversial for photovoltaic (PV) applications, allowing the generation of harmonics in the range of few kHz without clear limitations [3,4]. On the contrary in the low frequency range the limits are more stringent than those for home applications due to the fact that PV systems are viewed as generation sources [4]. There is also no standard on PV inverter topology [5].

An overview of likely concerns that can occur when great amount of distributed generation units would be installed into the distribution network is presented in this paper. Results from number of different studies along with a short overview of the potential issues are presented including more precise discussion of more severe ones.

Harmonic distortion appears to be the one of the problems frequently discussed in theory in case of distribution generation units connected to grid through power electronic inverters. High harmonic distortion is observed especially in situations where loading of the inverter is small.

More severe are the situations where a number of generation units are connected to the network at the same time. This is due to that individual components are complied with the standards, but in practice in grid with other loads they do not. Situations like that are also not standardized.

2 HARMFUL EFFECTS OF THE DG

Connection of the distributed generation units to distribution networks should be observed in terms of power quality, reliability, network control and stability. For such operational aspects a number of problems could arise. Hereby a short list of possible issues in irrelevant order could be presented as [6,7]:

- malfunction of harmonic-sensitive equipment [8],
- exceeding the thermal limits of conductors,
- raise of the voltage harmonics distortion,
- decrease in lifetime of components [1],
- malfunction of the protection system,
- under- or over-voltage of the network,
- non reception of the tariff signal,
- increase of the network outages,
- reactive power generation [10],
- decrease of power factor,
- voltage flicker [2],
- resonance [9],
- power losses,
- dc injection,
- islanding.

The main issues are drawn out and their possible causes are explained in following paragraphs. Influence of inverter technology and strength of grid and resonance case are emphasized.

2.1 Cause of the effects

The performance of PV plants in terms of power quality depends on the inverter structure, external conditions such as solar irradiance and temperature, type and amount of load and characteristics of the supply system [11,12,13,14].

The harmonics produced by DG in the distribution network is mainly influenced by the factor of equivalent impedance in the place of common coupling (PCC) [13] which

DG is connected to. The further the electrical distance, the larger the line impedance is. Harmonics are present in the output current of the DG because of use of power semiconductor devices in the DG unit grid interface converters. Furthermore the control of the converters for providing variable power flow of the DG units can produce different harmonic levels for different output power along with interharmonics that may be present as the switching frequency of power-electronic devices varies [15]. Consequently, since the switching frequency is arbitrary, the harmonics are also arbitrary [5].

Some projects with large number of small PV inverters in a low voltage network have shown high levels of voltage distortion, although the emission level of an individual PV inverter satisfies the PQ standards [10,12,16]. Combined harmonic current emissions of those devices provide high harmonic loading of the supplying units and may lead to voltage harmonics exceeding accepted limits. This may be enforced because of changes of the impedance and resonance frequencies of the network, e.g. due to the inverters capacitance [17,18].

Real-world measurements in networks with a high penetration of PV generation have even showed that the PV inverters, under certain circumstances, could switch off undesirably or increase their harmonic emission significantly [19]. When power-electronic sources are operated in parallel, two particular effects become apparent which affect harmonic generation: attenuation and cancellation. Attenuation occurs since the generated currents cause voltage variations that in turn affect the other sources; the impact is such that reduces the currents causing the disturbance. Cancellation is the result of the harmonic current components of the different sources being to some extent out of phase, resulting in a reduction in that particular harmonic for the aggregate [7].

2.2 Influence of the inverter

Inverters are required by the DGs to provide the desired power output to the distribution grid. Power electronic converters can be found with wind turbines, photovoltaic systems, fuel cells, micro turbines, sterling engine as well as battery storage, and magnetic storage systems [13]. It is required that any converter system connected to the grid would not in any way degrade the quality of supply at the PCC significantly. There is a large difference, however, between inverters with voltage control and current control in respect to their harmonic effects on the grid [20].

Most new inverter designs are based on high-speed switching components, such as IGBTs and implement pulse width modulation (PWM) to generate the injected sine wave [16]. These inverters are capable of near-sine voltage and current output and they individually satisfy the requirements stated in standards [21]. The magnitude and the order of harmonic currents injected by converters depend on the technology and topology of an inverter[24] and mode of its operation [25]. The harmonic content of most modern sine wave inverters is typically less than 3% current THD [20] and less than 5% current THD with each of the H-bridges switching only at fundamental frequency [22].

For use in individual households [23], the inverters for distributed generation units offered typically are based on single-phase self-commutated voltage-source converters in the 1–5 kW power range. These inverters consist of different power stages, with high-frequency and line-frequency transformers or even transformerless designs [24].

Fig. 1 outlines the measurement of total harmonic distortion of current (THD_I) on the AC-side for the period of one day with changing solar radiation, indicated by the generated power in the lower part of the figure. The harmonic current emission of the converters depends on power output, being comparatively high for low generation and low for generated power exceeding the value of approximately 15%...20% of the rated power [11,12,14].

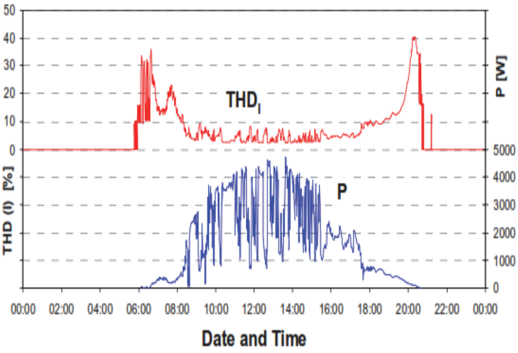


Fig. 1 Daily evolution of the power and THD_I for the PV plant [11]

Inverters that are most commonly used in grid connected PV systems (voltage source inverters controlled using a look up table for the desired waveform) are the most susceptible to harmonic distortion of the grid voltage waveform and can easily result in 2-3 times the current distortion of rated output [14]. Also non-sinusoidal shape of the grid voltage increases the harmonic currents produced by inverters where the current control electronics is not able to react adequately [3].

The level of current distortion is shown to be very dependent on the type of inverter control used. For commonly applied inverter design and control, the level of harmonic distortion has been found to vary approximately inversely with the level of power delivered and also with grid impedance [14]. In practical cases, the measured harmonic emission may exceed the typical values obtained in laboratory tests [12].

Inverters are potentially sensitive to voltage harmonics and interharmonics, particularly the current control unit, power conversion stage and the grid interface. This is due to possibility of tripping of protective functions due to fluctuations of the grid voltage and frequency [3].

Most commercial inverters for the grid connection of small generators are designed to operate at unity power factor, but the inverter fails to maintain unity power factor at low power outputs. This is explained by the fixed modulation index employed as the feed forward element in the controller [7].

Some inverters combine the reference source and the synchronization in the grid voltage, by using the shape of the grid voltage as a reference source. In case of polluted grid voltage the reference source will also be distorted and the current control loop of the inverter pollutes its output current accordingly [16]. When a positive–negative imbalance exists on the network voltage waveform (equivalent to even order harmonics) the resulting distortion might affect the operation of PWM controlled inverters, especially when their synchronization with the grid is based on the zero crossings of the voltage waveform [3].

Inverters with fast switching power electronic components are potential electromagnetic interference (EMI) sources. For this reason high frequency filtering of inverter outputs is required. Additionally a low frequency filter is used to filter distortions at the switching frequency, which lies generally below the EMI filtering range. The filter components of these filters are inductors and capacitors located at the input and output side of the inverter [16].

In order to make the inverter cost-effective, manufacturers try to minimize the need for external reactors and instead increase the size of the output capacitor [24]. The output capacitors of the inverter strongly reduce the current source behaviour of the inverter and can also be responsible for setting up a resonance circuit together with the network reactance (transformer and cable reactance). These effects are not detected or reduced by the current control loop of the inverter [16].

AC voltage components acting on the capacitances that develop on the DC and AC parts of PV systems and supporting structure capacitances to earth, also high-frequency voltage components on EMI filters at the inverter's input and output may cause leakage current flow in the ground wire. Simulations carried out for PV systems with transformerless inverters have provided some theoretical evidence of these effects [26].

2.3 Importance of grid strength

Although the quality of a network supply is conventionally assessed in terms of voltage harmonics, the grid impedance determines how these relate to the output current [7]. Power quality from inverters is significantly influenced by minor distortion of the voltage waveform on the network into which current is being sourced. For example in [7] a case analysis is presented for connecting the DG unit into an ideal grid with resistive load. The voltage distortion about 3.2% was indicated whereas connection to the low voltage network gave almost 5.7% with all other conditions remaining the same. Similar range was observed when distortion was measured for inverter connected with the real grid and then in the islanded operation, values of voltage THD were 6,2% and 3,3% respectively [7].

In another case [24] a test with inverters connected into networks with different voltage distortions was carried out. It was concluded that all the inverters are able to operate at average voltage THD value of 3%, but at in some cases maximum allowed should be limited to 8%, as after this inverters could start to trip.

Generally researches have shown that in strong networks the harmonic current distortion arising from PV units does not seem to contribute significantly to current harmonics. The sources of harmonics are rather the existing electrical loads. When emission of low-order even current harmonics appears to be influenced by technical aspects of inverters in weak networks, it appears to be constant in strong grids. Higher frequency harmonics tend to be attenuated more quickly [27,28,29].

2.4 Resonance issue

Resonance phenomena of the network and DG inverters circuits can be responsible for higher than expected distortion levels in networks because the current control of an inverter has a large influence on the initiation and size of the resonance [16]. The resonance phenomenon for networks with large numbers of inverters and can be divided into the parallel and series resonance. In practice these two phenomena are linked in one circuit and increased in both voltage and current distortions are practically measured [10].

Parallel resonance of the parallel network capacitance C_P (inverter, household and cable) and the supply inductance L_P (transformer leakage and cable), results in distortion harmonics I_h generated internally, i.e. within the point of common connection (PCC). In this case the inverter can be assumed to be the harmonic source I_h. The impedance due to presence of resonance is high, resulting in higher voltage distortion at the PCC, or where the inverter and household load is connected [10].

Series resonance of the network capacitance C_S and the supply reactance L_S can occur due to externally generated or injected distortion. In this case the background supply voltage distortion is the initiator. Here the impedance at the resonance is low, resulting in higher current distortion through the load and inverter capacitor [10].

When one of the harmonics present in the network background distortion (series resonance mechanism) corresponds with the series resonance frequency, very high resonant currents will flow in the network, damped only by the associated network resistance. The load is parallel to the network resistance for a parallel resonance and can be ignored since it is much higher than the network resistance [10].

These resonances between existing network components and the inverters typically reside between the 5th and 40th harmonic orders [10]. Simulation results [10] show that the most dominant parallel resonance frequency is likely between the 17th and 23rd harmonic and another parallel resonance is present around the 11th and 13th harmonics. In practice switching frequencies of 20 – 500 kHz are used in inverters different power stages [16].

In practice the equivalent capacitance of connected appliances can have a significant influence. For example the equivalent capacitance can vary over a wide range for the home connection. The typical values for the inverter input capacitance can also vary also over a wide range. In case of commercial inverters in the 1 – 3 kW power range typical values of 0.5 – 10 F for the output capacitance are used [24]. The resonances are also affected by the grid voltage disturbances [16].

3 DISCUSSION

The discussed issues likely to arise in case of installing distributed generation units through power electronic inverters suggests that distribution network operators and their customers should observe the DG units installation carefully. The amount of small generating units is increasing tremendously at the same time when common power electronic loads are doing the same. This means more complex harmonic distortion at PCC which may lead severe consequences in weak grids.

At present time there is a small microgrid with different generation units installed at Power Engineering Faculty of Tallinn University of Technology. Measurements done so far have shown that voltage distortion due to nonlinear load is already around 5% which is also the limit fixed by various standards. During a work day voltage THD can reach even over 6% in some cases as seen from Fig. 2.

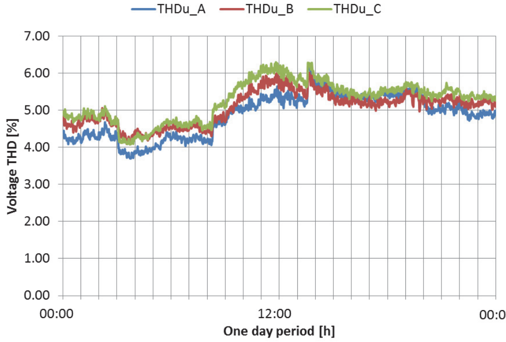


Fig. 2. Measured voltage THD during one work day

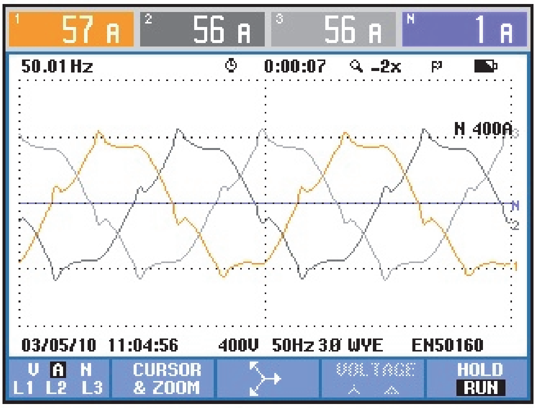


Fig. 3. Measured currents at one feeder

Currents of one measured feeder in the faculty building are presented in Fig. 3. High current distortions were detected in all feeders which have large amount of nonlinear loads consisting amount of computers, compact fluorescent lamps and air ventilation system.

High voltage and current distortions have been suspected of causing malfunctioning of numerous supply blocks in the building. Here it serves a clear proof that further analysis of possible degradation of power quality by new devices is necessary before proceeding with connections of additional DG units.

4 CONCLUSION

It can be concluded that the impact of distribution generation units which utilize power electronic inverters to power quality depends mostly on the penetration level of DG in the distribution network as well as on the DG technology.

The condition of the grid is important as in electrically weaker network the influence of DG units to power quality is higher. At the same time the distortion of individual inverter is highly dependent on its technology.

Even if normally the inverters are individually compliant with standards, once they are connected to the real network distortions can grow higher than permissible. One cause of that is occurrence of the resonance phenomenon. This is a complex effect, which requires special measurement scenarios to detect and also special measures to eliminate. The work on the methods to determine the expected resonance characteristics and the countermeasures will be further continued by the authors of the paper.

ACKNOWLEDGEMENTS

This research work has been supported by Estonian Archimedes Foundation (project „Doctoral School of Energy and Geotechnology II“).

REFERENCES

[1] I.T. Papaioannou et al., "Harmonic impact of small photovoltaic systems connected to the LV distribution network," in 5th International Conference on European Electricity Market, 2008. EEM 2008, 2008, pp. 1 - 6.

[2] W. Zhou, H. Xie, and Y. Tong, "Propagation Mechanisms Research of Harmonics Produced by Distributed Generations in Distribution Network," in 15th IEEE International Conference on Harmonics and Quality of Power, Hong Kong, China, 2012.

[3] E. Caamaño-Martín et al., "Interaction between photovoltaic distributed generation and electricity networks," Progress in Photovoltaics: Research and Applications, Vol. 16, No. 7, pp. 629–643, Nov 2008.

[4] M. Liserre, R. Teodorescu, and F. Blaabjerg, "Stability of grid-connected PV inverters with large grid impedance variation," in 2004 IEEE 35th Annual Power Electronics Specialists Conference PESC 04, Aachen, Germany, 2004, pp. 4773 - 4779.

[5] J.M. Carrasco et al., "Power-Electronic Systems for the Grid Integration of Renewable Energy Sources: A Survey," IEEE Transactions on Industrial Electronics, Vol.

53, No. 4, pp. 1002 - 1016 , August 2006.

[6] T. Tran-Quoc, C. Andrieu, and N. Hadjsaid, "Technical impacts of small distributed generation units on LV networks," in IEEE Power Engineering Society General Meeting 2003, 2003.

[7] D.G. Infield, P. Onions, A.D. Simmons, and G.A. Smith, "Power quality from multiple grid-connected single-phase inverters," IEEE Transactions on Power Delivery, Vol. 19, No. 4, pp. 1983 - 1989, Oct 2004.

[8] A.R. Oliva, J.C. Balda, "A PV dispersed generator: a power quality analysis within the IEEE 519," IEEE Transactions on Power Delivery, Vol. 18, No. 2, pp. 525 - 530, April 2003.

[9] Z. Chen, E. Spooner, "Grid power quality with variable speed wind turbines," IEEE Transactions on Energy Conversion, Vol. 16, No. 2, pp. 148 - 154, 2001.

[10] J.H.R. Enslin et al., "Harmonic interaction between large numbers of photovoltaic inverters and the distribution network," in 2003 IEEE Bologna Power Tech Conference Proceedings, Bologna, Italy, 2003.

[11] F. Batrinu, G. Chicco, J. Schlabbach, and F. Spertino, "Impacts of grid-connected photovoltaic plant operation on the harmonic distortion," in IEEE Mediterranean Electrotechnical Conference, 2006. MELECON 2006, Benalmádena (Málaga), Spain, 2006, pp. 861 - 864.

[12] G. Chicco, J. Schlabbach, and A.F. Spertino, "Characterisation and assessment of the harmonic emission of grid-connected photovoltaic systems," in Power Tech, 2005 IEEE Russia, 2005, pp. 1 - 7.

[13] T. Ackermann, V. Knyazkin, "Interaction between distributed generation and the distribution network: operation aspects," in IEEE/PES Transmission and Distribution Conference and Exhibition 2002: Asia Pacific, 2002, pp. 1357 - 1362.

[14] A.D. Simmons and D.G. Infield, "Current waveform quality from grid-connected photovoltaic inverters and its dependence on operating conditions," Progress in Photovoltaics: Research and Applications, vol. 8, no. 4, pp. 411–420, July/August 2000.

[15] M. Aiello, A. Cataliotti, S. Favuzza, G. Graditi, "Theoretical and experimental comparison of total harmonic distortion factors for the evaluation of harmonic and interharmonic pollution of grid-connected photovoltaic systems," IEEE Transactions on Power Delivery, Vol. 21, No. 3, pp. 1390 - 1397 , July 2006.

[16] P.J.M. Heskes and J.H.R. Enslin, "Power Quality Behaviour of Different Photovoltaic Inverter Topologies," in 24th International Conference PCIM-2003, Nürnberg, Germany, 2003.

[17] J.F.G. Cobben, "Power Quality Implications at the Point of Connection," Technische Universiteit Eindhoven, Eindhoven, Netherlands, Dissertation 2007.

[18] C. Bendel et al., "EMC and Safety Design for Photovoltaic Systems," European Commission, Kassel, Germany, Contract JOR3-CT98-0246, 2002.

[19] J.F.G. Cobben, "PV and PQ, interaction en limits," Technical University Eindhoven, Eindhoven, Final Year Thesis 2002.

[20] M.A. Eltawil, Z. Zhao, "Grid-connected photovoltaic power systems: Technical and potential problems—A review," Renewable and Sustainable Energy Reviews, Vol. 14, No. 1, pp. 112–129, January 2010.

