Impact of Modern Lighting Technology on the Power Line Communications Channel

by

Allan Ashraf Emleh

A thesis submitted to the Faculty of Engineering and the Built Environment in the fulfillment of the requirements for the degree of

Doctor Ingeneriae

in

Electrical and Electronic Engineering Science

at the

University of Johannesburg

Supervisor: Prof. Hendrik C. Ferreira

Co-supervisor: Dr. Arnold S. de Beer

November 2017

Abstract

In this study, we look at the impact of modern lighting technology on Power Line Communications (PLC). Power Line Communications has become important due to the Smart Grid and Internet of Things (IoT) development. Modern lighting technology has been developed to make efficient use of electric energy. This technology uses power converters to enable the use of different lighting sources. A byproduct of this conversion process is electronic noise. This noise can interfere with the PLC channel. In this study, different lighting technologies are investigated from a noise standpoint and compared to PLC signal levels. Both narrowband and broadband PLC frequency ranges are investigated. This study shows that the influence of noise on the PLC channel depends predominantly on the conversion topology as well as whether filters have been used. The measurement results show that the influence on data communication system can vary in impact from low to severe. Results were obtained for low energy, high energy, indoor and outdoor lighting sources. A common front end topology encounted is the bridge rectifier and high frequency DC-DC converter combination. These topologies are investigated in details. The study presented here shows that lighting technology (causing interference) needs special consideration when designing PLC systems. Of particular importance is the use of filters which ensure compliance with interference standards and limit the noise effects on the PLC signal.

Acknowledgements

- My sincere and deep gratitude goes to my promoter, Professor Hendrik Ferreira for his genuine academic and financial support, as well as his encouragement, guidance and inspiration during the journey of this research.

- A strong word of thanks to my co-supervisor Dr. Arnold de Beer for the support and friendly environment he offered during this research.

- To my parents, wife, and kids: thank you for the continued love and appreciation.

- I thank Prof. Han Vinck for his valuable comments and help, as well as Prof. Theo Swart for his proofreading.

- I also thank all my colleagues at the Department of Electrical & Electronic Engineering Science, University of Johannesburg, for creating a friendly platform to conduct research.

Author’s Publications

Journal Publications

1. A. Emleh, A. S. de Beer, L. Cheng, H. C. Ferreira and A. J. H. Vinck, “Analysis of a Bridge Rectifier and High Frequency Converters Used in LED Lighting and the Impact on the PLC Channel,” *Submitted to the International Journal of Electronics and Communications*, November 2017.

Conference Publications

1. A. Emleh, A. S. de Beer, L. Cheng, H. C. Ferreira and A. J. H. Vinck, “An Overview of Colour LED & CFL Lighting Interference on the Low Voltage PLC Network,” *Proceedings of the IEEE International Conference on Telecommunications and Signal Processing*, Barcelona, Spain, July 5-7, 2017, pp. 220 – 224.

2. A. S. de Beer, A. Emleh, H. C. Ferreira and A. J. H. Vinck, “Influence of LED Tubes on the Throughput of an Indoor Broadband PLC Channel,” *Proceedings of the IEEE International Conference on Telecommunications and Signal Processing*, Barcelona, Spain, July 5-7, 2017, pp. 251 – 254.

3. A. Emleh, A. S. de Beer, H. C. Ferreira and A. J. H. Vinck, “Noise Generated by Modern Lamps and the Influence on the Smart-Grid Communication Network,” *Proceedings of the IEEE International Conference on Smart Grid Communications*, Miami, FL, USA, November 2-5, 2015, pp. 7 – 12.

4. A. Emleh, A. S. de Beer, H. C. Ferreira and A. J. H. Vinck, “On Mercury Vapor Lamps and Their Effect on the Smart-Grid PLC Channel,” *Proceedings of the IEEE*

International Conference on Applied Measurements for Power Systems, Aachen, Germany, September 23-25, 2015, pp. 78 – 83.

5. A. Emleh, A. S. de Beer, H. C. Ferreira and A. J. H. Vinck, “The Influence of High Pressure Sodium Lamps on the Power Line Communications Channel,” *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications*, Austin, TX, USA, March 29 - April 1, 2015, pp. 172 – 177.