[21] P.P. Barker and R.W. De Mello, "Determining the impact of distributed generation on power systems. I. Radial distribution systems," in IEEE Power Engineering Society Summer Meeting, 2000, pp. 1645 - 1656.

[22] L.M. Tolbert, F.Z. Peng, and T.G. Habetler, "Multilevel converters for large electric drives," IEEE Transactions on Industry Applications, Vol. 35, No. 1, pp. 36 - 44, 1999.

[23] M. Calais, J. Myrzik, T. Spooner, and V.G. Agelidis, "Inverters for single-phase grid connected photovoltaic systems-an overview ," in IEEE 33rd Annual Power Electronics Specialists Conference, pesc 02, 2002, pp. 1995 - 2000.

[24] J.H.R. Enslin and P.J.M. Heskes, "Harmonic interaction between a large number of distributed power inverters and the distribution network," IEEE Transactions on Power Electronics, vol. 19, no. 6, pp. 1586 - 1593 , November 2004.

[25] N. Mohan, T. Undeland, and W. Robbins, Power Electronics: Converters, Applications, and Design. USA: John Wiley &Sons, 1995.

[26] C. Bendel, P. Funtan, J. Kirchof, and G. Klein, "Sicherheitsaspekte bei Einsatz und Prüfung von transformatorlosen Wechselrichtern— Ergebnisse aus dem Projekt SIDENA," in Proceedings 21 Symposium Photovoltaische Solarenergie, Staffelstein, Germany, 2006.

[27] International Energy Agency, "Utility aspects of grid connected photovoltaic power systems," IEA, Photovoltaic Power Systems Programme. Task 5 IEA-PVPS T51: 1998, 1998.

[28] International Energy Agency, "Demonstration test results for grid interconnected photovoltaic power systems," IEA, Photovoltaic Power Systems Programme. Task 5 IEA-PVPS T5-02: 1999, 1999.

[29] R. Hacker, J. Thornycroft, D. Munro, and E. Rudkin, "Co-ordinated experimental research into PV power interaction with the supply network- PHASE I," Energy Technology Support Unit (ETSU), ETSU S/P2/00233, 1999.

PAPER - VII

Modelling EVs in residential distribution grid with other nonlinear loads

J. Niitsoo, Student Member, IEEE, P. Taklaja, Member, IEEE, I. Palu, I. Kiitam
Department of Electrical Power Engineering
Tallinn University of Technology
Tallinn, Estonia
jaan.niitsoo@ttu.ee; paul.taklaja@ttu.ee; ivo.palu@ttu.ee; ivar.kiitam@ttu.ee

***Abstract*—Unregulated charging of electric vehicles (EVs) could impact load characteristics in distribution networks. Difficulties with power quality may appear in residential networks where the grid is weak. For providing greater capabilities to EV charging, the power quality aspects have to be considered in addition to the load increase analysis. This paper discusses the harmonic content of the EV charging load and the changing power quality indicators in the residential distribution network. Actual EV charging measurement results are presented and averaged current harmonic amplitude and phase angles values for EV charging load modelling are proposed. Results of different modelling scenarios are presented and analyzed. The results of the study showed an extensive harmonic distortion in residential load current and voltage distortion at the substation's busbar. The results pointed out in the paper can be further used for modelling the actual harmonic loads of the EVs in distribution networks.**

Keywords—current measurement, electric vehicles, load modelling, power quality, power system harmonics

I. INTRODUCTION

The appliances and electric devices connected to the public mains network are designed to operate with a sinusoidal voltage at rated power. However, many of the connected loads are of nonlinear type, meaning that they draw current with a distorted sine waveform. This causes distorted sine voltage drop, thus resulting in distorted network voltage waveform. The overall distortion level is described by total harmonic distortion (THD).

It has to be pointed out that the THD_I (total harmonic distortion of current) does not reveal the levels of the individual harmonics, which could still exceed the limits for specific harmonics regardless of THD_I value. For the correct estimation of the harmonic levels, phase angle values of individual harmonics are also required in addition to magnitudes. It is reported that 10% smaller harmonic current magnitudes can be seen compared to the simple summing of magnitudes [1].

Some loads draw current with total harmonic distortion over 100%, but their active power consumption is not as significant when compared to other harmonic generating apparatuses [2]. In this case, harmonic distortion may increase significantly when numerous harmonic emitting devices are utilized in bulk.

Chargers of the modern EVs that are intended for charging at home are actually operating very close to the levels of the usual residential customers and drawing 10 – 15 A of current [3]. The charging of EVs could bring severe addition of power electronic load which generates harmonics and associated power quality issues in residential networks.

The total impact depends on the number of appliances, their power ratings, and their harmonic diversity. Harmonic angle diversity is also relevant when multiple appliances are operating simultaneously, creating either reinforcement or cancellation of harmonic magnitudes [4]. The attenuation effect is dependent only on the phase angle, but the effect's severity is dependent on the magnitude of the harmonic voltage [5].

Nonlinear loads absorb distorted currents which flow through the impedances of the power distribution system and result in distortion of system bus voltage [6]. Harmonics travel upwards within the network and affect the voltage waveform, which may become notably distorted, deviating extensively from a proper sinusoidal signal.

Distorted voltage and current in the distribution system may bring along unwanted effects, e.g. overloading, over-voltages, mechanical stress, malfunction of critical control and protection equipment and lower the efficiency of appliances. Distortion affects all customers fed through the point of common coupling (PCC).

The share of nonlinear loads is growing rapidly worldwide. It has been estimated that in 2012, 60% of the power system loads in USA were nonlinear loads [4]. Therefore, due to increase in this number and addition of EVs, the power quality research observing the corresponding challenges is becoming more important than ever before.

The purpose of the present study is to demonstrate and analyze possible power quality situations in the observable residential distribution network. The paper examines the impact of nonlinear domestic loads and EVs in distribution grid. For the analysis, measured power consumption and current waveforms of different home appliances and EVs have been used. Magnitudes and phase angles of each harmonic up to the 50th order were applied for all modelled loads. The main purpose of this paper is the use of actual measurement data of different devices for modelling the effects on the residential distribution network and give an estimate of the important values for further modelling of EVs.

978-1-4799-7993-6/15/$31.00 ©2015 IEEE

II. DISTORTION ANALYSIS

In electrical power networks, distorted sine wave can be observed by dividing it into numerous components, each having an integer-multiple frequency of the mains frequency. For different waveforms, there is a different harmonic content present, referring to individual harmonic magnitudes and phase shift compared to the mains frequency component. The measurements of loads presented onwards in this paper are all indicated as magnitudes and phase shift of each individual harmonic up to the 50th order.

The distortions can be observed individually by comparing different harmonic components and calculating harmonic distortion (HD). A more general approach to quantifying the distortions is using the total harmonic distortion level (THD). The total harmonic distortion can be observed as current harmonic distortion THD_I and/or voltage distortion THD_U. Another option is to observe the harmonic distortion as a geometrical sum of positive (THD1), negative (THD2) and zero (THD0) sequence component distortions as total harmonic distortion THDtot. These harmonic distortion indicators can be calculated using (1), (2), (3) and (4), respectively.

$$HD = \frac{i_i}{i_1} \tag{1}$$

$$THD_I = \frac{1}{i_1}\sqrt{i_{rms}^2 - i_1^2} \times 100 \tag{2}$$

$$THD_U = \frac{1}{u_1}\sqrt{u_{rms}^2 - u_1^2} \times 100 \tag{3}$$

$$THD_{tot} = \sqrt{THD_1^2 + THD_2^2 + THD_0^2} \tag{4}$$

EV batteries require DC for charging, but all uncontrolled rectifiers inject a high content of current harmonics into AC power networks. Based on literature, it can be concluded that over time, the amount of distortion from EV charging has decreased. The measurement in the 90's showed that the use of uncontrolled or low-control rectifiers causes average THD_I of 50% [7]. It should be pointed out that the chargers with high THD_I represent the older topologies, not likely used in modern vehicles.

One option for obtaining the harmonic patterns of the EV chargers is to perform actual case measurements of the EV charging currents. The charging profiles of the EVs have been researched before [8, 9, 10]. Measurement results, however, have not revealed the individual harmonic magnitude and phase angle values in sufficient detail. Therefore in the present paper, real measurements were conducted with different EVs and distortion analysis modelling was performed using real harmonic current values in the current source model.

III. METHOD

The residential distribution network and the loads for assessing the load flow were modelled in DIgSILENT Power Factory software. The model consisted of three-phase residential loads at 0.4 kV voltage level composed of different single phase loads. Single phase EV charger's loads were also connected to the residential load busbar in different modelling scenarios. The schematic of one residential load model is given in Fig. 1.

The composed residential network and loads were connected to the distribution network substation via 1.4 km long overhead line (OHL) (Fig. 2). Distribution network substation was connected to 10 kV network with short-circuit power of 200 MVA and short-circuit current 11.5 kA. High voltage (HV) busbar is modelled as a slack bus. Transformer used in the distribution substation was modelled with the following parameters:

- nominal power 25 kVA;
- relative short circuit voltage 4.5%;
- mag. impedance/ short circuit impedance ratio 3;
- vector group Yyn.

Several parameters used in the simulation were selected on the basis of all the objects in Elektrilevi Ltd.'s (Estonia's main distribution grid operator) network which have been marked as power quality problematic issues for 1st of July in 2013. The length of OHL between substation and customer's PCC was taken as an average of all the lines between substations and customers with power quality problems. The diameter of the line and nominal power of transformer were selected as most often occurring in the list of objects.

The HV bus harmonic voltage distortion from external grid was modelled. Harmonic voltage amplitudes and phase angles up to the 50th order were taken from a measurement conducted by Elektrilevi at one of the objects where power quality issues were stated. Overall harmonic voltage distortion at 10 kV bus was measured and modelled around 2%, which is a common value for this grid.

For modelling EV loads, actual charging process of five different EVs were measured earlier. All vehicles were produced in 2012 or 2013 and are commercially available from the internationally well-known car manufacturers. The EV chargers of different EV manufacturers and types have a quite different harmonic pattern. The load models of averaged values were composed based on the measurements, including the amplitudes and angles of harmonics up to the 50th order. For the sake of discretion, the models of the cars will not be associated with particular results and the general data of the measured EVs is denoted in the following paragraphs using EV 1 to EV 5.

In order to model the network response of nonlinear loads, 14 different home appliances were measured in addition to EVs. The results of the corresponding measured active and reactive power level values, harmonic current magnitudes and harmonic current phase shift angle values of measured devices are presented in [11, 12]. Modelled devices were divided in a matter where similar active power consumption was seen in every phase. In the model, it is presumed to be the worst case scenario where all the nonlinear devices are working and no coincidence factors were taken into account.

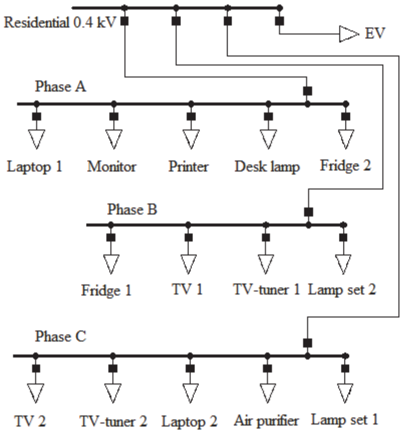


Fig. 1. Schematic of residential load model

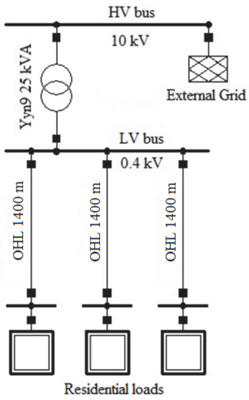


Fig. 2. Schematic of distribution grid model

For the purpose of assessing the effect of adding EV charging loads on the grid, the current distortions at residential load 0.4 kV feeders and voltage distortions at distribution network substation's low-voltage busbar were observed.

IV. MEASUREMENT RESULTS OF EVS

For this study, charging of five different EVs was conducted and the results are presented as follows. Firstly, general data is given in Table I, where power and THD values during constant power charging time are presented. The ramp-up and topping charging values have not been presented at this time, as although the THD_I values can be higher, the actual harmonic currents values are lower than for the constant power mode charging.

According to Table I it may be concluded that current distortion of EVs was similar to results in aforementioned literature. Three EVs out of five had current distortion around 10…12% and two had substantially lower values, around 3…4%.

TABLE I. GENERAL DATA FOR EVS DURING CONSTANT POWER

EV	Active power [kW]	Reactive power [kVAr]	*THD_I*
1	2.2	0.2	4.2
2	2.4	0.5	12.3
3	2.9	0.2	3.4
4	2.4	0.1	10.5
5	2.2	0.4	11.2
mean	2.5	0.3	8.1

TABLE II. HARMONIC CURRENT AMPLITUDES (%) OF EVS

Nr	EV 1	EV 2	EV 3	EV 4	EV 5	Arithmetic Mean
1	100	100	100	100	100	100
3	8.7	11.9	3.3	2.6	11.1	7.5
5	3.7	0.4	0.9	2	2.3	1.9
7	3.1	0.6	0.9	1.1	1.4	1.4
9	1.2	0.6	0.2	0.5	1.5	0.8
11	0.8	1.1	0.9	0.7	1	0.9
13	1.7	1.1	1.3	0.9	0.8	1.2
15	0.4	0.6	0.3	0.3	0.9	0.5
17	0.4	0.5	0.1	0.1	0.2	0.3
19	0.7	0.3	0.1	0.3	0.2	0.3
21	0.8	0.3	0.4	0.9	0.4	0.6
23	0.4	0.2	0.5	0.8	0.1	0.4
25	0.3	0.2	0.4	0.7	0.1	0.3
27	0	0.5	0.1	0.5	0.3	0.3
29	0.7	0.2	0.2	0.6	0.3	0.4
31	0.7	0.1	0.2	0.6	0.1	0.4
33	0.8	0.3	0.2	0.3	0.2	0.4
35	0.2	0.2	0.2	0.5	0.2	0.2
37	0.1	0.1	0.1	0.4	0.2	0.2
39	0.2	0.2	0.2	0.5	0.2	0.3
41	0.1	0.1	0.1	0.4	0.2	0.2
43	0.1	0.1	0.2	0.4	0.2	0.2
45	0.3	0.2	0.1	0.4	0.2	0.2
47	0.1	0.1	0.1	0.3	0.2	0.2
49	0.1	0.1	0.1	0.3	0.2	0.1

TABLE III. HARMONIC CURRENT PHASE ANGLES (°) OF EVS

Nr	EV 1	EV 2	EV 3	EV 4	EV 5	Geometric Mean
1	0	0	0	0	0	0
3	8	33	158	327	6	39
5	157	180	335	338	294	248
7	255	269	205	213	299	245
9	46	120	287	320	126	145
11	326	256	20	67	221	120
13	30	305	298	334	26	119
15	257	199	30	194	142	133
17	207	162	246	247	291	226
19	40	168	313	55	219	121
21	154	304	165	217	166	195
23	278	110	315	32	196	144
25	60	225	127	191	317	160
27	200	345	190	47	139	153
29	138	161	93	152	228	148
31	268	316	224	324	195	260
33	44	165	58	108	105	86
35	144	156	171	288	204	187
37	295	270	158	75	339	200
39	273	45	151	228	109	136
41	321	258	321	45	234	195
43	99	42	99	193	241	114
45	203	187	252	185	132	188
47	165	309	49	149	258	157
49	153	93	211	313	23	117

The characteristics of individual current harmonic magnitudes and phase angles for odd harmonics during the constant power charging are presented in Table II and Table III, respectively. Graphical illustration for third and fifth harmonics as most significant individual harmonics are seen in Fig. 3 and Fig. 4, respectively, where X and Y coordinates are calculated with formulas (5) and (6).

$$X = A \times \cos \alpha \tag{5}$$

$$Y = A \times \sin \alpha \tag{6}$$

Mains frequency current phase angles are taken zero as in ideal case and other angles are calculated in relation to mains current. In the paper [13], phase angles for the first four EVs are presented in relation to voltage.

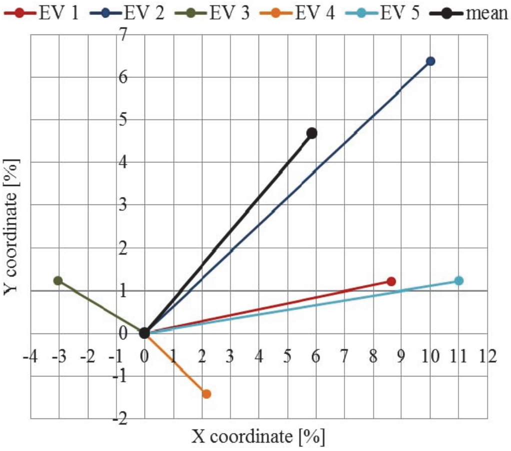


Fig. 3. Third current harmonics of EVs

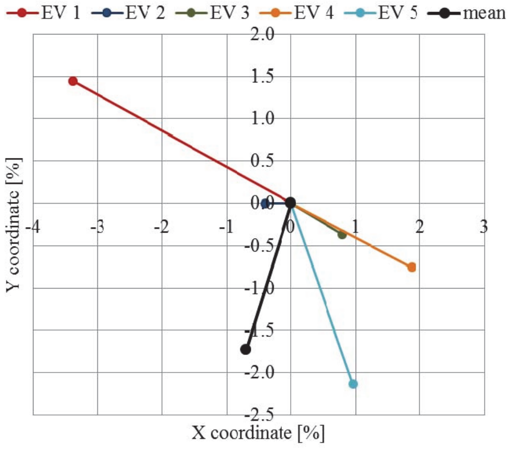


Fig. 4. Fifth current harmonics of EVs

It is clear that the different harmonic amplitudes and phase angles are rather different for the various EVs. Therefore two simulations with different EVs may lead to entirely different results. For more successful modelling, the mean values based on five EVs are presented. The arithmetic mean of amplitudes (7) and geometric mean for phase angles (8) was calculated.

$$AM = \frac{1}{n}(a_1 + a_2 + \ldots + a_n) \tag{7}$$

$$GM = \sqrt[n]{a_1 \times a_2 \times \ldots \times a_n} \tag{8}$$

In Table IV, average harmonic currents of measured EVs for all orders up to the 50th are presented. Different values are given for distinguishable harmonic orders and groups with similar dimension. Phase angles of current harmonics are presented in Table V, where average values were calculated for four quarters: phase angles between 0…90, 90…180, 180…270 and 270…360 degrees separately for odd and even harmonics and 3rd and 33rd because of their discrepancy.

TABLE IV. AVERAGE HARMONIC CURRENT AMPLITUDES (%)

Order	Amplitude
2	0.4
3	7.5
4;6;8;10	0.2
5	1.9
7	1.4
9;11;13;15	0.65
12…50 even	0.06
17…49 odd	0.25

TABLE V. AVERAGE HARMONIC CURRENT PHASE ANGLES (°)

Order	Angle
2; 4; 8; 12; 14; 18; 22; 28; 32; 36; 40; 42; 46	200
3	40
5; 7; 17; 21; 31; 35; 37; 41; 45	210
6; 10; 16; 20; 24; 26; 30; 34; 38; 44; 48; 50	150
9; 11; 13; 15; 19; 23; 25; 27; 29; 39; 43; 47; 49	140
33	90

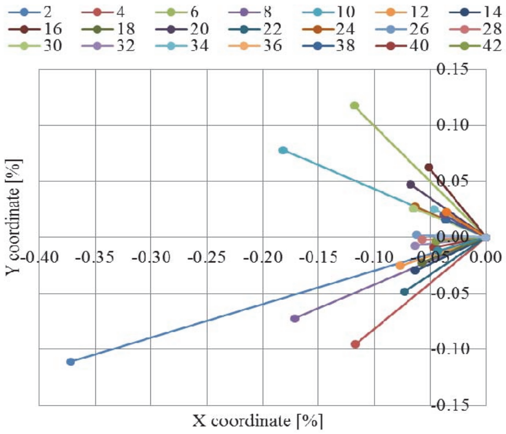


Fig. 5. Average even current harmonics of EVs

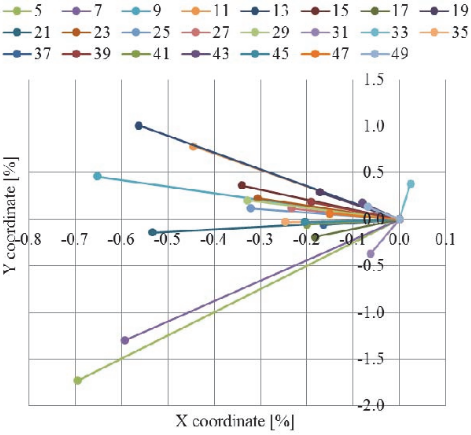


Fig. 6. Average odd current harmonics of EVs

Average even harmonics of mean EV are graphically presented in Fig. 5. It can be observed that all phase angles of mean EV remained between 130 and 220 degrees and authors hereby proposed two different values for even harmonics as already given in Fig. 4.

Average odd harmonics of mean EV are graphically represented in Fig. 6, except the third harmonic, which was significantly greater than all others. It can be seen that most of the phase angles of the mean EV remained in the second and third quarters. As already mentioned, the 3rd and 33rd harmonics were distinctive. So four different phase angle values for odd harmonics are proposed.

V. MODELLING RESULTS

Modelling was conducted in five different scenarios for EV 5. In the first three scenarios only one EV was connected, but in different phases for each time. In the fourth scenario three EVs were connected to phase C and in the fifth scenario all three EVs were connected to different phases.

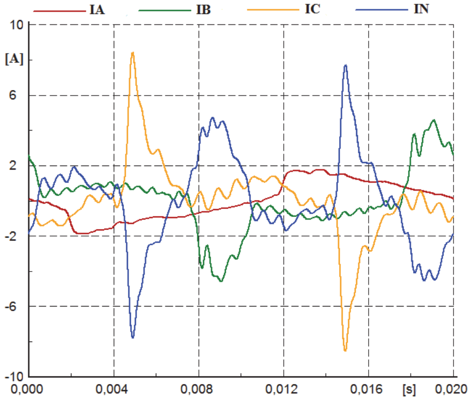


Fig. 7. Currents in 0.4 line without EV load

Current curves before addition of EVs are depicted in Fig. 7. Values of harmonic distortions are given in tables later on.

A. Modelling with EV 5

Modelled current THD I values in low voltage OHL are given in Table VI. It can be seen that the distortion in current decreased notably when EV 5 was connected compared to the situation without EV 5. This was due to the fact that the EV was the dominant load and much greater than other nonlinear loads connected together. Distortion in the neutral wire still remained quite high, which may lead to severe consequences. Illustration of current curves in case EV 5 is connected to phase C is shown in Fig. 8.

Voltage distortions at the substation's busbar are presented in Table VII, where corresponding values of EV 5 currents can be seen. Decrease was only in two first cases. In the case where EV 5 was connected to phase C, a slight increase of distortion was observed. In phase C, the value of THD I was out of limits fixed in [14] already without EV connection.

TABLE VI. CURRENT *THD_I* VALUES IN OHL (ONE EV 5 CONNECTIONS)

	Without EV	**One EV 5 in phase A**	**One EV 5 in phase B**	**One EV 5 in phase C**
THD_A	31.7	11.5	31.7	31.7
THD_B	89.6	89.6	12.3	89.6
THD_C	135.6	135.6	135.6	14.9
THD_N	351	16.9	19	21.4
THD_tot	101.5	19.8	17.7	17.6

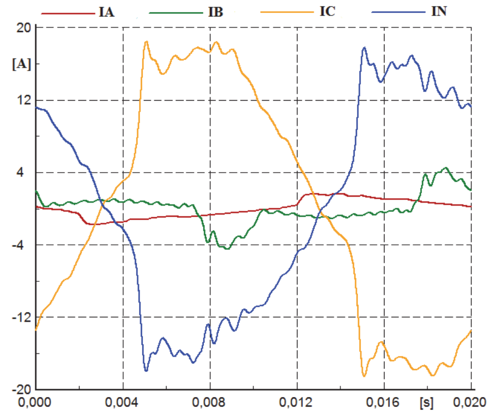


Fig. 8. Current curves in case of EV 5 connected to phase C

TABLE VII. VOLTAGE *THD_U* VALUES AT SUBSTATION (ONE EV 5 CONNECTIONS)

	Without EV	**One EV 5 in phase A**	**One EV 5 in phase B**	**One EV 5 in phase C**
THD_A	3.8	3.1	3.4	3.8
THD_B	7	6	6.8	6.4
THD_C	8.3	6.7	7.1	8.9
THD_tot	6.7	5.5	6	6.7

TABLE VIII. CURRENT *THD_I* VALUES IN FIRST OV LINE (THREE EV 5 CONNECTIONS)

	Without EV	**Three EV 5s in phases C**	**Three EV 5s in phases A, B, C**
THD_A	31.7	31.7	31.7
THD_B	89.6	89.6	89.6
THD_C	135.6	14.9	14.9
THD_N	351	21.1	21.5
THD_tot	101.5	17.5	17.6

TABLE IX. VOLTAGE *THD_U* VALUES AT SUBSTATION (THREE EV 5 CONNECTIONS)

	Without EV	**Three EV 5s in phases C**	**Three EV 5s in phases A, B, C**
THD_A	3.8	4.7	2.7
THD_B	7	7.7	5.6
THD_C	8.3	11.2	6.4
THD_tot	6.7	8.2	5.2

In case of three EV 5s connection current distortions decreased as like with one EV. Corresponding results are presented in Table VIII, where distortions are observed only at one 0.4 kV line to residential load. It can be concluded that EV loads on other feeders do not notably affect current distortions in the observable line and the results are comparable to the case with only one EV.

Voltage distortions for corresponding scenarios are presented in Table IX, where a remarkable increase of THD U can be observed when EVs at all feeders were connected to the same phase. Voltage distortions in the situation where three EVs are connected simultaneously into different phases, were even lower than in case of no EVs. The distortion in the neutral wire was smallest compared to all other cases due to harmonic cancellation.

VI. DISCUSSION AND CONCLUSIONS

For determining the impact of current harmonics on the network and the voltage harmonics, the actual harmonic current values would have to be used. Secondly, modern household devices tend to contain more power electronic circuits and therefore an increase of harmonic currents can also be expected even without the charging of EVs.

The EV chargers of various EV manufacturers and types are very likely to have different harmonic patterns, meaning they have different individual current harmonic magnitude levels and phase angle values. For this purpose, general values for further modelling of mean EVs were presented in this paper. Modelling comparison with one actual EV showed that those results are adequate, but in subsequent papers, modelling with other EVs should be executed and a comparison of results included.

It is assumed, by observing a number of studies, that an EV penetration rate of 20…25% would be tolerable to present distribution networks [15]. This figure is aimed to apply for both overload as well as power quality issues. Hopefully, the results for mean EV presented in this paper could lead to more accurate estimations.

REFERENCES

[1] L. Kütt, E. Saarijärvi, M. Lehtonen, H. Mõlder and J. Niitsoo, "A Review of the Harmonic and Unbalance Effects in Electri-cal Distribution Networks due to EV Charging," in 13th International Conference on Environment and Electrical Engineering (EEEIC), Wroclaw, Poland, 2013.

[2] J. Niitsoo and I. Palu, "Distorted load impacts on distribution grid," in Proceedings of the 12th International Scientific Conference Electric Power Engineering 2011, Kouty nad Desnou, Czech Republic, 2011.

[3] S. Shao and M. Pipattanasomporn, "Demand Response as a Load Shaping Tool in an Intelligent Grid With Electric Vehicles," IEEE Transactions on Smart Grid, vol. 2, no. 4, pp. 624-631, 2011.

[4] M. Rawa, D. Thomas and M. Sumner, "Simulation of non-linear loads for harmonic studies," in 11th International Conference on Electrical Power Quality and Utilisation (EPQU), Lisbon, Portugal, 2011.

[5] J. Yong, L. Chen and S. Chen, "Modeling of Home Appliances for Power Distribution System Harmonic Analysis," IEEE Transactions on Power Delivery, vol. 25, no. 4, pp. 3147 - 3155 , October 2010.

[6] M. Aiello, A. Cataliotti, S. Favuzza and G. Graditi, "Theoretical and experimental comparison of total harmonic distortion factors for the evaluation of harmonic and interharmonic pollution of grid-connected photovoltaic systems," IEEE Transactions on Power Delivery, vol. 21, no. 3, pp. 1390 - 1397 , July 2006.

[7] S. H. Berisha, G. G. Karady, R. H. Ahmad, R. Hobbs and D. Karner, "Current harmonics generated by electric vehicle battery chargers," in Proceedings of the 1996 International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth, 1996., 1996.

[8] J. Meyer, S. Hahle, P. Schegner and C. Wald, "Impact of electrical car charging on unbalance in public low voltage grids," in 11th International Conference on Electrical Power Quality and Utilisation (EPQU), 2011.

[9] N. Melo, F. Mira, A. De Almeida and J. Delgado, "Integration of PEV in Portuguese distribution grid: Analysis of harmonic current emissions in charging points," in 11th International Conference on Electrical Power Quality and Utilisation (EPQU), 2011.

[10] J. Trovao, P. Pereirinha, L. Trovao and H. Jorge, "Electric Vehicles Chargers Characterization: Load Demand and Harmonic Distortion," in International Conference on Electrical Power Quality and Utilisation (EPQU), 2011.

[11] J. Niitsoo, J. Kilter, I. Palu, P. Taklaja and L. Kütt, "Harmonic Levels of Domestic and Electrical Vehicle Loads in Residential Distribution Networks," in Proceedings of AFRICON 2013, Mauritius, 2013.

[12] J. Niitsoo, I. Palu, J. Kilter, P. Taklaja and T. Vaimann, "Residential Load Harmonics in Distribution Grid," in Proceedings of 3rd International Conference on Electric Power and Energy Conversion Systems (EPECS 2013), Istanbul, Turkey, 2013.

[13] L. Kütt, E. Saarijärvi, M. Lehtonen, H. Mõlder and J. Niitsoo, "Current Harmonics of EV Chargers and Effects of Diversity to Load Current Distortions in Distribution Networks," in International Sustainable Mobility and Connected Vehicle Leadership Forum VEC-IEVC 2013 , Silicon Valley, CA, USA, 2013.

[14] EN 50160:2010, "Voltage Characteristics in Public Distribution Systems. European standard.," 2010.

[15] L. Kütt, E. Saarijärvi, M. Lehtonen, H. Mõlder and J. Niitsoo, "A Review of the Effects of Electric Vehicle Charging to Distribution Network Operation and Power Quality," in Proceedings of The 8th International Conference on Electrical and Control Technologies, Kaunas, Lithuania, 2013.

PAPER - VIII

Smart Grid and Renewable Energy, 2015, 6, 148-163

http://dx.doi.org/10.4236/sgre.2015.66014

Power Quality Issues Concerning Photovoltaic Generation in Distribution Grids

Jaan Niitsoo[1], Marek Jarkovoi[2], Paul Taklaja[1], Joni Klüss[3], Ivo Palu[1]

[1]Department of Electrical Power Engineering, Tallinn University of Technology, Tallinn, Estonia
[2]Department of Electrical Engineering, Tallinn University of Technology, Tallinn, Estonia
[3]Department of Electrical Engineering and Automation, Aalto University, Helsinki, Finland
Email: jaan.niitsoo@ttu.ee

Received 8 May 2015; accepted 16 June 2015; published 19 June 2015

Abstract

Unregulated utilization of renewable generation including residential photovoltaic (PV) systems can have a significant impact on load characteristics in distribution networks. For improving PV generation capabilities, power quality aspects have to be coordinated with present load characteristics. This paper discusses the harmonic content of PV generation and the influence to power quality indicators in residential distribution networks. PV generation measurement results including current harmonic amplitude and phase angle values are presented. Results of different modelling scenarios are analysed and a simplified model of harmonics in PVs is offered. The results of the study showed a moderate additional harmonic distortion in residential load current and voltage distortion at the substation's busbar when PVs were added. Novelty of the paper is that harmonic current values at higher orders are presented and analysed. The results pointed out in this paper could be further used for modelling the actual harmonic loads of the PVs in distribution networks.

Keywords

Current Measurement, Load Modelling, Photo Voltaic, Power Quality, Power System Harmonics

1. Introduction

Harmonic voltage levels in low-voltage networks represent an important aspect of power quality. From the point of view of electromagnetic compatibility, they must be kept within the compatibility levels to enable satisfactory

How to cite this paper: Niitsoo, J., Jarkovoi, M., Taklaja, P., Klüss, J. and Palu, I. (2015) Power Quality Issues Concerning Photovoltaic Generation in Distribution Grids. *Smart Grid and Renewable Energy*, **6**, 148-163.
http://dx.doi.org/10.4236/sgre.2015.66014

operation of all the equipment supplied by the network. Furthermore, since electricity is also defined as a product, utility companies could be held responsible for excessively high harmonic levels and any resulting damage to customers' property [1]. As such, in Europe, the harmonic voltage limits specified in EN 50160 standard should be met.

Distorted voltage and current in the distribution system may result in undesirable effects, such as overloading, over-voltages, mechanical stress, malfunction of critical control and protection equipment, and lower the efficiency of appliances. Distortion affects all customers fed through the point of common coupling (PCC).

The development of electronics for the general public as well as industrial applications has led to a rapid increase in the number of non-linear loads. In addition to the increased number of electronic devices, also resistive devices such as incandescent lamps are ever more frequently replaced by energy saving lamps utilizing non-linear elements. For example, depending on type and brand, switching power supplies absorb distorted currents which flow through the impedances of the power distribution system and result in distortion of system bus voltage [2]. Harmonics can travel upwards within the network and affect the grid voltage waveform, which may become notably distorted, deviating extensively from a proper sinusoidal signal.

Residential photovoltaic (PV) generators are the dominant renewable energy source in urban and metropolitan areas. This technology is enjoying rapid growth due to a combination of subsidies, the abundance of sunshine, and the low impact of the technology on the urban landscape [3]. As photovoltaic systems incorporate power converters, which are harmonic generating devices, they will have an influence on the power quality of the supply network. High harmonic distortion levels have also been observed in certain remote regions such as winter sports resorts and rural areas far away from substations.

Distributed generation (DG) impacts the network. This impact is dependent on the location, characteristics of the distributed energy source, related power electronic device, network configurations, voltage level at the connection point, and the capacity of DG relative to load consumption [3]. Consequently, utilities are faced with the risk that the permissible levels defined in standard EN 50160 will be exceeded in a significant number of networks in the future [1]. It has been estimated that already in 2012, 60% of the power system loads in USA were nonlinear loads [4].

Over the past decade, power quality (PQ) issues have become increasingly important in the distribution grid with the widespread use of non-linear electronic equipment. The most cited PQ problems that may arise due to grid connected PV generation are voltage dips and fluctuations, harmonic distortion, transient phenomena and reverse power flow. These effects result in potential damaging of sensitive electronic equipment and capacitor banks, overheating of transformers and neutral conductors and additional losses in the power system. Degraded power quality entails additional costs for both the electricity distributor and its customers [3] [5].

The purpose of the present study is to demonstrate and analyse possible power quality situations in a residential distribution network by examining the impact of nonlinear domestic loads and PV inverters. For the analysis, measured power consumption and current waveforms of different home appliances and PV inverters have been used. Novelty is that magnitudes and phase angles of each harmonic up to the 50th order were applied for all modelled loads. The main purpose of this paper is to present the use of actual measurement data from different devices for modelling the effects on the residential distribution network and give an estimation of the important values for further modelling.

2. Theory

In electrical power networks, a distorted sine wave can be divided into numerous components, each having an integer-multiple frequency of the main frequency. Different waveforms have different harmonic content referring to individual harmonic magnitudes and phase shift relative to the main frequency component. Hereafter in this paper, the presented measurements of loads are all indicated as magnitudes and phase shift of each individual harmonic up to the 50th order.

Distortions can be observed individually by comparing different harmonic components and calculating harmonic distortion (HD). A more general approach to quantifying the distortions is using the total harmonic distortion level (THD). Total harmonic distortion can be expressed separately for current harmonic distortion as $\mathrm{THD_I}$ and for voltage distortion as $\mathrm{THD_U}$. The harmonic distortion indicators can be calculated using corresponding Equations (1), (2), (3) and (4),

$$\mathrm{HD_I} = \frac{i_i}{i_1} \tag{1}$$

$$\mathrm{HD_U} = \frac{u_i}{u_1} \tag{2}$$

$$\mathrm{THD_I} = \frac{1}{i_1}\sqrt{i_{rms}^2 - i_1^2} \times 100 \tag{3}$$

$$\mathrm{THD_U} = \frac{1}{u_1}\sqrt{u_{rms}^2 - u_1^2} \times 100 \tag{4}$$

where i_i is current of order i, i_1 is current of 1st order, u_i is voltage of order i and u_1 is voltage of 1st order.

It has to be pointed out that $\mathrm{THD_I}$ (total harmonic distortion of current) does not reveal the magnitudes of individual harmonics, which could still exceed the limits for specific harmonics regardless of $\mathrm{THD_I}$ value. For the correct estimation of the harmonic levels, phase angle values of individual harmonics are also required in addition to magnitudes. It is reported that 10% smaller harmonic current magnitudes can be seen when phase angle information is included compared to the simple summing of magnitudes without phase angle values [6].