6. A. Emleh, A. S. de Beer, H. C. Ferreira and A. J. H. Vinck, “The Influence of Fluorescent Lamps with Electronic Ballast on the Low Voltage PLC Network,” *Proceedings of the IEEE International Power Engineering and Optimization Conference*, Langkawi, Malaysia, March 24-25, 2014, pp. 276 – 280.

7. A. Emleh, “The Impact of the Light Sources on the Low Voltage PLC Network,” *Proceedings of the International Workshop on Advances in Communications*, Boppard, Germany, ISBN: 978-3-9813030-7-0, May 14-16, 2014, p. 34.

8. A. Emleh, A. S. de Beer, H. C. Ferreira and A. J. H. Vinck, “Effects of Plasma Lamps on the Power-line Communications Channel,” *Proceedings of the IEEE International Symposium on Electronics in Marine*, Zadar, Croatia, September 25-27, 2013, pp. 125 – 128.

9. A. Emleh, A. S. de Beer, H. C. Ferreira and A. J. H. Vinck, “The Impact of the CFL Lamps on the Powerline Communications Channel,” *Proceedings of the IEEE International Symposium on Power Line Communications and its Applications*, Johannesburg, South Africa, March 24-27, 2013, pp. 225 – 229.

10. A. S. de Beer, A. Emleh, H. C. Ferreira and A. J. H. Vinck, “Effects of LED Lamps on the Power-line Communications Channel,” *Proceedings of the IEEE International Symposium on Power Line Communications and its Applications*, Johannesburg, South Africa, March 24-27, 2013, pp. 209 – 213.

Other Publications

1. A. Sheri, A. S. de Beer, S. Padmanaban, A. Emleh and H. C. Ferreira, “Characterization of a Power Line Cable for Channel Frequency Response — Analysis and Investigation,” *Proceedings of the IEEE International Conference on Environment and Electrical Engineering and IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, Milan, Italy, June 6-9, 2017, pp. 1 – 4.

2. A. Emleh, “Interference Detection of Modern Light Sources on PLC Network,” *Proceedings of the IEEE SA ITSC Workshop on Visible Light Communications and its Applications,* Johannesburg, South Africa, November 17, 2016, pp. 3 – 4.

3. A. Emleh and H. C. Ferreira, “The Effect of the Light Sources on the Transmission Lines of the Low Voltage Network,” *Proceedings of the IEEE Seminar on Future Directions & African Winter School on Information Theory and Communications*, Protea Kruger Gate, South Africa, August 16-21, 2015, p. 18.

4. D. E. D. Farouk, A. Emleh and H. C. Ferreira, “Using Street Lights for Transmitting, Broadcasting and Controlling Communication Signals Over Low Voltage PLC Network” , *Proceedings of the IEEE Seminar on Future Directions & African Winter School on Information Theory and Communications*, Protea Kruger Gate, South Africa, August 16-21, 2015, p. 15.

5. A. Emleh, A. S. de Beer, H. C. Ferreira and A. J. H. Vinck, “Noise Detection on the Low Voltage Network PLC Channel for Direct and Indirect Connections,” *Proceedings of the IEEE Mediterranean Electrotechnical Conference*, Beirut, Lebanon, April 13-16, 2014, pp. 203 – 207.

6. M. Wilson, H. C. Ferreira, R. Heymann and A. Emleh, “Bit Error Recording and Modelling of In-Vehicle Power Line Communication”, *Proceedings of the IEEE International Symposium on Power Line Communications and its Applications*, Glasgow, Scotland, March 30 - April 2, 2014, pp. 58 – 63.

7. E. Cocker, F. Ghazzi, U. Speidel, M. C. Dong, V. Wong, A. J. H. Vinck, H. Yamamoto, H. Yokoo, H. Morita, H. C. Ferreira, A. Emleh, R. McFadzien, S. Palelei and R. Eimann, “Measurement of Buffer Requirement Trends for Real Time Traffic Over TCP,” *Proceedings of the IEEE International Conference on High Performance Switching and Routing*, Vancouver, Canada, pp. 120 – 124, 1-4 July 2014.