Harmonic currents in a network largely depend on the harmonic characteristics of the connected devices, their phase angles and the background distortion level of the supply voltage. Harmonic current emission spectrum information of a device (or a group of devices connected at a PCC) under different supply voltage conditions is very useful for analysing the device's influence in the network. This can be further utilised to determine the probability density profile of each order harmonic currents in the network considering their "time-varying" behaviour [7].

Some loads draw current with total harmonic distortion over 100%, but their active power consumption is not as significant when compared to other harmonic generating devices [8]. In such cases, harmonic distortion may increase significantly when numerous harmonic emitting devices are utilized in bulk. The total impact depends on the number of appliances, their power ratings, and their harmonic diversity. Harmonic angle diversity is also relevant when multiple appliances are operating simultaneously, creating either emergence or cancellation of harmonics [4]. The attenuation effect is dependent only on the phase angle, but the effect's severity is dependent on the magnitude of the harmonic voltage [9].

The harmonic generation of a PV system depends on the inverter technology, solar irradiance, temperature, loads, and the supply system characteristics. The harmonic distortion generated in PV plants can occur as a result of intrinsic and extrinsic effects. Intrinsic harmonic distortions are related to inverter deficiencies, e.g. components and control loop nonlinearities, measurement inaccuracies, and limited pulse-width modulation (PWM) resolution. Connection to a weak and distorted electrical grid can be considered an extrinsic effect on the output waveform of a PV plant. A distorted voltage acts like a disturbance in the inverter control system, causing distortion of the current waveform generated by the inverter [10].

Several factors affect the power quality characteristics of the PV inverter output current. Both the current THD and the output reactive power are related to the output active power levels, which in turn are strongly dependent on solar irradiance levels. Most of the inverters consume or feed reactive power into the network depending on their output active power and their technology. During operation at low solar irradiance levels (e.g. sunrise, sunset, cloudy days), current THD values can increase rapidly, since the THD factor is inversely proportional to the output active power of the PV inverters. Nevertheless, THD is notably reduced as the output active power of the PV Inverters increases and reaches its nominal value. The intrinsic characteristics of the control circuit and nonlinear components of PV inverters may explain the current distortion behaviour in the low power generation stages [10] [11].

Varying power density of renewable energy resources (*i.e.* irradiance level and temperature in PV conversion) potentially cause voltage and frequency variation or sag/swell patterns in the grid. Also, application of power converters as interfaces between energy sources and the grid and their interaction with other system components may cause high harmonics distortion [12].

In small and distributed or decentralized PV controlled systems, the CSIs (current source inverters) can generate highly distorted current waveforms so that their cumulative effect in high penetration PV systems can create hot spots within transformers; ultimately generating excessive eddy or copper loss [13].

The differing influences of harmonics in distribution networks are not necessarily visible/evident initially. However, harmonics can have serious long-term consequences, of which the most important ones are [14]:

- Overloading of consumer's electrical installations and power system elements by higher order frequencies of currents and voltages;
- Increased heating of neutral conductors caused by triple current harmonics (frequency multiplier of number 3). The increased level of the triple harmonics in the neutral conductor can cause serious damage and even lead to fires because the neutral conductor is not usually overload protected;
- Increased transformer heating caused by higher (order and magnitude) harmonics, as well as saturation effects in the core;
- Higher harmonics the power system can cause interference to telecommunication lines;
- Overstressing and resonant condition on the capacitors bank.

3. Methods

The residential distribution network and loads for assessing load flow were modelled using DIgSILENT Power Factory software. The model consisted of a three-phase residential load at 0.4 kV voltage level composed of different single phase loads. The schematic of the residential load model is presented in **Figure 1**.

The compiled residential load was connected to the distribution network substation via a 1.4 km long overhead line (OHL) as depicted on **Figure 2**. The distribution network substation was connected to a 10 kV network with short-circuit power of 200 MVA and short-circuit current 11.5 kA. The high voltage (HV) busbar is modelled as a slack bus. The transformer used in the distribution substation was modelled with the following parameters:

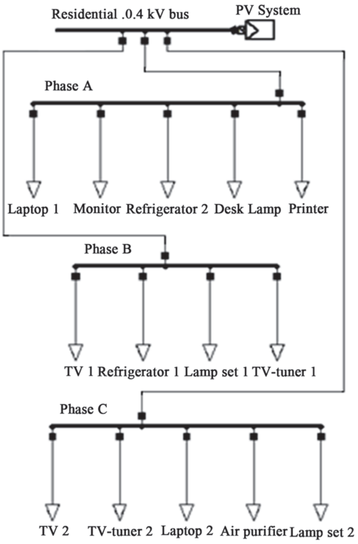


Figure 1. Schematic of residential load model.

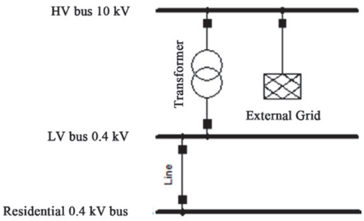


Figure 2. Schematic of distribution grid model.

- nominal power 25 kVA;
- relative short circuit voltage 4.5%;
- magnetizing impedance/ short circuit impedance ratio 3;
- vector group Yyn.

Implemented parameters in the simulation were selected based on power quality problematic issues identified in Elektrilevi's network (Estonia's main distribution grid operator) for July 1, 2013. The length of the OHL between substation and customer's PCC was defined as an average of all the lines between substations and customers with power quality problems. Similarly, the selected diameter of the line and nominal power of the transformer are the most common values for the identified problematic components.

Harmonic voltage amplitudes and phase angles up to the 50th order were obtained from measurements conducted by Elektrilevi at one of the sites where power quality issues were identified. Harmonic voltage distortion at the 10 kV bus was measured and modelled around 2%, which is a common value for this grid.

For modelling PV generation, three different commercially available PVs were measured for one week. The first measured system was single phase while the remaining were three phase systems. For all three systems, harmonic current amplitudes and angles up to 50th order were measured and used in the models in DIgSILENT. A mean load model of averaged values was composed for the single phase system and it was compared with other models composed of actual measurement results. PV inverters were connected to residential load's busbar as was described in **Figure 1**.

In order to model the network response of nonlinear loads, 14 different home appliances were measured. The results of the corresponding measured active and reactive power, harmonic current magnitudes and harmonic current phase shift angles of measured devices are presented in [15] [16]. Modelled devices were arranged in a manner where similar active power consumption was seen in every phase. The model is presumed to be the worst case scenario where all the nonlinear devices are in operation and coincidence factors are not taken into account.

4. Results

First, modelling results are given for the case where one single phase PV system was integrated to the existing grid. In the second and third case, different three phase systems were installed. All three scenarios were examined at three different power levels (stage 1—near 30%, stage 2—near 60%, stage 3—near 100%). Exact power level ratios depended on the availability of measurement data. Initial values of voltage THD in the grid before adding PV generations are presented in **Table 1**.

1) First case—single phase PV

A single phase PV inverter is connected to the residential busbar at phase C. Measurement results for the three different power levels are given at **Table 2** and **Table 3**. From the tables, it is apparent that current distortion decreases with increasing current. The same conclusion can be made by observing the power factor (PF) value which approaches unity with increasing current. Interestingly in this case, reactive power Q appears to be independent of the current level and changes polarity. In the paper the PF is the real power factor which accounts all values up to 50th order, the cos(fi) stands for displacement power factor which accounts only the main frequency components.

Table 1. Initial modelled voltage THD values [%].

Phase A	Phase B	Phase C
6.4	6.2	7.7

Table 2. Measured power values for single phase PV inverter.

Stage	Urms [V]	Irms [A]	P [W]	Q [var]	S [VA]
1—30%	233.6	3.45	739	322	807
2—60%	238.8	9.08	2125	−425	2168
3—100%	239.1	11.73	2783	−257	2805

Table 3. Measured power quality values for single phase PV inverter.

Stage	cos(fi)	PF	THD_U [%]	THD_I [%]
1—30%	1	0.92	1.01	4.27
2—60%	1	0.98	0.82	1.98
3—100%	1	0.99	1	1.67

Voltage and current distortion during a 15 h period is shown in **Figure 3**. Voltage distortion at the measurement point was notably low (around 1%) throughout the observed time period and similarly, current distortions are not greatly affected by grid disturbances.

Active power P, reactive power Q, and apparent power S are displayed in **Figure 4**. Results are in line with the prior conclusion for reactive power where Q is mainly capacitive throughout the measurement period. It can also be confirmed that reactive power is independent of current (compare with P and S).

As is evident in **Figure 5**, cos(φ) remained near unity throughout the measurement period, whereas PF varied considerably. The observed fluctuations in PF are a result of current distortion which is evident when comparing the current THD and PF curves in **Figure 3** (THD_I) and **Figure 5** (PF).

Table 4 presents the harmonic currents and phase angles up to the 21st order for the single phase PV inverter with the corresponding power levels described in **Table 4**. Phase angles are as percentages of main order current angle which is taken zero, main order current are taken 100%. Average values are also calculated and presented for modelling mean one phase PV. Even and higher order harmonics are left out due to their marginal dimension. All presented harmonic current amplitudes exhibited relatively moderate values, except for the third harmonic which was more notable.

For modelling mean PV generation, average values of the presented current harmonic amplitudes and angles (**Table 4**) were calculated. Main frequency current phase angles were defined zero as in ideal case and other angles were calculated in relation to mains current. **Figure 6** shows a graphical representation of the calculated average harmonics, where X and Y coordinates are calculated using Formulas (5) and (6). As it can be seen that the most notable component of the current is 3rd order harmonic.

$$X = A \times \cos\alpha \tag{5}$$

$$Y = A \times \sin\alpha \tag{6}$$

In the case where one single phase PV was added to the grid, voltage THD was observed to increase in all phases. Voltage distortion increased more as PV power level increased. Voltage THD for all power output stages and modelled mean PV are presented in **Table 5**. All values are given in percentages relative to initial conditions prior to the installation of PVs.

2) Second case—first three phase PV

In this case, a three phase PV inverter is connected to the existing network. Measurement results for three different power levels are given in **Table 6**. Once again, current distortion decreases when current (power) is increasing and same conclusion can be made observing the power factor (PF) value which approaches unity with increasing current. However, diverging from the first case, here total reactive power generation (Q_tot) is growing when current is increasing.

Table 7 provides reactive power and PF values for each phase. In addition to the aforementioned increase in total reactive power, observed reactive power changes were diverse for different phases. It is most probably due to different nature of specific phase load.

Harmonic currents up to 21st order of first three phase PV inverter are given in **Table 8** at the different power levels described in **Table 2**. In this case, the most notable harmonic was the 9th which exhibited values in the proximity of 2% in all phases, even at highest power level. Also the 13th harmonic had prominent values in phases B and C at highest power level. At the lower power level, most of the harmonics had significantly high values, even exceeding 6% at times.

Phase angles of harmonic current amplitudes displayed in **Table 8** are given in **Table 9**. It was observed that angles change with changing currents and as such, no mean values could be presented for this three phase PV inverter.

Voltage and current distortion of the first three phase PV inverter over a 15 hour period is shown in **Figure 7**.

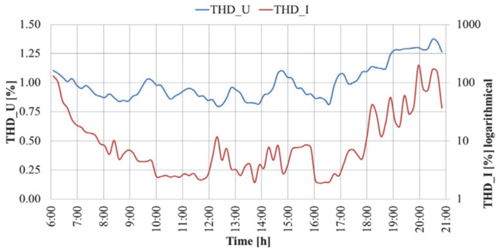


Figure 3. Measured voltage THD and current THD of single phase PV inverter.

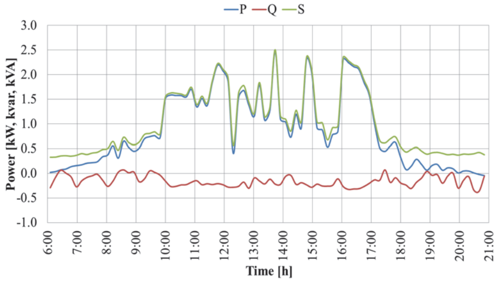


Figure 4. Measured power values of single phase PV inverter.

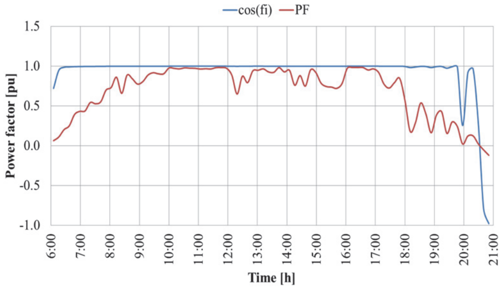


Figure 5. Measured power factors of single phase PV inverter.

Table 4. Harmonic currents [%] and phase angles [˚] of single phase PV inverter.

Order	I_1	Angle_1	I_2	Angle_2	I_3	Angle_3	I_mean	Angle_mean
1	100	0	100	0	100	0	100	0
3	1.92	28	1.20	62	1.01	52	1.38	47
5	0.48	97	0.31	146	0.26	139	0.35	127
7	1.08	175	0.27	159	0.27	164	0.54	166
9	0.88	116	0.33	145	0.35	146	0.52	135
11	0.89	104	0.38	60	0.32	52	0.53	72
13	0.69	75	0.21	73	0.20	77	0.37	75
15	0.23	109	0.08	104	0.10	107	0.14	107
17	0.35	88	0.07	145	0.06	190	0.16	141
19	0.29	287	0.10	259	0.10	271	0.16	272
21	0.63	209	0.20	205	0.17	209	0.33	208

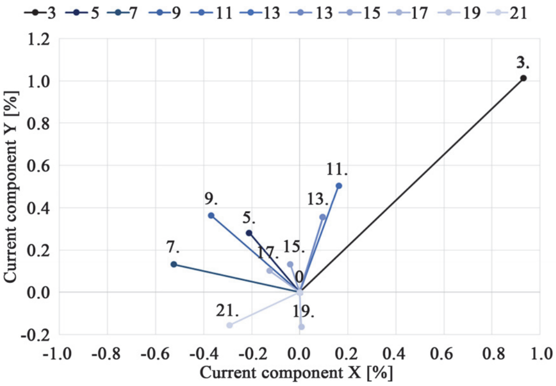


Figure 6. Mean harmonic current values of single phase PV inverter.

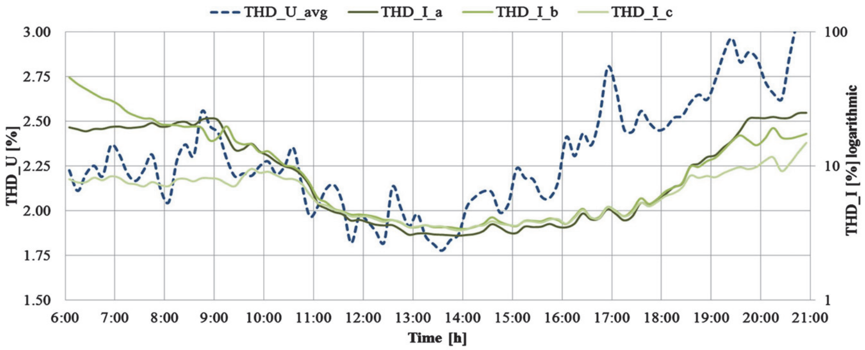


Figure 7. Measured voltage and current THD values of first three phase PV inverter.

Table 5. Measured power values for single phase PV inverter.

Stages	THD_U_a	THD_U_b	THD_U_c
1—30%	3.5	2.9	2.9
2—60%	12.9	10.2	9.7
3—100%	15.7	11.9	13.8
Mean	11.2	7.2	7.5

Table 6. Measured values for first three phase PV inverter.

Stage	1—30%	2—60%	3—100%
THD_U_avg [%]	2.33	1.98	2.03
THD_I_avg [%]	11.29	4.38	3.3
P_tot [kW]	1.06	2.78	3.88
Q_tot [kvar]	0.28	0.43	0.47
S_tot [kVA]	1.62	3.01	4.04
cos(fi)_avg	0.99	1	1
PF_avg	0.65	0.92	0.96

Table 7. Measured Q and PF values of first three phase PV inverter.

Stage	1—30%	2—60%	3—100%
Q_a [Var]	−335	−207	−104
Q_b [Var]	−104	−61	−98
Q_c [Var]	718	695	669
PF_a	0.68	0.97	1
PF_b	0.94	1	1
PF_c	0.52	0.84	0.9

Table 8. Measured harmonic currents [%] of first three phase PV inverter.

Order	Stage 1—30%			Stage 2—60%			Stage 3—100%		
	I_a	I_b	I_c	I_a	I_b	I_c	I_a	I_b	I_c
1	100	100	100	100	100	100	100	100	100
3	5.01	4.19	2.56	0.87	1.09	1.43	0.7	0.87	1.03
5	6.68	5.7	3.66	0.62	0.58	0.45	0.94	0.92	1.05
7	2.72	4.85	3.95	1.31	1.62	1.34	0.14	0.31	0.8
9	3.81	4.28	3.43	3.07	3.27	3.07	2.07	1.96	1.97
11	5.14	6.69	5.07	0.96	1.12	1.09	0.61	0.83	0.43
13	0.54	2.66	1.09	0.34	0.91	0.93	0.4	1.52	1.5
15	2.79	2.55	1.69	0.66	0.91	0.61	0.78	0.86	0.59
17	0.66	1.45	0.99	0.98	0.31	1.1	0.35	0.7	0.18
19	0.65	0.49	0.42	0.9	0.16	0.94	0.25	0.11	0.17
21	1.11	0.71	0.95	0.26	0.44	0.37	0.59	0.45	0.34

Table 9. Measured phase angles [˚] of harmonic currents of first three phase PV inverter.

	Stage 1—30%			Stage 2—60%			Stage 3—100%		
Order	Angle_a	Angle_b	Angle_c	Angle_a	Angle_b	Angle_c	Angle_a	Angle_b	Angle_c
1	0	0	0	0	0	0	0	0	0
3	275	170	262	38	26	57	281	17	271
5	214	35	220	85	303	227	278	182	340
7	11	202	344	196	226	288	91	285	17
9	143	320	139	19	31	75	166	29	171
11	181	147	219	100	145	219	124	234	51
13	39	201	76	262	326	74	42	147	110
15	314	132	286	336	18	98	205	96	218
17	227	161	43	195	254	335	118	310	98
19	65	229	58	23	233	88	23	241	27
21	268	307	255	204	98	171	264	108	243

Voltage distortion at the measurement point remained at a moderate level (around 2.25%) throughout most of the time period. Correlation with current distortion was not detected.

Reactive power generation is shown in **Figure 8**. The figure shows that while reactive power is phases A and B was moderately consumed, reactive power was generated in phase C at a much higher level.

Power indices over the 15 hour period are presented in **Figure 9**. The figure supports the previous conclusion that reactive power (Q_tot) is mainly inductive. It also confirms that reactive power is independent of current in this case (compare with active power P_tot and apparent power S_tot).

Figure 10 shows that cos(φ) was near unity for the entire duration, whereas PF varied more. PF in phase C was especially poor. Changes in the PF were attributed to current distortion which could be seen when comparing current THD and PF (THD_I in **Figure 7** and corresponding PF in **Figure 10**).