8. A. Emleh, A. S. de Beer, H. C. Ferreira and A. J. H. Vinck, “Interference Detection on Power-line Communications Channel When In-Building Wiring System Acts as an Antenna,” *Proceedings of the IEEE International Symposium on Electronics in Marine*, Zadar, Croatia, September 25-27, 2013, pp. 141 – 144.

9. A. Emleh, H. C. Ferreira, A. J. Han Vinck and A. Snyders, “Received Noise on Powerline Communications where the In-Building Wiring Acts as an Antenna,” *Proceedings of the IEEE AFRICON Conference*, Livingstone, Zambia, September 13-15, 2011, pp. 1 – 6.

10. A. Emleh and H. C. Ferreira, “Experimental Results on the Impulsive Noise measurements in a Narrowband Powerline Communications Channel,” *Proceedings of the IEEE African Winter School on Information Theory and Communications*, Kruger National Park, South Africa, ISBN number: 978-3-9813030-2-5, June 1-4, 2010, p. 10.

11. A. Emleh, “Impulsive Noise Measurements in Narrowband Powerline Communications Channel,” Proceedings of the Germany-Africa Workshop on Information and Communication Technology, Essen, Germany, ISBN: 3-9807929-9-4, November 11-13, 2008, p. 21.

Table of Contents

List of Figures

List of Tables

List of Acronyms

AC	Alternating Current
ARIB	Association of Radio Industries and Businesses
BB	Broadband
CENELEC	Comité Européen De Normalisation Electrotechnique
CFL	Compact Fluorescent Lamp
CISPR	International Special Committee on Radio Interference
CM	Common Mode
CSK	Colour Shift Keying
CSMA	Carrier Sense Multiple Access
dB	Decibel
DC	Direct Current
DFT	Discrete Fourier Transform
DM	Differential Mode
DUT	Device Under Test
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
FCC	Federal Communications Commission
GPS	Global Positioning System
HDR	High Data Rate
HF	High Frequency
HID	High Intensity Discharge
HPSL	High Pressure Sodium Lamp
HV	High Voltage
Kb/s	Kilobit per Second
LED	Light Emitting Diode

LDR	Low Data Rate
LF	Low Frequency
LISN	Line Impedance Stabilisation Network
LV	Low Voltage
MF	Medium Frequency
MHL	Metal Halide Lamp
MV	Medium Voltage
MVL	Mercury Vapour Lamp
NB	Narrowband
OFDM	Orthogonal Frequency Division Multiplexing
PC	Personal Computer
PLC	Power Line Communication
PSK	Phase Shift Keying
SCR	Silicon Controlled Rectifier
SNR	Signal-To-Noise Ratio
SW	Short Wave
THD	Total Harmonic Distortion
UNB	Ultra-Narrowband
UWB	Ultra-Wideband
VLC	Visible Light Communication
VLF	Very Low Frequency
VHF	Very High Frequency

List of Symbols

$\overrightarrow{A_k}$	Antenna (Potential) Vector
A	Amplitude
Att	Required Attenuation
μ	Permeability
$\vec{k}$	Spatial Wave (Frequency) Vector
R	Resistance
Z_o	Characteristic Impedance
L	Inductance
L_{in}	Internal Inductance
L_{ex}	External Inductance
γ	Propagation Constant
f_o	Fundamental Frequency
f_c	Cut-off Frequency
f_{sw}	Switching Frequency
f	Frequency
μ_r	Relative Permeability
μ_o	Vacuum Permeability
σ	Conductivity
δ	Dissipation Factor of the Insulation
a	Radius of the Conductor
d	Distance Between Two Conductors

C	Capacitance
c	Speed of Light
G	Conductance
ϵ_r	Relative Permittivity
ϵ_o	Vacuum Permittivity
B	Bandwidth
$\frac{S}{N}$	Signal to Noise Ratio
λ	Wavelength
n	Multiplier for Fundamental Frequency
T	Period
V_{DC}	DC Voltage
V_L	Load Voltage
FF	Form Factor
R_L	Load Resistance
R_F	Forward Resistance
i_L	AC Current
I_{DC}	DC Current
I_L	Load Current

Chapter 1 – Introduction

The electrical power line channel is a harsh and challenging medium due to severe load and noise impairments [1]. Many research papers highlight the impact of the interference elements such as the radiated and conducted noise that affect the electric wiring systems when utilised as a medium for data communications purpose [2-4].

Information sent over the power line channel is comprised of bits or packets on the data link layer, using analogue electronic signals on the physical layer such as frequency-shift keying (FSK) and orthogonal frequency-division (OFD) modulated signals. Interference plays a major role within the power line channel in that it leads to the bits being lost or packets being corrupted. The unknown characteristics of the power cable, the undefined topology of the network and the unpredictable fluctuation of the power line impedance level, as well as the unpredictable interference sources, the dynamic of loads and impedance mismatching make the communication over the power line channel very difficult.

Nevertheless, power line communication (PLC) has started to gain momentum in the past two decades; especially the use of the power line channel as a component of a smart grid. In fact up to now, smart-metering has been an active research area in electrical engineering. In the future, every household can be connected to a data network of power lines where information and communications technology (ICT) services would be provided in real-time. This would be a more cost-effective method in comparison to other communication systems as the existing household wiring infrastructure that is connected to the power line network is utilised.

New business opportunities have been explored in the current market which have led to more research areas in the power line field and extensions of it. Visible light communication (VLC) is one of the new research areas that has been focused on as it can be an efficient way of communication [5]. A main disadvantage for this means of communications is that the power supplies of these light sources inject noise into the power line grid.

In this thesis, indoor and outdoor light sources and their effect on the power line network will be investigated. Light sources operate using the existing electric wiring grid where they can be considered one of the main applications having an influence on the PLC channel. The research presented here illustrates the common issues, as well as main differences among the different types of light sources whether they are indoor or outdoor, low energy or high energy. Energy saving lamps are widely used all around the world and this can affect the smart grids technology that uses PLC. Detailed comparisons of the different types of energy saving lamps is given and illustrated in this thesis.

Distortion of the voltage and current waveforms can cause a negative impact on the PLC channel. Light sources are one of the main interference factors that can create total harmonic distortion (THD) exceeding 90%. In this thesis we investigate a wide range of light sources from different technologies and highlight the negative impact of those light sources when the power line channel is utilised as a communications medium, since this research area is one of the major concerns with regard to the power quality within residential and industrial areas.

Different challenges in bandwidth and frequency limitations, as well as noise generation and interference factors have been addressed over the duration of our study. Additionally, the light sources' conducted and radiated harmonic emissions on the power line communications have been considered.

Most "old fashioned" and modern lamps create an undesirable noise on the power line network. In-building lights, street lamps and industry lighting had been considered in this study and a preliminary general lighting model is given for future studies of lighting sources.

1.1 LIGHTING TECHNOLOGIES

PLC uses electrical signals to carry information over the power line. The communication channel is defined as the transmission medium between two devices (nodes) upon which an exchange of data occurs [6, 7]. The quality of any communication depends on the amount of contamination on the channel itself. The main contamination factors on a communication channel are the interference from other sources as well as noise at the receiver, in addition to electrical signal attenuation at various frequencies. Higher noise levels make it more difficult to detect signals on the communication medium. Several researchers have studied the noise levels in their measurements on the power line grid [8-14]. Attenuation is dependent on the length of the cable and mismatched impedance within the power line grid. The input and output impedance within the grid varies with time, from a few milli-ohms to several kilo-ohms [8, 12, 14-17].

Various loads connected to the grid result in noise being generated on the power line channel. These loads include light sources used by households, municipalities and industries. Loads also act as signal "sinks" – low impedance for the PLC frequencies.

1.2 OVERVIEW OF LIGHT SOURCES

Using the existing wiring system inside and outside of buildings as a communication medium is a great opportunity for households, industries and academic researchers alike. This, however, has a number of hindrances, as noise and interference are the main challenges on the power line channel.

Light sources play a major role within this field because the power line system sees them as sources of noise. Light sources are usually connected directly to 220VAC mains and can be divided into two main parts: low energy and high energy light sources. The low energy light sources are usually used for indoor purposes and the high energy light sources are used for outdoor purposes.

The following explanation gives a short overview and introduction about each light source mentioned within this thesis. Further details about the light sources are given in Chapters 4 and 5.