Results of having the first three phase PV in the grid are presented in **Table 10**. For this case, results are not uniform and voltage THD did not increase in all the stages. Slight harmonic cancellation in phases A and C could be noticed at stage 2. In other stages voltage distortion increased moderately. All values are given in percentages compared to the initial conditions where no PVs were installed.

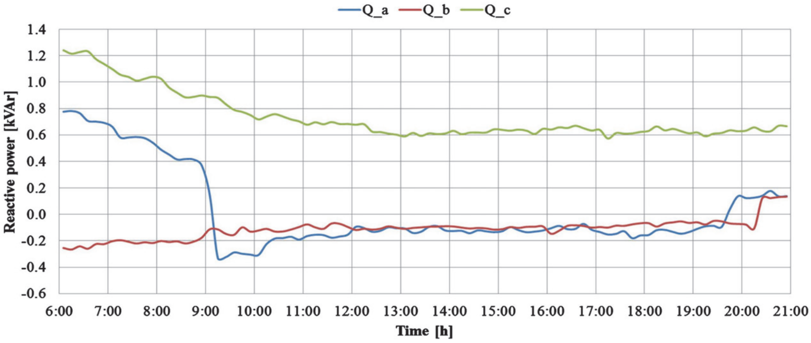


Figure 8. Measured reactive power values of first three phase PV inverter.

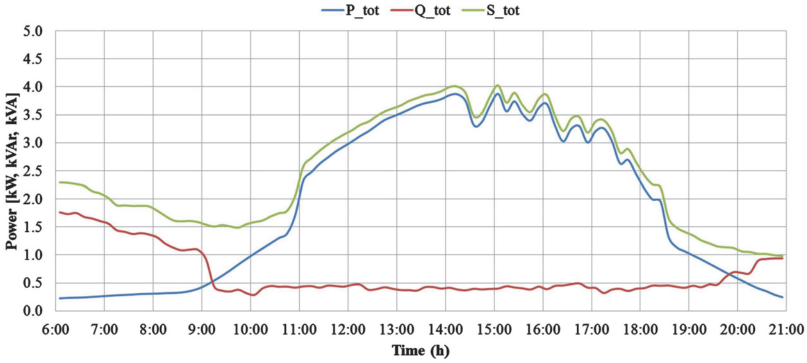


Figure 9. Measured power values of first three phase PV inverter.

Table 10. Voltage THD of grid with PV compared to grid without PV [%].

Stages	THD_U_a	THD_U_b	THD_U_c
1—30%	4.4	4.2	4.5
2—60%	−1.4	0.6	−1.7
3—100%	6.0	6.7	5.0

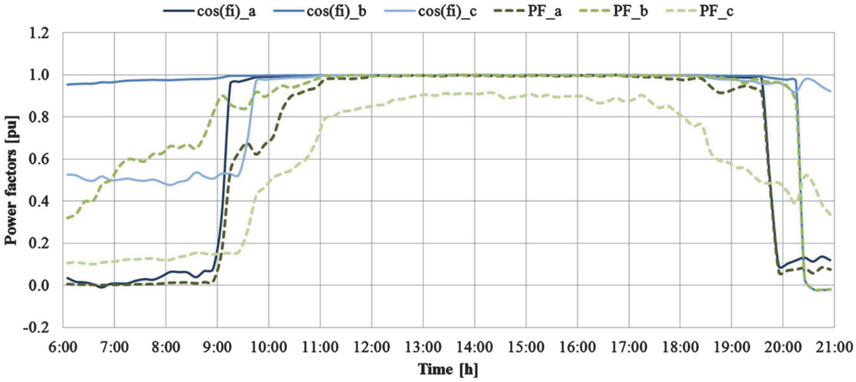


Figure 10. Measured power factor values of first three phase PV inverter.

3) Third case—second three phase PV

In this case, the three phase PV inverter is replaced with another inverter. Measurement results for three different power levels are given at **Table 11**. As evident from the table, current distortion decreases with increasing current and similarly, the power factor (PF) value approached unity. Only total reactive power (Q_tot) did not exhibit a linear change.

Reactive power and PF values for each phase are given in **Table 12**. In addition to the aforementioned total reactive power nonlinearity, reactive power changes were observed to differ for different phases also.

Table 13 presents harmonic currents up to 21st order of second three phase PV inverter at different power levels as described in **Table 11**. In this case harmonics were notable only at lower power levels. For the first stage, high amplitudes were seen in majority of the presented orders.

Phase angles presented harmonic current amplitudes in **Table 13** are displayed in **Table 14**. Angles were observed to change with changing currents and as such, no mean values could be presented for this three phase PV inverter.

Voltage and current distortion of second three phase PV inverter throughout the 15 h time period is shown in **Figure 11**. Voltage distortion at the measurement point was mainly low level (around 1.1%). Correlation between voltage and current distortion was not detected.

Reactive power generation is shown in **Figure 12**. Reactive power in phases A was maintained near zero, while reactive power in the other phases changed frequently in both magnitude and polarity.

Power (P, Q, and S) during the investigated time period is shown in **Figure 13** and supports the earlier observation that total reactive power oscillated around zero. A slight correlation with current could be observed in the middle of the day (compare fluctuation in Q_tot with active power P_tot and apparent power S_tot around 14:00).

Figure 14 displays how cos(φ) was maintained near unity majority of the day. Similarly, PF remained rather constant with only minor deviations. The PF curves reached unity with a slight delay and started diminish earlier. The small variation in the middle of the day was in correlation with the rise in total reactive power shown in **Figure 13** (Q_tot at 14:00).

The impact of the second three phase PV is presented in **Table 15**. Results are not uniform and voltage THD did not increased in all the cases. Higher harmonic cancellation could be noticed compared to the previous case with the first three phase PV. A definite assessment concerning distortion changes cannot be done. All values are given in percentages compared to initial conditions where no PVs were installed.

4) Comparison of results

It could be concluded that changes in voltage THD values increase as power output of PVs grows. For the one phase PV installation, it was clear that voltage harmonics increased in all three phases. For the three phase PV installations, the two cases showed different outcomes. With the first three phase PV, notable degradation was observed. However, a conclusive assessment could not be done with second three phase PV installation. Voltage THD results at the highest power level for all three cases are depicted in **Figure 15**.

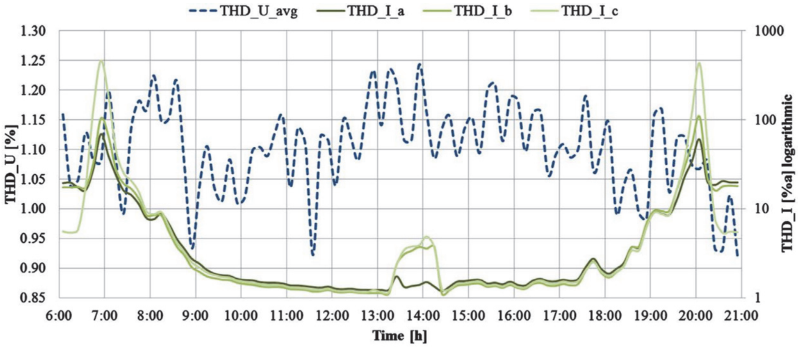


Figure 11. Measured voltage and current THD values of second three phase PV inverter.

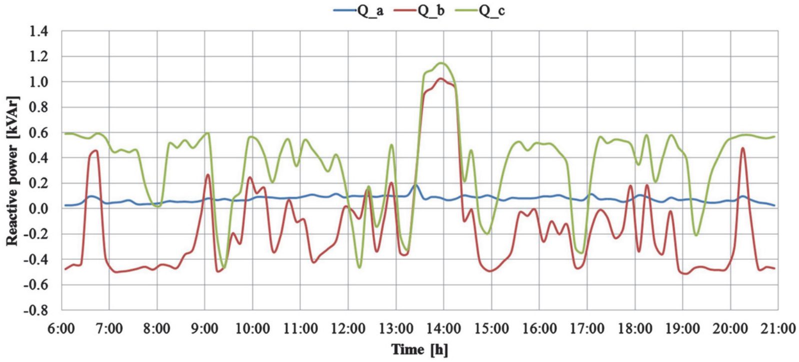


Figure 12. Measured reactive power values of second three phase PV inverter.

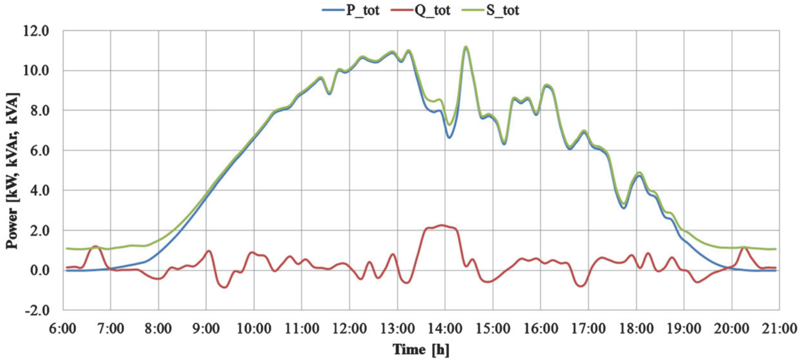


Figure 13. Measured power values of second three phase PV inverter.

Table 11. Measured values for second three phase PV inverter.

Stage	THD_U_avg [%]	THD_I_avg [%]	P_tot [kW]	Q_tot [kVAr]	S_tot [kVA]	cos(fi)_avg	PF_avg
1—30%	1.18	5.34	1.9	0.17	2.20	1.00	0.84
2—60%	1.18	1.77	5.82	−0.75	5.95	1.00	0.98
3—100%	1.07	1.19	10.19	−0.16	10.26	1.00	0.99

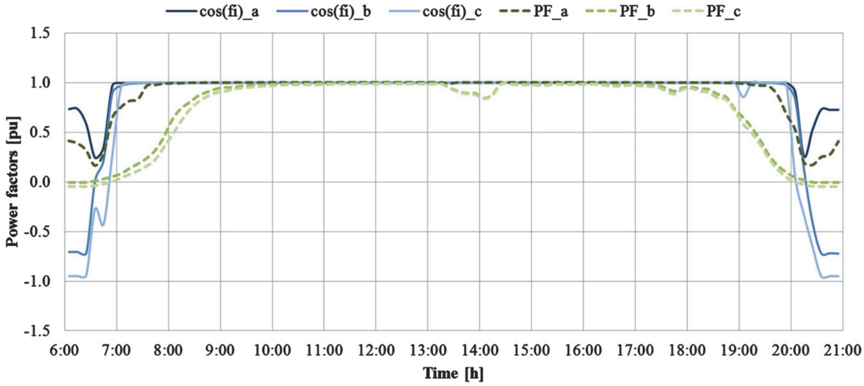


Figure 14. Measured power factor values of second three phase PV inverter.

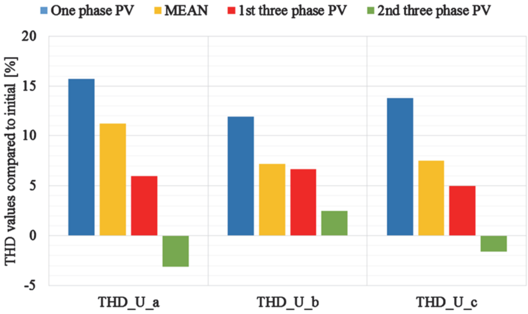


Figure 15. Voltage THD values at third stage for different PVs compared to initial conditions [%].

Table 12. Measured reactive power and PF values of second three phase PV inverter.

Stage	Q_a [Var]	Q_b [Var]	Q_c [Var]	PF_a	PF_b	PF_c
1—30%	52	−431	544	1.00	0.79	0.77
2—60%	66	−459	−360	1.00	0.97	0.96
3—100%	123	−434	149	1.00	0.99	0.99

Table 13. Measured harmonic currents [%] of first three phase PV.

Order	Stage 1—30%			Stage 2—60%			Stage 3—100%		
	I_a	I_b	I_c	I_a	I_b	I_c	I_a	I_b	I_c
1	100	100	100	100	100	100	100	100	100
3	4.12	3.03	3.30	1.02	0.85	0.93	0.84	0.68	0.71
5	1.53	1.74	1.98	0.24	0.36	0.36	0.60	0.59	0.61
7	1.60	1.32	1.31	0.69	0.59	0.64	0.32	0.42	0.39
9	1.56	1.56	1.60	0.49	0.42	0.48	0.18	0.19	0.21
11	0.80	0.32	0.43	0.66	0.71	0.68	0.19	0.21	0.19
13	1.04	1.10	1.17	0.28	0.41	0.39	0.27	0.19	0.20
15	1.46	1.00	1.24	0.53	0.46	0.49	0.26	0.23	0.26
17	0.74	0.93	0.74	0.26	0.21	0.13	0.22	0.18	0.20
19	0.31	0.28	0.23	0.27	0.23	0.29	0.06	0.05	0.08
21	0.34	0.45	0.49	0.13	0.09	0.15	0.15	0.13	0.14

Table 14. Phase angles [˚] of harmonic currents of second three phase PV.

Order	Stage 1—30%			Stage 2—60%			Stage 3—100%		
	angle_a	angle_b	angle_c	angle_a	angle_b	angle_c	angle_a	angle_b	angle_c
1	0	0	0	0	0	0	0	0	0
3	205	193	198	16	16	16	19	247	17
5	53	32	38	219	212	208	202	324	198
7	80	330	334	245	259	248	346	60	341
9	191	172	178	68	49	45	148	66	135
11	201	252	111	213	194	200	207	300	197
13	326	331	323	328	320	328	175	73	342
15	98	71	82	101	87	88	141	83	115
17	303	233	255	304	286	311	20	135	157
19	286	283	235	25	325	205	186	113	183
21	101	60	45	98	67	96	327	296	317

Table 15. Voltage THD of grid with second three phase PV inverter compared to grid without PV [%].

Stages	THD_U_a	THD_U_b	THD_U_c
1—30%	1.2	−3.2	−2.3
2—60%	−0.6	3.5	1.2
3—100%	−3.1	2.5	−1.6

5. Discussion

While the discreet disturbances of harmonic distortion may not cause immediate and easily-observed impacts, it can cause some equipment to malfunction, and result in additional power losses in both customer and network equipment [17]. As harmonic levels change considerably from one week to another, it is very difficult to assess the long-term evolution of harmonic levels only from measurements carried out over a short period [1]. This paper clearly concludes that power quality problems may occur when PV utilization is not sufficiently considered.

Harmonic current angles of small generators such as PVs are seldom considered. One aim of this paper is to draw attention to this topic which could lead to advances in modelling PV inverters with different topologies. To help mitigate harmonic distortion problems, models with appropriate harmonic current amplitudes and phase angles could be used to select most suitable devices.

This study only examines one household and one PV at time. The described effects may escalate when a larger number of devices are considered. Special attention is need in situations where devices have similar harmonic patterns and the harmonic cancellation effect is minimal. Additional measurements should be performed to obtain unified values for modelling PV generators more accurately. It would be necessary to have measurement data extending over entire years in order to acquire results independent of any disturbance. Furthermore, flicker and voltage level issues should be accounted for as they may have a significant influence in real applications.

6. Conclusions

Firstly, it can be concluded that current harmonic distortion of the PV's output is correlated with current. Distortion decreases when the PV is operating at a higher loading level. PVs function accurately under ideal conditions. Due to unstable energy availability (*i.e.*, variable solar radiation), continuous variation in power quality parameters is to be expected. In the presented research, two PVs showed considerable harmonic current distortion (average THD over 5%) even at full loading. Only one PV had average current THD under 2% which was considered a very good achievement.

All of the measured PV systems had quite different harmonic patterns when compared with each other throughout their loading range. As such, it is difficult to propose simplified values for modelling without measuring and analysing a greater number of devices. Also, for more reliable harmonic current phase angle data, laboratory tests should be performed.

Secondly, contrary to theory, reactive power generation of PVs was not observed to be correlated to active power. Measured devices showed different levels and variation of reactive power in different phases. These differences may be hazardous in cases where high reactive power values and variations in one phase and zero reactive power in other another phase are not considered. It was also observed that main order reactive power was compensated more efficiently than higher order reactive power which was evident when comparing cos(φ) and PF.

Relative to the initial conditions where no PVs were installed, modelling one PV results in voltage distortion exceeding 10%. The influence is dependent on grid structure and topology of the PV. In case of PV with less distorted current working at high power level, minor improvement of voltage distortion was observed.

References

[1] Berthet, L., Eyrolles, P., Gauthier, J. and Sabeg, S. (2007) Harmonic Level Measurements on French Low-Voltage Networks. 19*th International Conference on Electricity Distribution*, Vienna.

[2] Aiello, M., Cataliotti, A., Favuzza, S. and Graditi, G. (2006) Theoretical and Experimental Comparison of Total Harmonic Distortion Factors for the Evaluation of Harmonic and Interharmonic Pollution of Grid-Connected Photovoltaic Systems. *IEEE Transactions on Power Delivery*, **21**, 1390-1397. http://dx.doi.org/10.1109/TPWRD.2005.860231

[3] Jayasekara, N. and Wolfs, P. (2010) Analysis of Power Quality Impact of High Penetration PV in Residential Feeders. 20*th Australasian Universities Power Engineering Conference* (*AUPEC*), Christchurch.

[4] Rawa, M., Thomas, D. and Sumner, M. (2011) Simulation of Non-Linear Loads for Harmonic Studies. 11*th International Conference on Electrical Power Quality and Utilisation* (*EPQU*), Lisbon, 17-19 October 2011, 1-6. http://dx.doi.org/10.1109/EPQU.2011.6128915

[5] Renders, B., Degroote, L., Driesen, J. and Vandevelde, L. (2007) Profits of Power-Quality Improvement by Residential Distributed Generation. 42*nd International Universities Power Engineering Conference*, Brighton, 4-6 September 2007, 377-381. http://dx.doi.org/10.1109/upec.2007.4468976

[6] Kütt, L., Saarijärvi, E., Lehtonen, M. and Niitsoo, J. (2013) A Review of the Harmonic and Unbalance Effects in Electrical Distribution Networks Due to EV Charging. 13*th International Conference on Environment and Electrical Engineering* (*EEEIC*), Wroclaw.

[7] Bhattacharyya, S., Cobben, S., Ribeiro, P. and Kling, W. (2012) Harmonic Emission Limits and Responsibilities at a Point of Connection. *IET Generation*, *Transmission & Distribution*, **6**, 256-264. http://dx.doi.org/10.1049/iet-gtd.2011.0376

[8] Niitsoo, J. and Palu, I. (2011) Distorted Load Impacts on Distribution Grid. *Proceedings of the* 12*th International Scientific Conference Electric Power Engineering* 2011, Kouty nad Desnou.

[9] Yong, J., Chen, L. and Chen, S. (2010) Modeling of Home Appliances for Power Distribution System Harmonic Analysis. *IEEE Transactions on Power Delivery*, **25**, 3147-3155. http://dx.doi.org/10.1109/TPWRD.2010.2051960

[10] Block, P., Salamanca, H., Teixeira, M., Dahlke, D., Shiono, O. and Dodadon, A. (2014) Power Quality Analyses of a Large Scale Photovoltaic System. *The* 5*th International Renewable Energy Congress IREC* 2014, Hammamet, 25-27 March 2014, 1-6. http://dx.doi.org/10.1109/irec.2014.6826946

[11] Kontogiannis, K., Vokas, G., Nanou, S. and Papathanassiou, S. (2013) Power Quality Field Measurements on PV Inverters. *International Journal of Advanced Research in Electrical Electronics and Instrumentation Engineering*, **2**, 5301-5314.

[12] Anwari, M., Hamid, M. and Taufik (2008) Power Quality Behavior of Single Phase Fed Adjustable Speed Drive Supplied from Grid of PV Generation. 2*nd IEEE International Conference on Power and Energy* (*PECon* 08), Bahru.

[13] Hasanzadeh, A., Edrington, C. and Bevis, T. (2012) Comprehensive Study of Power Quality Criteria Generated by PV Converters and Their Impacts on Distribution Transformers. 38*th Annual Conference on IEEE Industrial Electronics Society IECON* 2012, Montreal.

[14] Fekete, K., Klaic, Z. and Majdandzic, L. (2012) Expansion of the Residential Photovoltaic Systems and Its Harmonic

Impact on the Distribution Grid. *Renewable Energy*, **43**, 140-148. http://dx.doi.org/10.1016/j.renene.2011.11.026

[15] Niitsoo, J., Kilter, J., Palu, I., Taklaja, P. and Kütt, L. (2013) Harmonic Levels of Domestic and Electrical Vehicle Loads in Residential Distribution Networks. *Proceedings of AFRICON* 2013, Mauritius, 9-12 September 2013, 1-5. http://dx.doi.org/10.1109/AFRCON.2013.6757800

[16] Niitsoo, J., Palu, I., Kilter, J., Taklaja, P. and Vaimann, T. (2013) Residential Load Harmonics in Distribution Grid. *Proceedings of* 3*rd International Conference on Electric Power and Energy Conversion Systems* (*EPECS* 2013), Istanbul, 2-4 October 2013, 1-6. http://dx.doi.org/10.1109/epecs.2013.6713054

[17] Nicholson, G., Gosbell, V. and Parsotam, A. (2007) Analysis of Harmonic Distortion Levels on a Distribution Network. P*ower Engineering Conference*, AUPEC 2007, Perth, 9-12 December 2007, 1-7. http://dx.doi.org/10.1109/aupec.2007.4548035

PAPER - IX

Smart Grid and Renewable Energy, 2015, 6, 164-177
Published Online June 2015 in SciRes. http://www.scirp.org/journal/sgre
http://dx.doi.org/10.4236/sgre.2015.66015

Power Quality Issues Concerning Photovoltaic Generation and Electrical Vehicle Loads in Distribution Grids

Jaan Niitsoo[1], **Paul Taklaja**[1], **Ivo Palu**[1], **Joni Klüss**[2]

[1]Department of Electrical Power Engineering, Tallinn University of Technology, Tallinn, Estonia
[2]Department of Electrical Engineering and Automation, Aalto University, Helsinki, Finland
Email: jaan.niitsoo@ttu.ee

Received 8 May 2015; accepted 26 June 2015; published 29 June 2015

Abstract

The high utilization level of renewable generation including residential photovoltaic (PV) systems together with the uncontrolled charging of electric vehicles (EVs) can have a significant impact on load characteristics in distribution networks. Harmonic content of PV generation, EV charging loads, and their influence on power quality indicators in residential distribution networks are discussed in this paper. For investigating likely power quality scenarios, PV generation and EV charging measurement results including current harmonic amplitude and phase angle values are used and compared with present load characteristics. Different modelling scenarios are analysed and a simplified model of harmonics in PVs and EVs is offered. The results of the study show moderate additional harmonic distortion in residential load current and voltage distortion at the substation's busbar when PV generation and EV loading are added. The scenarios presented in this paper can be further used for modelling the actual harmonic loads of the PVs and EVs in distribution networks.

Keywords

Current Measurement, Distributed Generation, Electric Vehicles, Load Modelling, Photo Voltaic, Power Quality, Power System Harmonics

1. Introduction

Power distribution networks are designed to operate with sinusoidal voltage. The deviation of the actual voltage waveform from an ideal sine wave is a fundamental aspect related to power quality. This deviation can be de-

How to cite this paper: Niitsoo, J., Taklaja, P., Palu, I. and Klüss, J. (2015) Power Quality Issues Concerning Photovoltaic Generation and Electrical Vehicle Loads in Distribution Grids. *Smart Grid and Renewable Energy*, **6**, 164-177.
http://dx.doi.org/10.4236/sgre.2015.66015

scribed as a sum of harmonic voltage components. A higher level of harmonics correlates to larger distortion. From the point of view of electromagnetic compatibility, harmonics must be kept within given compatibility levels to enable satisfactory operation of all equipment supplied by the network. Furthermore, since electricity is also defined as a product, utility companies could be held responsible for excessively high harmonic levels and any resulting damage to customers' property [1].

The appliances and electric devices connected to the public power supply network are also designed to operate with a sinusoidal voltage at rated power. However, many of the connected loads are nonlinear, meaning that they draw current with a distorted sine waveform. It has been estimated that already in 2012, 60% of the power system loads in USA were nonlinear loads [2]. Nonlinear current in turn provides nonsinusoidal voltage drop, thus resulting in distorted network voltage. In particular, distortion levels may increase significantly when numerous harmonic emitting devices are utilized in bulk [3].

Distorted voltage and current may result in undesirable effects not only for the distribution system, but also for the customers. Nonlinear loads inject harmonic currents and induce increased voltage drops over both phase and neutral conductors [4]. As a result, potential damage to sensitive electronic equipment and capacitor banks, overheating of transformers and neutral conductors, and additional losses in the power system are likely. Degraded power quality entails additional costs for both the electricity distributor and its customers as these effects cause premature aging and failure in power system devices [5]-[7].

Advances in power electronics has led to the widespread use of switching converters for the general public use as well as industrial applications. Power electronic converters draw non-sinusoidal current from the grid and this has led to a rapid increase in the number of nonlinear loads. In addition to the increased number of electronic devices, also resistive devices such as incandescent lamps are ever more frequently replaced by energy saving lamps utilizing nonlinear elements. Depending on type and brand, switching power supplies absorb distorted currents which flow through the impedances of the power distribution system and result in distortion of system bus voltage [8].

Similarly, modern EV chargers employ switching power converters. Due to the high energy requirement of the EV, charging at home can use power levels very close to the ones of the actual residential customers drawing, 10 - 15 A [9]. The charging of EVs produces considerable additional power electronic load which can generate harmonics and result in associated power quality issues in residential networks.

Power electronics is also implemented in residential photovoltaic (PV) generators, which is currently the dominant renewable energy source in urban and metropolitan areas. The inverters required to supply households from the PVs are nonlinear power supplies, meaning that they provide distorted waveform outputs that increase the levels of harmonics. This technology is enjoying rapid growth due to a combination of subsidies, the abundance of sunshine, and the low impact of the technology on the urban landscape [5].

The present study identifies and analyses possible power quality scenarios in a residential distribution network by examining the impact of nonlinear domestic loads such as EVs and PV inverters. Measured power consumption and current waveforms of different home appliances, EVs and PV inverter have been used for the analysis. All loads considered in the model were provided with magnitudes and phase angles of each harmonic up to the 50th order. The main purpose of this paper is to present the use of actual measurement data from different devices for modelling the effects on the residential distribution network and give an estimation of the important values for further modelling.

2. Theoretical Background

In electrical power networks, a non-sinusoidal periodic waveforms can be presented as a sum of numerous harmonic components (harmonics), each having an integer-multiple frequency of the main frequency. Different waveforms have different harmonic content, referring to different patterns of individual harmonic magnitudes and phase shift compared to the main frequency component. Hereafter in this paper, the presented measurements of loads are all indicated as magnitudes and phase shift of each individual harmonic up to the 50th order.

Distortions can be observed individually by comparing different harmonic components and calculating harmonic distortion (HD). A more general approach to quantifying the distortions is using the total harmonic distortion level (THD). Total harmonic distortion can be expressed separately for current harmonic distortion as THDI and for voltage distortion as THDU. The total harmonic distortion indicators can be calculated using corresponding Equations (1) and (2),

$$\mathrm{THD_I} = \frac{1}{i_1}\sqrt{i_{\mathrm{rms}}^2 - i_1^2} \times 100 \tag{1}$$

$$\mathrm{THD_U} = \frac{1}{u_1}\sqrt{u_{\mathrm{rms}}^2 - u_1^2} \times 100 \tag{2}$$

where i_1 is current of 1st order and u_1 is voltage of 1st order.

THD does not reveal the magnitudes of individual harmonics, which could still exceed the limits for specific harmonics regardless of THD value. For the correct estimation of the harmonic levels, calculations have to make use of magnitude and phase angle values of individual harmonics. Harmonic phase angle diversity is relevant when multiple appliances are operating simultaneously, creating either reinforcement or cancellation of harmonic magnitudes [2]. It is reported that 10% smaller harmonic current magnitudes can be seen when phase angle information is included compared to the simple summing of magnitudes without phase angle values [10]. The attenuation effect is dependent only on the phase angle, but the effect's severity is dependent on the magnitude of the harmonic voltage [11].

The combined influence of harmonics from different sources is highly dependent on network topology, mutual conductor impedances and phase balance. The resulting harmonic distortion in the distribution network can increase or decrease due to the variation of phase angles for different harmonic sources. A special situation occurs in the case of a balanced three phase load consisting of identical nonlinear loads. Since the triplen harmonics sum in neutral, the three phase supply system neutral conductor total current can be higher than the phase current [4] [12]. For example in the Netherlands and in Denmark, analysis has shown that the 15th harmonic current, which is one of the triplen harmonics, has exceeded the tolerable limits in several cases [12]. Therefore, phase balance is a significant factor for harmonic emission in distribution networks [7].

The harmonic generation of a PV system depends on the inverter technology, and operation conditions, including solar irradiance, temperature, loads, and the supply system characteristics. Both the current THD and the output reactive power are related to the output active power levels, which in turn are strongly dependent on solar irradiance levels. Most of the inverters consume or feed reactive power into the network depending on their output active power and their technology. During operation at low solar irradiance levels (e.g. sunrise, sunset, cloudy days), current THD values can increase rapidly since the THD factor is inversely proportional to the output active power of the PV inverters. Nevertheless, THD is notably reduced as the output active power of the PV inverters increases and reaches its nominal value [13]-[15].

Varying power density of renewable energy not only potentially cause supply voltage sag or swell patterns but also frequency variations in the LV grids. The application of power converters as interfaces between energy sources and the LV grid and their interaction with other system components may cause high harmonics distortion [16] [17]. The effects of the nonlinear residential load on voltage THD are most significant on a local level, and equipment failures due to voltage distortion are more likely to occur along distribution feeders than farther upstream. The results show that recommended voltage THD limits can easily be exceeded, particularly at nearby distribution feeder tap points, if the loading equipment is highly nonlinear [18].

EV batteries require DC for charging, but all uncontrolled rectifiers inject a high content of current harmonics into AC power networks. Based on literature, it can be concluded that over time and with the development of power supply technologies, the amount of distortion from EV charging has decreased. Measurements in the 1990's showed that the use of uncontrolled or low-control rectifiers caused average current THD of 50% [19]. Measurements of modern commercial EVs have indicated an average charging current THD around 11%…12% [20] [21], but values as low as 4.5% [22] have also been indicated.

Monitoring of 100 distribution network feeders in USA revealed that the average voltage THD at PCC (Place of Common Coupling) was 4.73% [23]. It may be assumed that the stated percentage is quite common for many distribution grids. Power supply standards (EN50160) have set the upper voltage THD limit for public networks at 8% [24]. Nevertheless, severe cases have been revealed where distortion has been higher than 17% [25].

3. Methods

The 50 Hz residential distribution network at 0.4 kV and loads for assessing load flow were modelled using DIgSILENT Power Factory software. The model consisted of a three-phase residential load at 0.4 kV voltage level composed of different single phase loads. The schematic of the residential load model is presented in **Figure 1**.

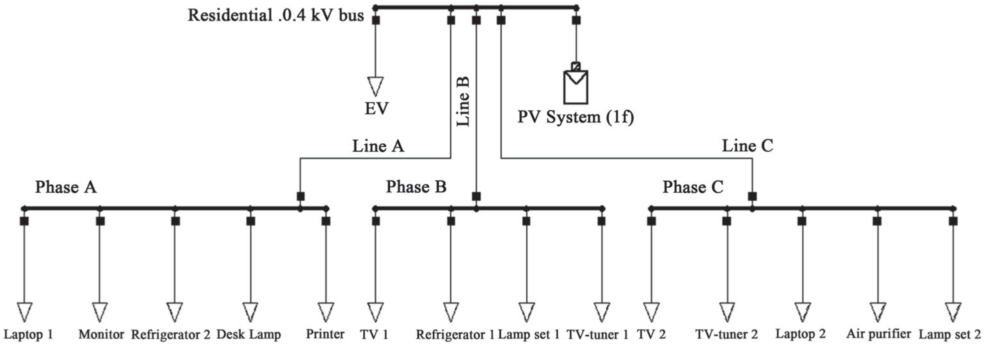


Figure 1. Schematic of residential load model.

The compiled residential load was connected to the distribution network substation via a 1.4 km long 4 × 95 mm^2 overhead line (OHL) as depicted on **Figure 2** and it is the only consumer of this substation. The distribution network substation was connected to a 10 kV network with short-circuit power of 200 MVA and short-circuit current 11.5 kA. The high voltage (HV) busbar is modelled as a slack bus. The transformer used in the distribution substation was modelled with the following parameters:

- nominal power 25 kVA;
- relative short circuit voltage 4.5%;
- zero sequence impedances $r_0 = 0.02$ pu and $x_0 = 0.04$ pu;
- magnetizing impedance/short circuit impedance ratio 3;
- vector group Yyn.

Implemented parameters in the simulation were selected based on power quality problematic issues identified in Elektrilevi’s network (Estonia’s main distribution grid operator) for July 1, 2013. The length of the OHL between substation and customer’s PCC was defined as an average of all the lines between substations and customers with power quality problems. Similarly, the selected diameter of the line and nominal power of the transformer are the most common values for the identified problematic components.

Harmonic voltage amplitudes and phase angles up to the 50th order were obtained from measurements conducted by Elektrilevi at one of the sites where power quality issues were identified. Harmonic voltage distortion at the 10 kV bus was measured and modelled around 2%, which is a common value for this grid.

For modelling PV generation, one single phase PV was measured for one week. For modelling EV loads, actual charging process of five different EVs were measured. All vehicles were produced in 2012-2013 and are commercially available on the markets. In each case, harmonic current amplitudes and phase angles up to 50th order were measured and used in the models in DIgSILENT. Both PV and EV were connected to residential load’s busbar as was described in **Figure 1**. Also a mean load model of averaged values was composed for the single phase PV system and EV.

In order to model the network response of nonlinear loads, 14 different home appliances were measured. The results of the corresponding measured active and reactive power, harmonic current magnitudes and harmonic current phase shift angles of measured devices are presented in [26] [27]. Modelled devices were arranged in a manner where similar active power consumption was seen in every phase. In the model, all nonlinear devices are in operation and coincidence factors are not taken into account, thus representing the presumed worst case scenario.

4. Results

Three cases modelling the residential distribution network are presented. Initial conditions represent the loads common to present day households.

1) First case: one single-phase PV unit connected to the PCC in addition to the initial load.
2) Second case: one EV charging load connected to the PCC in addition to the initial load.
3) Third case: EV charging load and PV inverter are connected to the PCC in addition to the initial load.

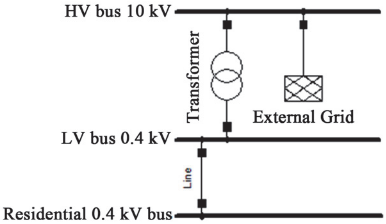


Figure 2. Schematic of distribution grid model.

Initial values of voltage and current in the grid before adding PV generations or EV load are presented in Table 1. Voltage THD and power factor (PF) values are listed in Table 2 and power values are listed in Table 3.

A) *First Case—Single Phase PV*

Measurement results for three different power levels (1—near 30%, 2—near 60%, 3—near 100%) of the single phase PV are given in Table 4. From the table, it can be assumed that current distortion is slightly correlated with current and decreases as current increases. Also voltage and voltage distortion variations may somewhat have an effect on the current distortion, but are here ignored due to very low values of voltage THD and the fact that current itself is more affected by voltage. The same conclusion can be made by observing the power factor (PF) value which approaches unity with increasing current. Interestingly in this case, reactive power Q appears to be independent of the current level and changes polarity.

Voltage and current distortion during a 15 h period is shown in Figure 3. Voltage distortion at the measurement point was notably low (around 1%) throughout the observed time period and similarly, current distortions are not greatly affected by grid disturbances.

Power quality indexes are illustrated in Figure 4. Results are in line with the prior conclusion for reactive power where Q is mainly capacitive throughout the measurement period. It can also be confirmed that reactive power is independent of current (compare with active power P and apparent power S).

As is evident in Figure 5, $\cos(\varphi)$ remained near unity throughout the measurement period, whereas PF varied considerably. The observed fluctuations in PF are a result of current distortion which is evident when comparing the current THD (THD_I in Figure 3) with the PF curve in Figure 5.

Table 5 and Table 6 present the harmonic currents and phase angles up to the 21st order for the single phase PV inverter with the corresponding power levels (1—near 30%, 2—near 60%, 3—near 100%) described in Table 4. Average values are also calculated and presented for modelling mean one phase PV. Even and higher order harmonics are left out due to their marginal dimension. All presented harmonic current amplitudes exhibited relatively moderate values, except for the third harmonic which was more notable.

For modelling mean PV generation, average values of the presented current harmonic amplitudes and angles (Table 5 and Table 6) were calculated. Main frequency current phase angles were defined zero as in the ideal case and other angles were calculated in relation to mains current. Figure 6 shows a graphical representation (vector quadrant) of the calculated average harmonics, where X and Y components of current are calculated using Formulas (3) and (4). Where A is mean harmonic (3rd, 5th, 7th etc. order) current in percentages to main frequency current and α is mean harmonic (3rd, 5th, 7th etc. order) current angle in degrees to main frequency current.

$$\mathrm{X} = \mathrm{A} \times \cos\alpha \tag{3}$$

$$\mathrm{Y} = \mathrm{A} \times \sin\alpha \tag{4}$$

A single phase PV inverter was connected to the residential busbar at different phases one at a time. The resulting voltages and currents are presented in Table 7. Voltage THD and PF is shown in Table 8 and power values are displayed in Table 9.