1.2.1 Light Emitting Diodes

LED (Light Emitting Diode) lamps have recently come on to the market as energy efficient alternatives to incandescent light bulbs and are reported [18] to have 68% energy savings when compared to halogen lamps. Although energy effective, they inject conductive noise into the power line system. This can have a detrimental effect on the performance of a PLC system [19].

1.2.2 Compact Fluorescent Lamps and Fluorescent Tubes

In case of Compact Fluorescent Lamps (CFLs) and fluorescent tubes, distortion to the voltage and current waveforms in the in-building power line communications channel increases due to the harmonic impact caused by the CFLs and fluorescent tubes [20]. In this case, the current total harmonic distortion can exceed 100% [21].

To analyse the harmonic impact of large-scale in-building loads, we investigate the effects of the CFL lamps and fluorescent tubes when seen as interference sources on the power line communications channel since they are one of the main power-quality concerns in residential areas [22].

1.2.3 Plasma Lamps

A standard plasma lamp device is an indoor light source that uses an electric current which has an oscillating frequency of 35kHz and a range of 2 to 5 kilovolts. When a plasma lamp is powered, the gas mixture inside it gets ionised and usually gives rise to many beams of coloured light discharges which extends from the inner glass orb to the outer glass container. The outer glass container heats up to very high temperatures, not sufficient to determine a failure of the lamp but enough to cause light emissions. These lamps are ideal sources of static charge which could result in a very high voltage discharge even through different protective casings. To obtain the desired effects, plasma lamps use high frequency electric currents and present a series of potential hazards to different operators and other widely used electrical devices.

The operation of many house appliances and digital devices, such as the touch-pad of a laptop can easily get affected because of the high frequency of the current that can reach 35 kilohertz, which produces parasitic frequencies in the radio spectrum.

1.2.4 Metal Halide Lamps

The metal halide lamp (MHL) is a high energy light source, typically 150, 250, 400, 575 and 1200 watts, mostly used for outdoor purposes and is a compound mixture of gases, such as: metal with bromine, argon or iodine which gives an average luminosity of 65-115 lumens per watt, but require a few minutes of a warm-up period in order to reach the full light output status. MHLs are used for industrial, commercial, and public spaces, such as parking lots, factories, security lighting, street lighting, sports arenas and automotive headlamps. Fig. 1.1 shows the inside components of a metal halide lamp [23].

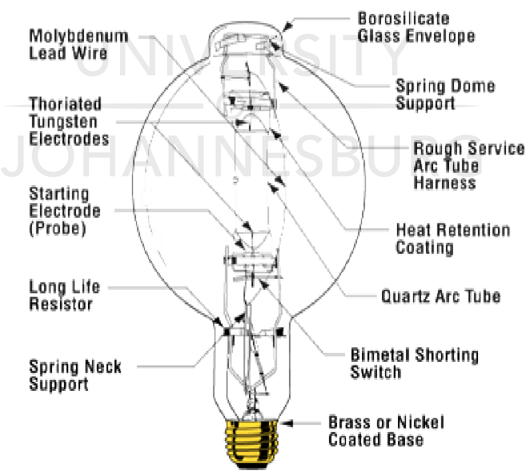

Figure 1.1: The inside structure of the metal halide lamp. From [24].

1.2.5 Mercury Vapor Lamps

Mercury vapor lamps (MVLs) are gas discharge lamps that are coated with phosphor on the outer bulb to provide thermal insulation and often protection from the ultraviolet radiation produced by the light. They are more efficient than many other light sources with luminous efficacies of more than 60 lumens per watt (a lumen is a measure of the amount of light that a given fixture produces) [25]. At first, they were constructed in a low pressure tube and used in many places and occasions. Nowadays, they are high pressure lamps with a fused quartz inner discharge tube. MVLs contain an arc that goes through argon gas and heats the tube. This operation causes the tube to vaporise the mercury and creates a strong bright light between two electrodes that sit around the arc tube.

MVLs are high energy lamps that are primarily used outdoor in sport arenas, landscaping, street lighting and signs, function stages, parking lots and industrial areas. They come in different shapes and designs (see Fig. 1.2), as well as different wattage outputs [25]. MVLs are long-life bulbs, lasting around 24000 hours.