As it can be seen from Table 7 voltage in the phase where the PV is connected rises more than 5%. Significant voltage THD rise due to the connected PV could not be seen. Instead, THD decreased slightly in cases where PV was connected to phase A and C as evident in Table 8. Due to the change in reactive power, seen in Table 9, the PF value changed in the phase where the PV was installed.

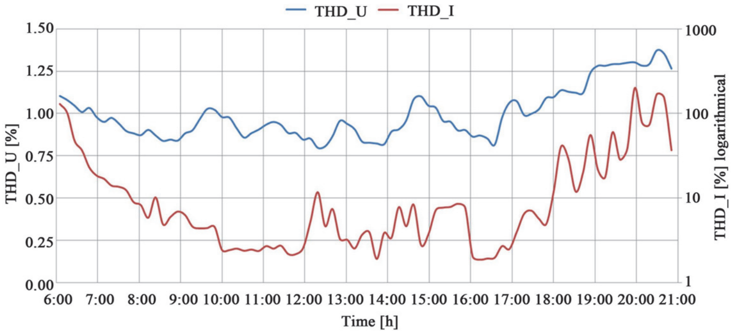


Figure 3. Measured voltage THD and current THD of single phase PV inverter.

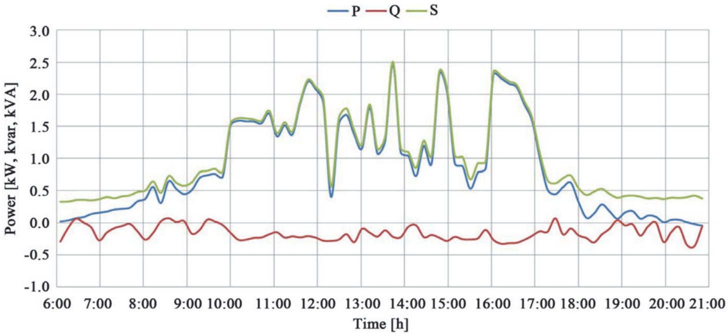


Figure 4. Measured power values of single phase PV inverter.

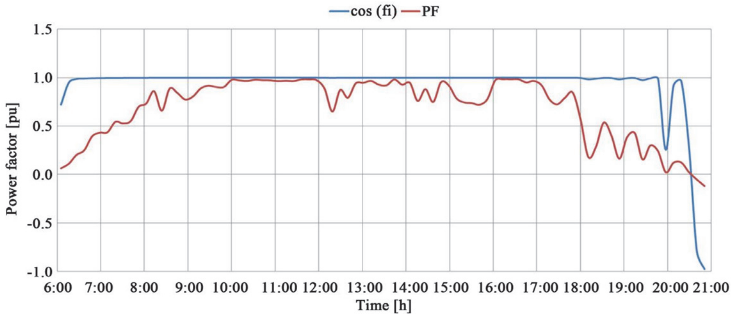


Figure 5. Measured power factors of single phase PV inverter.

Table 1. Initial modelled voltage [V] and current [A] values.

U_a	U_b	U_c	I_a	I_b	I_c	I_n
230	230	231	1.0	1.3	1.3	0.7

Table 2. Initial modelled voltage THD [%] and PF values.

THD_a	THD_b	THD_c	PF_a	PF_b	PF_c
2.9	2.1	3.2	1.00	0.92	0.84

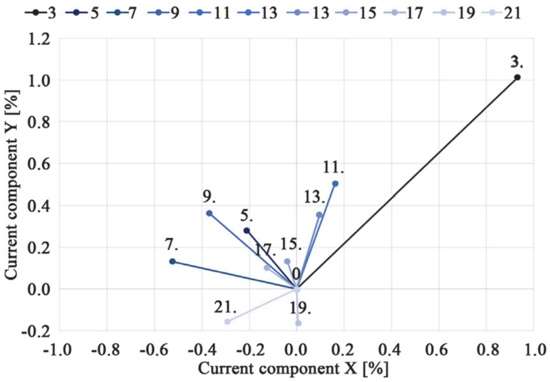


Figure 6. Mean harmonic current vectors (from 3rd to 21st order) in percentages compared to fundamental harmonic current vector (1st order) values of single phase PV inverter.

Table 3. Initial modelled active [kW] and reactive power [kvar] values.

P_a	P_b	P_c	Q_a	Q_b	Q_c
0.23	0.28	0.25	−0.01	−0.12	−0.16

Table 4. Measured values for single phase PV inverter.

Power level	1% - 30%	2% - 60%	3% - 100%
THD_U [%]	1.01	0.82	1
THD_I [%]	4.27	1.98	1.67
U_{rms} [V]	233.6	238.8	239.1
I_{rms} [A]	3.45	9.08	11.73
P [W]	739	2125	2783
Q [var]	322	−425	−257
S [VA]	807	2168	2805
cos(fi)	1	1	1
PF	0.92	0.98	0.99

Table 5. Harmonic currents of single phase PV inverter.

Order	I_1 [%]	I_2 [%]	I_3 [%]	I_mean [%]
1	100	100	100	100
3	1.92	1.2	1.01	1.38
5	0.48	0.31	0.26	0.35
7	1.08	0.27	0.27	0.54
9	0.88	0.33	0.35	0.52
11	0.89	0.38	0.32	0.53
13	0.69	0.21	0.2	0.37
15	0.23	0.08	0.1	0.14
17	0.35	0.07	0.06	0.16
19	0.29	0.1	0.1	0.16
21	0.63	0.2	0.17	0.33

Table 6. Harmonic current phase angles of single phase PV inverter.

Order	Angle_1 [˚]	Angle_2 [˚]	Angle_3 [˚]	Angle_mean [˚]
1	0	0	0	0
3	28	62	52	47
5	97	146	139	127
7	175	159	164	166
9	116	145	146	135
11	104	60	52	72
13	75	73	77	75
15	109	104	107	107
17	88	145	190	141
19	287	259	271	272
21	209	205	209	208

Table 7. Modelled voltage [V] and current [A] values for first case.

Phasing	U_a	U_b	U_c	I_a	I_b	I_c	I_n
PV in A	246	223	229	11.0	1.3	1.3	12.3
PV in B	228	245	224	1.0	10.8	1.3	11.2
PV in C	224	228	246	1.0	1.3	10.9	12.3

Table 8. Modelled voltage THD [%] and PF values for first case.

Phasing	THD_a	THD_b	THD_c	PF_a	PF_b	PF_c
PV in A	2.7	2.2	3.2	−1	0.91	0.85
PV in B	3	2.1	3.3	1	−1	0.83
PV in C	3	2.1	3	1	0.93	−1

Table 9. Modelled active [kW] and reactive power [kvar] values for first case.

Phasing	P_a	P_b	P_c	Q_a	Q_b	Q_c
PV in A	−2.58	0.28	0.25	0.23	−0.13	−0.16
PV in B	0.23	−2.54	0.25	−0.01	0.13	−0.17
PV in C	0.24	0.28	−2.56	−0.02	−0.11	0.09

B) *Second Case—EV*

Measurements were recorded for the charging of five different EVs. Power and THD values while EVs were charging at constant power level are presented in Table 10. As the power values (P and Q) were quite similar for all five EVs, the current distortion varied more. Three EVs out of five had current distortion around 10%…12% and two had substantially lower values, around 3%…4%.

The characteristics of individual current harmonic magnitudes and phase angles for odd harmonics during the constant power charging are presented in Table 11 and Table 12. The highest current amplitudes were observed at 3rd, 5th, 7th and 13th orders. For successful modelling, the mean values based on five EVs were calculated. The arithmetic mean of amplitudes (AM) and geometric mean for phase angles (GM) was calculated as follows:

Table 10. General data for EVs during constant power charging time.

EV	P [kW]	Q [kVAr]	THD_I [%]
1	2.2	0.2	4.2
2	2.4	0.5	12.3
3	2.9	0.2	3.4
4	2.4	0.1	10.5
5	2.2	0.4	11.2
Mean	2.5	0.3	8.1

Table 11. Harmonic current amplitudes [%] of EVs.

Order	EV 1	EV 2	EV 3	EV 4	EV 5	Arithmetic mean
1	100	100	100	100	100	100
3	8.7	11.9	3.3	2.6	11.1	7.5
5	3.7	0.4	0.9	2	2.3	1.9
7	3.1	0.6	0.9	1.1	1.4	1.4
9	1.2	0.6	0.2	0.5	1.5	0.8
11	0.8	1.1	0.9	0.7	1	0.9
13	1.7	1.1	1.3	0.9	0.8	1.2
15	0.4	0.6	0.3	0.3	0.9	0.5
17	0.4	0.5	0.1	0.1	0.2	0.3
19	0.7	0.3	0.1	0.3	0.2	0.3
21	0.8	0.3	0.4	0.9	0.4	0.6

Table 12. Harmonic current phase angles [˚] of EVs.

Order	EV 1	EV 2	EV 3	EV 4	EV 5	Geometric mean
1	0	0	0	0	0	0
3	8	33	158	327	6	39
5	157	180	335	338	294	248
7	255	269	205	213	299	245
9	46	120	287	320	126	145
11	326	256	20	67	221	120
13	30	305	298	334	26	119
15	257	199	30	194	142	133
17	207	162	246	247	291	226
19	40	168	313	55	219	121
21	154	304	165	217	166	195

$$AM = \frac{1}{n}\left(a_1 + a_2 + \cdots + a_n\right) \tag{5}$$

$$GM = \sqrt[n]{a_1 \cdot a_2 \cdot \cdots \cdot a_n} \tag{6}$$

The most significant individual harmonics (3rd and 5th) are illustrated in **Figure 7** and **Figure 8**. As evident from the figures, the directions of the currents are different.

In this case, mean EV was added to the grid at the residential busbar at different phases one at a time. The resulting voltages and currents are shown in **Table 13**, voltage THD and PF in **Table 14** and power values in **Table 15**.

The EV load causes voltage drop in phase where it is connected more than 5% in each case. Voltage THD was observed to increase up to 0.5% in two cases, but remained at same level when EV was connected to phase C. Power factor changed slightly due to additional EV load and slightly improved in the phase where it was connected.

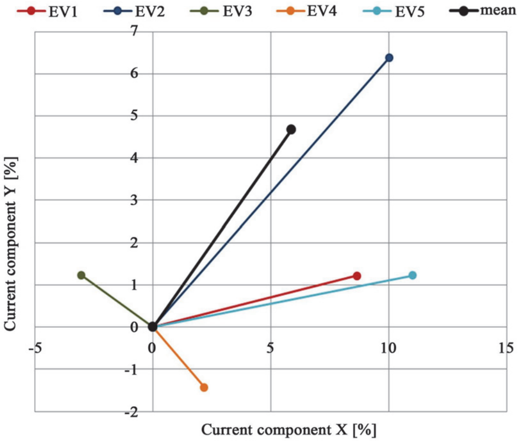


Figure 7. Third current harmonics of EVs.

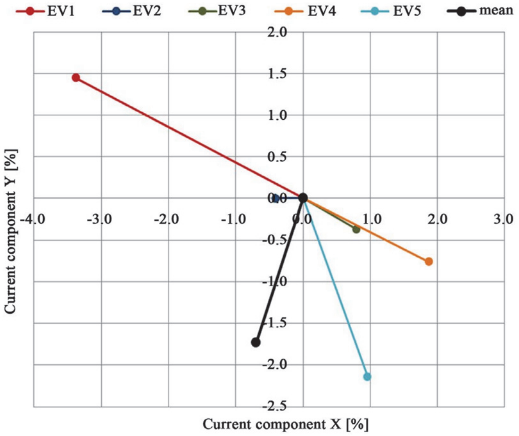


Figure 8. Fifth current harmonics of EVs.

Table 13. Modelled voltage [V] and current [A] values for second case.

Phasing	U_a	U_b	U_c	I_a	I_b	I_c	I_n
EV in A	214	235	235	12.8	1.3	1.3	11.6
EV in B	235	213	236	1.0	13.0	1.3	12.5
EV in C	235	234	215	1.0	1.3	12.8	11.3

Table 14. Modelled voltage THD [%] and PF values for second case.

Phasing	THD_a	THD_b	THD_c	PF_a	PF_b	PF_c
EV in A	3.4	2.1	3.1	0.99	0.92	0.82
EV in B	2.8	2.6	3.0	1.00	1.00	0.85
EV in C	2.9	2.2	3.2	1.00	0.91	1.00

Table 15. Modelled active [kW] and reactive power [kvar] values for second case.

Phasing	P_a	P_b	P_c	Q_a	Q_b	Q_c
EV in A	2.86	0.28	0.24	0.32	−0.11	−0.17
EV in B	0.23	2.91	0.25	−0.02	0.21	−0.16
EV in C	0.23	0.27	2.87	−0.01	−0.13	0.17

C) *Third Case—PV and EV*

In this case, a PV and EV where both installed at the residential load's busbar. To investigate differences in harmonic cancellation, the PV and EV were installed both on the same phases as well as separate phases.

Voltages and currents are presented in Table 16. It was observed that in arrangements where PV and EV are in same phase voltage drops near to undesirable levels in the phase where the EV is connected while increasing over the 10% limit in the phase where the EV is connected. Also in those cases neutral currents rise much higher than phase currents. The best practice is to install both in same phase. Voltages over the 10% limit and high neutral currents are marked as bold in Table 16.

Voltage THD and PF values are presented in Table 17. In the worst case (EV in A and PV in C), voltage THD decreases in one phase up to 0.6%, but placing EV and PV both on the same phase can lead to slightly decreased voltage THD in some situations (EV in C and PV in C).

Placing the devices onto the same phase leads to slight growth of reactive power in the same phase as evident in Table 18. Active power is compensated due to opposite direction of power flow of the EV and PV.

5. Discussion

While the discreet disturbances of harmonic distortion may not cause immediate and easily-observed impacts, it can cause some equipment to malfunction, and result in additional power losses in both customer and network equipment [28]. As harmonic levels change considerably from one week to another, it is very difficult to assess the long-term evolution of harmonic levels only from measurements carried out over a short period [1]. This paper clearly concludes that power quality problems may occur when dispersed generation and powerful nonlinear load utilization is not sufficiently considered. Moreover, modern household devices tend to contain more power electronic circuits and therefore an increase of harmonic currents can also be expected even without the PVs or EVs.

Harmonic current angles of small generators such as PVs or powerful nonlinear loads such as EVs are seldom considered. For determining the impact of current harmonics on the network and the voltage harmonics, the actual harmonic current values would have to be used. One aim of this paper is to draw attention to this topic which could lead to advances in modelling nonlinear generations and loads with different topologies. To help mitigate harmonic distortion problems, models with appropriate harmonic current amplitudes and phase angles could be used to select most suitable devices.

Table 16. Modelled voltage [V] and current [A] values for third case.

Phasing	U_a	U_b	U_c	I_a	I_b	I_c	I_n
EV in A and PV in A	231	228	232	2.2	1.3	1.3	3.3
EV in A and PV in B	212	**250**	229	12.9	10.7	1.3	**18.3**
EV in A and PV in C	207	234	**250**	13.1	1.3	10.8	**22.1**
EV in B and PV in A	**250**	206	235	10.9	13.3	1.3	**22.6**
EV in B and PV in B	232	230	229	1.0	1.8	1.3	2.3
EV in B and PV in C	229	211	**251**	1.0	13.1	10.8	**19.5**
EV in C and PV in A	**250**	228	212	10.9	1.3	12.9	**18.8**
EV in C and PV in B	234	**249**	208	1.0	10.8	13.1	**21.4**
EV in C and PV in C	228	231	231	1.0	1.3	1.6	2.5

Table 17. Modelled voltage THD [%] and PF values for third case.

Phasing	THD_a	THD_b	THD_c	PF_a	PF_b	PF_c
EV in A and PV in A	3.2	2.2	3.1	−0.12	0.92	0.84
EV in A and PV in B	3.4	2.1	3.2	0.99	−1.00	0.82
EV in A and PV in C	3.5	2.1	2.9	1.00	0.93	−1.00
EV in B and PV in A	2.6	2.6	3.0	−1.00	1.00	0.86
EV in B and PV in B	2.9	2.4	3.1	1.00	−0.04	0.84
EV in B and PV in C	2.8	2.6	2.8	1.00	1.00	−1.00
EV in C and PV in A	2.6	2.3	3.2	−1.00	0.90	1.00
EV in C and PV in B	2.9	2.2	3.3	1.00	−1.00	1.00
EV in C and PV in C	2.9	2.2	2.9	1.00	0.92	−0.14

Table 18. Modelled active [kW] and reactive power [kvar] values for third case.

Phasing	P_a	P_b	P_c	Q_a	Q_b	Q_c
EV in A and PV in A	−0.06	0.28	0.25	0.51	−0.12	−0.16
EV in A and PV in B	2.86	−2.53	0.25	0.37	0.14	−0.17
EV in A and PV in C	2.91	0.28	−2.58	0.29	−0.11	0.09
EV in B and PV in A	−2.59	2.96	0.25	0.23	0.18	−0.15
EV in B and PV in B	0.23	−0.02	0.25	−0.01	0.42	−0.16
EV in B and PV in C	0.23	2.92	−2.56	−0.02	0.27	0.1
EV in C and PV in A	−2.57	0.28	2.88	0.24	−0.13	0.22
EV in C and PV in B	0.23	−2.55	2.93	0	0.13	0.14
EV in C and PV in C	0.23	0.28	−0.05	−0.01	−0.12	0.37

This study only examines one household and one PV or EV at time. The described effects may escalate when a larger number of devices are considered. Special attention is needed in situations where devices have similar harmonic patterns and the harmonic cancellation effect is minimal and grid is weak. General values for further modelling of PVs and EVs were presented in this paper, but additional measurements should be performed to obtain unified values for modelling PV generators and EV loads more accurately. It would be necessary to have measurement data extending over entire years in order to acquire results independent of any disturbance. Furthermore, flicker and voltage level issues should be accounted for as they may have a significant influence in real applications.

6. Conclusions

Firstly, it can be concluded that current harmonic distortion of the PV's output is notably correlated with current and distortion decreases when the PV is operating at a higher loading level. The same conclusion can be made by observing the PF value of the PV which approaches unity with increasing current. Whereas when PF varied considerably, cos(φ) remained near unity throughout the measurement period, which means that main order reactive power is compensated more efficiently than higher order reactive power. EVs showed higher current distortions than PV. Three EVs out of five had current distortion around 10%…12% and two had substantially lower values, around 3%…4%.

Voltage distortion may rise when PVs and EVs are connected to a residential load. The rise is much dependant on grid strength and worse situation may occur in cases where less powerful transformers and thinner cables are utilized. The present study showed that most reasonable option is to connect both PV and EV on same phase. Installing the EVs and PVs separately or installing both on separate phases, results in notable increase in voltage distortion.