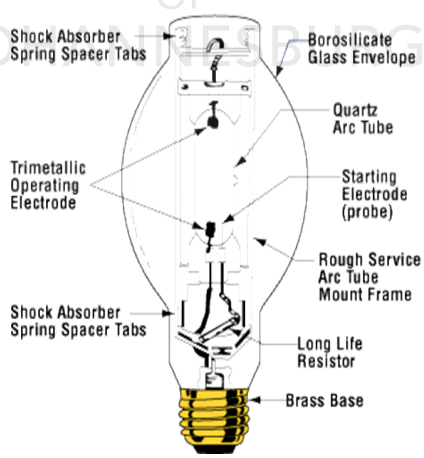

Figure 1.2: The inside structure of the mercury vapor lamp. From [26].

1.2.6 High Pressure Sodium Lamps

For a long time, this type of lamp has been used as one of the main outdoor lighting sources. Many countries around the world still use the high pressure sodium lamps since they are highly efficient light sources. Their strong yellow light colour restricts their usage to the outdoor areas only. They are mainly used in sport arenas, parking lots, harbours, street lighting, commercial and open industrial areas, as well as security lighting, events stages and landscaping. They are gas discharge lamps and come in different shapes, designs and sizes, as shown in Fig. 1.3. They range from 35 – 1000 watts and give an average luminous output of 70 – 160 lumens/Watt. They are considered long-life bulbs, in the vicinity of 20000 hours [27-29].

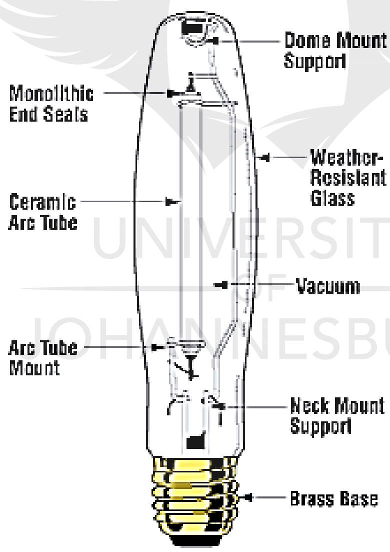

Figure 1.3: The inside structure of the high pressure sodium lamp. From [30].

1.3 THESIS OUTLINE

The outline of this thesis is as follows. Chapter 2 presents a wide study and overview of previous work directly or indirectly related to the topic in this thesis. Details, concepts and results that provide a deeper fundamental understanding of the subject matter and the manner in which the researchers extracted their studies and presented their work is also discussed and illustrated in this chapter. This has been done due to the different ways to discuss and represent the advantages and disadvantages of the light sources.

The basic characteristics of the power lines are explored, the setup of the measurements and the experimental measurement procedure, as well as the instruments used for the duration of the measurement procedure are illustrated in Chapter 3. This chapter includes a detailed study of the light source components as well as the characteristics of the different light sources used during the measurement procedure. Generally, the contribution of the experimental measurements and new results are placed and explained in the later chapters.

Chapters 4 and 6 focus on the different results obtained during the measurement procedure. Each light source has its own structure and characteristics, and injects an amount of noise into the wiring system of the power lines. Consequently, there exists a variation in results from one light source to another. This is explained in detail. It is also shown that in the low frequency band, *Comité Européen de Normalisation Electrotechnique* (CENELEC) band, there is a different level of interference from the one on the broadband spectrum, depending on the structure of the light source. In this chapter we investigate the problem and illustrate the background theory of the light sources. We also explain the way the light sources operate, the inside structure of the light sources where electronic components are used to make the wide range of modern light sources, as well as the structure of the electric ballasts that are used to operate and ignite some of the light sources.

A detailed comparison between different coloured light sources is shown and the related experiments are explained in Chapter 5. The new LED tubes technology is also described in this chapter.

Some mathematical explanations, as well as simulation results are given in Chapter 7. This is to verify that the practical measurements are accurate and the results are valid. Within this chapter, we shall be also summarising the key results from previous chapters and attempt to use this to place attention on creating and designing a preliminary general lighting model for future studies of lighting sources.