Even more severe changes occurred with voltage amplitudes and neutral currents. In cases where PV and EV both were installed, voltage in the phases where PV was connected rose over the 10% limit. Also the neutral currents rose nearly two times higher than phase currents where PV and EV where connected in separate phases. It concludes that modelling with different transformer powers and cable lengths and thicknesses should be conducted before installing nonlinear devices.

References

[1] Berthet, L., Eyrolles, P., Gauthier, J. and Sabeg, S. (2007) Harmonic Level Measurements on French Low-Voltage Networks. 19*th International Conference on Electricity Distribution*, Vienna, 21-24 May 2007.

[2] Rawa, M.J.H., Thomas, D.W.P. and Sumner, M. (2011) Simulation of Non-Linear Loads for Harmonic Studies. 11*th International Conference on Electrical Power Quality and Utilisation* (*EPQU*), Lisbon, 17-19 October 2011, 1-6. http://dx.doi.org/10.1109/EPQU.2011.6128915

[3] Niitsoo, J. and Palu, I. (2011) Distorted Load Impacts on Distribution Grid. *Proceedings of the* 12*th International Scientific Conference Electric Power Engineering* 2011, Kouty nad Desnou.

[4] Desmet, J., Debruyne, C., Vanalme, J. and Vandevelde, L. (2010) Power Injection by Distributed Generation and the Influence of Harmonic Load Conditions. *IEEE Power and Energy Society General Meeting*, Minneapolis, 25-29 July 2010, 1-6. http://dx.doi.org/10.1109/pes.2010.5590123

[5] Jayasekara, N. and Wolfs, P. (2010) Analysis of Power Quality Impact of High Penetration PV in Residential Feeders. 20*th Australasian Universities Power Engineering Conference* (*AUPEC*), Christchurch.

[6] Renders, B., Degroote, L., Driesen, J. and Vandevelde, L. (2007) Profits of Power-Quality Improvement by Residential Distributed Generation. 42*nd International Universities Power Engineering Conference*, Brighton, 4-6 September 2007, 377-381. http://dx.doi.org/10.1109/upec.2007.4468976

[7] Arghandeh, R., Onen, A., Jung, J. and Broadwater, R. (2013) Harmonic Interactions of Multiple Distributed Energy Resources in Power Distribution Networks. *Electric Power Systems Research*, **105**, 124-133. http://dx.doi.org/10.1016/j.epsr.2013.07.018

[8] Aiello, M., Cataliotti, A., Favuzza, S. and Graditi, G. (2006) Theoretical and Experimental Comparison of Total Harmonic Distortion Factors for the Evaluation of Harmonic and Interharmonic Pollution of Grid-Connected Photovoltaic Systems. *IEEE Transactions on Power Delivery*, **21**, 1390-1397. http://dx.doi.org/10.1109/TPWRD.2005.860231

[9] Shao, S.P.M. (2011) Demand Response as a Load Shaping Tool in an Intelligent Grid with Electric Vehicles. *IEEE Transactions on Smart Grid*, **2**, 624-631. http://dx.doi.org/10.1109/TSG.2011.2164583

[10] Kütt, L., Saarijärvi, E., Lehtonen, M. and Niitsoo, J. (2013) A Review of the Harmonic and Unbalance Effects in Electrical Distribution Networks Due to EV Charging. 13*th International Conference on Environment and Electrical Engineering* (*EEEIC*), Wroclaw.

[11] Yong, J., Chen, L. and Chen, S. (2010) Modeling of Home Appliances for Power Distribution System Harmonic

Analysis. *IEEE Transactions on Power Delivery*, **25**, 3147-3155. http://dx.doi.org/10.1109/TPWRD.2010.2051960

[12] Jensen, M.M. and Hansen, H. (2014) Triplen Harmonic Voltage Distortion in the Low-Voltage Network. *NORDAC* 2014, Stockholm.

[13] Block, P., Salamanca, H., Teixeira, M., Dahlke, D., Shiono, O. and Dodadon, A. (2014) Power Quality Analyses of a Large Scale Photovoltaic System. *The fifth International Renewable Energy Congress IREC* 2014, Hammamet, 25-27 March 2014, 1-6. http://dx.doi.org/10.1109/irec.2014.6826946

[14] Kontogiannis, K., Vokas, G., Nanou, S. and Papathanassiou, S. (2013) Power Quality Field Measurements on PV Inverters. *International Journal of Advanced Research in Electrical Electronics and Instrumentation Engineering*, **2**, 5301-5314.

[15] Ortega, M., Hernández, J. and García, O. (2013) Measurement and Assessment of Power Quality Characteristics for Photovoltaic Systems: Harmonics, Flicker, Unbalance, and Slow Voltage Variations. *Electric Power Systems Research*, **96**, 23-35. http://dx.doi.org/10.1016/j.epsr.2012.11.003

[16] Anwari, M., Hamid, M. and Taufik (2008) Power Quality Behavior of Single Phase Fed Adjustable Speed Drive Supplied from Grid of PV Generation. *The* 2*nd IEEE International Conference on Power and Energy* (*PECon* 08), Bahru, 1-3 December 2008, 1098-1102.

[17] van Lumig, M., Bhattacharyya, S., Gobben, J. and Kling, W. (2010) Power Quality Measurements Near DER and Disturbing Loads. *International Conference on Renewable Energies and Power Quality* (*ICREPQ*'11), Las Palmas de Gran Ganaria, 13-15 April 2010.

[18] Wang, Y.J., O'Connell, R. and Brownfield, G. (2001) Modeling and Prediction of Distribution System Voltage Distortion Caused by Nonlinear Residential Loads. *IEEE Transactions on Power Delivery*, **16**, 744-751. http://dx.doi.org/10.1109/61.956765

[19] Berisha, S., Karady, G., Ahmad, R., Hobbs, R. and Karner, D. (1996) Current Harmonics Generated by Electric Vehicle Battery Chargers. *Proceedings of the* 1996 *International Conference on Power Electronics*, *Drives and Energy Systems for Industrial Growth*, New Delhi, 8-11 January 1996, 584-589.

[20] Zamri, M., Wanik, C., Fadzil, M., Siam, M., Ayob, A., Yanto, S., Azah, M., Azit, A., Sulaiman, S., Azrin, M., Ali, M., Hussein, Z.F., Kamil, A. and Hussin, M. (2013) Harmonic Measurement and Analysis during Electric Vehicle Charging. *Engineering*, **5**, 215-220.

[21] Melo, N., Mira, F., de Almeida, A. and Delgado, J. (2011) Integration of PEV in Portuguese Distribution Grid: Analysis of Harmonic Current Emissions in Charging Points. 11*th International Conference on Electrical Power Quality and Utilisation* (*EPQU*), Lisbon, 17-19 October 2011, 1-6. http://dx.doi.org/10.1109/EPQU.2011.6128893

[22] Wenge, C., Stotzer, M., Winkler, T. and Komarnicki, P. (2011) Power Quality Measurements of Electric Vehicles in the Low Voltage Power Grid. 11*th International Conference on Electrical Power Quality and Utilisation* (*EPQU*) Lisbon, 17-19 October 2011, 1-5. http://dx.doi.org/10.1109/EPQU.2011.6128866

[23] Fekete, K., Klaic, Z. and Majdandzic, L. (2012) Expansion of the Residential Photovoltaic Systems and Its Harmonic Impact on the Distribution Grid. *Renewable Energy*, **43**, 140-148. http://dx.doi.org/10.1016/j.renene.2011.11.026

[24] McBee, K. and Simoes, M. (2012) Evaluating the long-Term Impact of a Continuously Increasing Harmonic Load Demand on Feeder Level Voltage Distortion. 2012 *IEEE Industry Applications Society Annual Meeting* (*IAS*), Las Vegas, 7-11 October 2012, 1-8. http://dx.doi.org/10.1109/IAS.2012.6374086

[25] Au, M.T., Navamany, J. and Yeoh, E.C. (2010) Impact of Medium Power Inverter-Based Residential Harmonic Loads and PFCs on Low Voltage Lines. 2010 *IEEE International Conference on Power and Energy* (*PECon*), Kuala Lumpur, 29 November-1 December 2010, 695-699. http://dx.doi.org/10.1109/pecon.2010.5697669

[26] EN 50160:2010 (2010) Voltage Characteristics in Public Distribution Systems. European Standard.

[27] Niitsoo, J., Kilter, J., Palu I., Taklaja, P. and Kütt, L. (2013) Harmonic Levels of Domestic and Electrical Vehicle Loads in Residential Distribution Networks. *Proceedings of AFRICON* 2013, Mauritius, 9-12 September 2013, 1-5. http://dx.doi.org/10.1109/AFRCON.2013.6757800

[28] Niitsoo, J., Palu, I., Kilter, J., Taklaja, P. and Vaimann, T. (2013) Residential Load Harmonics in Distribution Grid. *Proceedings of* 3*rd International Conference on Electric Power and Energy Conversion Systems* (*EPECS* 2013), Istanbul, 2-4 October 2013, 1-6. http://dx.doi.org/10.1109/EPECS.2013.6713054

DISSERTATIONS DEFENDED AT TALLINN UNIVERSITY OF TECHNOLOGY ON *POWER ENGINEERING, ELECTRICAL ENGINEERING, MINING ENGINEERING*

1. **Jaan Tehver**. Boiling on Porous Surface. 1992.

2. **Aleksandrs Cars**. Woodhips Combustion Technology. 1992.

3. **Endel Risthein**. Electricity Supply of Industrial Plants. 1993.

4. **Tõnu Trump**. Some New Aspects of Digital Filtering. 1993.

5. **Vello Sarv.** Synthesis and Design of Power Converters with Reduced Distortions Using Optimal Energy Exchange Control. 1994.

6. **Ivan Klevtsov**. Strained Condition Diagnosis and Fatigue Life Prediction for Metals under Cyclic Temperature Oscillations. 1994.

7. **Ants Meister**. Some Phase-Sensitive and Spectral Methods in Biomedical Engineering. 1994.

8. **Mati Meldorf**. Steady-State Monitoring of Power System. 1995.

9. **Jüri-Rivaldo Pastarus**. Large Cavern Stability in the Maardu Granite Deposit. 1996.

10. **Enn Velmre**. Modeling and Simulation of Bipolar Semiconductor Devices. 1996.

11. **Kalju Meigas**. Coherent Photodetection with a Laser. 1997.

12. **Andres Udal**. Development of Numerical Semiconductor Device Models and Their Application in Device Theory and Design. 1998.

13. **Kuno Janson**. Paralleel- ja järjestikresonantsi parameetrilise vaheldumisega võrgusageduslik resonantsmuundur ja tema rakendamine. 2001.

14. **Jüri Joller**. Research and Development of Energy Saving Traction Drives for Trams. 2001.

15. **Ingo Valgma**. Geographical Information System for Oil Shale Mining – MGIS. 2002.

16. **Raik Jansikene**. Research, Design and Application of Magnetohydrodynamical (MHD) Devices for Automation of Casting Industry. 2003.

17. **Oleg Nikitin**. Optimization of the Room-and-Pillar Mining Technology for Oil-Shale Mines. 2003.

18. **Viktor Bolgov**. Load Current Stabilization and Suppression of Flicker in AC Arc Furnace Power Supply by Series-Connected Saturable Reactor. 2004.

19. **Raine Pajo**. Power System Stability Monitoring – an Approach of Electrical Load Modelling. 2004.

20. **Jelena Shuvalova**. Optimal Approximation of Input-Output Characteristics of Power Units and Plants. 2004.

21. **Nikolai Dorovatovski**. Thermographic Diagnostics of Electrical Equipment of Eesti Energia Ltd. 2004.

22. **Katrin Erg**. Groundwater Sulphate Content Changes in Estonian Underground Oil Shale Mines. 2005.

23. **Argo Rosin**. Control, Supervision and Operation Diagnostics of Light Rail Electric Transport. 2005.

24. **Dmitri Vinnikov**. Research, Design and Implementation of Auxiliary Power Supplies for the Light Rail Vehicles. 2005.

25. **Madis Lehtla**. Microprocessor Control Systems of Light Rail Vehicle Traction Drives. 2006.

26. **Jevgeni Šklovski**. LC Circuit with Parallel and Series Resonance Alternation in Switch-Mode Converters. 2007.

27. **Sten Suuroja**. Comparative Morphological Analysis of the Early Paleozoic Marine Impact Structures Kärdla and Neugrund, Estonia. 2007.

28. **Sergei Sabanov**. Risk Assessment Methods in Estonian Oil Shale Mining Industry. 2008.

29. **Vitali Boiko**. Development and Research of the Traction Asynchronous Multimotor Drive. 2008.

30. **Tauno Tammeoja**. Economic Model of Oil Shale Flows and Cost. 2008.

31. **Jelena Armas**. Quality Criterion of road Lighting Measurement and Exploring. 2008.

32. **Olavi Tammemäe**. Basics for Geotechnical Engineering Explorations Considering Needed Legal Changes. 2008.

33. **Mart Landsberg**. Long-Term Capacity Planning and Feasibility of Nuclear Power in Estonia under Certain Conditions. 2008.

34. **Hardi Torn**. Engineering-Geological Modelling of the Sillamäe Radioactive Tailings Pond Area. 2008.

35. **Aleksander Kilk**. Paljupooluseline püsimagnetitega sünkroongeneraator tuuleagregaatidele. 2008.

36. **Olga Ruban**. Analysis and Development of the PLC Control System with the Distributed I/Os. 2008.

37. **Jako Kilter**. Monitoring of Electrical Distribution Network Operation. 2009.

38. **Ivo Palu**. Impact of Wind Parks on Power System Containing Thermal Power Plants. 2009.

39. **Hannes Agabus**. Large-Scale Integration of Wind Energy into the Power System Considering the Uncertainty Information. 2009.

40. **Kalle Kilk**. Variations of Power Demand and Wind Power Generation and Their Influence to the Operation of Power Systems. 2009.

41. **Indrek Roasto**. Research and Development of Digital Control Systems and Algorithms for High Power, High Voltage Isolated DC/DC Converters. 2009.

42. **Hardi Hõimoja**. Energiatõhususe hindamise ja energiasalvestite arvutuse metoodika linna elektertranspordile. 2009.

43. **Tanel Jalakas**. Research and Development of High-Power High-Voltage DC/DC Converters. 2010.

44. **Helena Lind**. Groundwater Flow Model of the Western Part of the Estonian Oil Shale Deposit. 2010.

45. **Arvi Hamburg**. Analysis of Energy Development Perspectives. 2010.

46. **Mall Orru**. Dependence of Estonian Peat Deposit Properties on Landscape Types and Feeding Conditions. 2010.

47. **Erik Väli**. Best Available Technology for the Environmentally Friendly Mining with Surface Miner. 2011.

48. **Tarmo Tohver**. Utilization of Waste Rock from Oil Shale Mining. 2011.

49. **Mikhail Egorov**. Research and Development of Control Methods for Low-Loss IGBT Inverter-Fed Induction Motor Drives. 2011.

50. **Toomas Vinnal**. Eesti ettevõtete elektritarbimise uurimine ja soovituste väljatöötamine tarbimise optimeerimiseks. 2011.

51. **Veiko Karu**. Potential Usage of Underground Mined Areas in Estonian Oil Shale Deposit. 2012.

52. **Zoja Raud**. Research and Development of an Active Learning Technology for University-Level Education in the Field of Electronics and Power Electronics. 2012.

53. **Andrei Blinov**. Research of Switching Properties and Performance Improvement Methods of High-Voltage IGBT based DC/DC Converters. 2012.

54. **Paul Taklaja**. 110 kV õhuliinide isolatsiooni töökindluse analüüs ja töökindluse tõstmise meetodid. 2012.

55. **Lauri Kütt**. Analysis and Development of Inductive Current Sensor for Power Line On-Line Measurements of Fast Transients. 2012.

56. **Heigo Mõlder**. Vedelmetalli juhitava segamisvõimaluse uurimine alalisvoolu kaarleekahjus. 2012.

57. **Reeli Kuhi-Thalfeldt**. Distributed Electricity Generation and its Possibilities for Meeting the Targets of Energy and Climate Policies. 2012.

58. **Irena Milaševski**. Research and Development of Electronic Ballasts for Smart Lighting Systems with Light Emitting Diodes. 2012.

59. **Anna Andrijanovitš**. New Converter Topologies for Integration of Hydrogen Based Long-Term Energy Storages to Renewable Energy Systems. 2013.

60 **Viktor Beldjajev**. Research and Development of the New Topologies for the Isolation Stage of the Power Electronic Transformer. 2013.

61. **Eduard Brindfeldt**. Visually Structured Methods and Tools for Industry Automation. 2013.

62. **Marek Mägi**. Development and Control of Energy Exchange Processes Between Electric Vehicle and Utility Network. 2013.

63. **Ants Kallaste**. Low Speed Permanent Magnet Slotless Generator Development and Implementation for Windmills. 2013.

64. **Igor Mets**. Measurement and Data Communication Technology for the Implementation in Estonian Transmission Network. 2013.

65. **Julija Šommet**. Analysis of Sustainability Assessment in Carbonate Rock Quarries. 2014.

66. **Tanel Kivipõld**. Real-Time Electricity Tariff System for Retail Market. 2014.

67. **Priit Uuemaa**. Industrial CHP Optimal Management Model in the Energy Market under Incomplete Information. 2014.

68. **Anton Rassõlkin**. Research and Development of Trial Instrumentation for Electric Propulsion Motor Drives. 2014.

69. **Toomas Vaimann**. Diagnostics of Induction Machine Rotor Faults Using Analysis of Stator Signals. 2014.

70. **Aivar Auväärt**. Development of Energy Reserve Optimization Methodology for Households with Renewable Power Systems. 2014.

71. **Raivo Attikas**. Modelling of Control Systems and Optimal Operation of Power Units in Thermal Power Plants. 2014.

72. **Liisa Liivik**. Semiconductor Power Loss Reduction and Efficiency Improvement Techniques for the Galvanically Isolated Quasi-Z-Source DC-DC Converters. 2015.

73. **Victor Astapov**. Technical-Economic Analysis of Distributed Generation Units in Power Systems. 2015.

74. **Tiit Hõbejõgi**. Possibilities to Optimize Low Voltage Network Investments in Rural Areas. 2016.

75. **Märt Ots**. Practical Implementation of Price Regulation in Energy Sector. 2016.

76. **Ilja Bakman**. High-Efficiency Predictive Control of Centrifugal Multi-Pump Stations with Variable-Speed Drives. 2016.

77. **René Nukki**. Research and Development of Exterior-Rotor Permanent Magnet Synchronous Machines for Light Aerial Vehicles. 2016.

78. **Imre Drovtar**. Demand Side Management Possibilities and Viability for Voltage Support Services in Estonia. 2016.

79. **Andrii Chub**. Research, Design and Implementation of Galvanically Isolated Impedance-Source DC-DC Converters. 2016.