Chapter 8 concludes the work done and discusses the subsequent research that might be done in the near future, based on our findings.

The efficiency of a channel to transfer information depends on the channel bandwidth and the noise present in the channel, and this is shown by the Shannon theorem. The study presented here has to do with how the noise is added to the channel due to lighting source in electric power grids. Many countries have banned the "old fashion" lamps and replaced them with energy saving lamps. Although this is good from an energy point of view, these lamps tend to cause interference to the power line channel that may also be used for communications and control.

The main contribution of this study is the description of how the light sources generate electromagnetic interference (EMI) in the power line channel. A further contribution is to model this and give a tool for estimating noise on PLC.

Chapter 2 – Literature Review

Summary:

Chapter 2 presents a wide study and overview of previous work directly or indirectly related to the topic in this thesis. Details, concepts and results are presented that provide a deeper fundamental understanding of the subject matter and the manner in which previous researchers extracted their studies and presented their work. This has been done due to the different ways to discuss and represent the advantages and disadvantages of the light sources.

2.1 INTRODUCTION

Information is one of the most important and significant necessities of our modern-day life and amongst the prominent pillars of the progress of civilisation; it is one inseparable link to all spheres of human activities. People are totally reliant on information for all issues throughout every process stage of their life; so, the information is still the only phenomenon that has accompanied people ever since human societies and civilisations have started to take shape on the face of earth. Humans focus on exchanging information, communicating and passing on information from generation to generation has been for the advantage and benefit of humanity.

The process of information evolution has been performed using various forms by employing a variety of media platforms available to the human person through human evolution history. These media forms and varieties have gone through successive stages of evolutional developments, in direct relation to the evolution, progress and development of human civilisations over the centuries. From drawing on animal skins in old times to the manuscripts of the middle ages, the exchange of information has evolved, regenerated and advanced to take the forms and means of printed paper and paperless media such as what we have today in the shape of books, magazines, encyclopaedias, laser disks and screens, as well as personal computers (PCs), satellites and other methods of systems and information spreading, gathering, storage and recovering of information.

In the past century, a growing interest in information has emerged as a national cultural heritage and identity that plays a direct significant strategic part in the activities of community. The emergence of technology has charmed, lured and wooed the attention of many countries with all their institutions and individuals alike to make relentless and interminable efforts in the fields of command and control of information sources at national, regional and international levels. This has resulted in creating and developing many communication systems and information networks. One of those communication systems is the PLC network.

2.2 POWER LINES

Using the existing infrastructure of the low voltage electric wiring as a communication medium is a great move and is a much more cost-effective solution in comparison to other communication systems. However, the power line medium is harsh and challenging as it was not designed and adapted for any application of communications, which makes it an interesting, challenging and complicated field. For many decades, the power line wiring system was designed to distribute electricity to the households in an efficient way, yet, limited communications applications have been implemented a short while after the inception of the power line, such as, voice signals, where utility companies implemented their telephone systems over the high-voltage (HV) distribution lines in the 1920's [31, 32], and at a later stage, the facility of load control to control peak energy demand on the low-voltage (LV) network was used by utility companies and known as ripple carrier signaling [31, 33]. By then, the utility companies managed their needs of setting-up bidirectional communication for their power stations and energy distribution. Communications over the low-voltage network is not simple and requires the transmitter power to be in the region of a few kilowatts; the reason for this demand is the topology of the low-voltage network which has a low carrier frequency.

Attenuation increases with frequency. Impedance is low, typically ranging from 1-100 ohms. Network topology affects both attenuation and frequency response as low impedance loads are switched in. More details on the LV network will follow in the next chapters.

Several years later, it was obvious that the MV and HV power line wiring grids were suitable for communications and data transmission but with some hindrances, such as connecting transformers that would link one network to another [34], since those transformers tend be seen as a source of attenuation on those networks. Around the 1940's, for political reasons, radio amateur broadcasting stations were asked to stop their broadcasts as these would interfere with military broadcasting signals. The radio amateur companies found a different way for broadcasting – the power line network was their solution to transmit their signals. Please refer to the Radio Amateur Handbook [35] for detailed information.

During the 1970's, an important innovation took place in the market – automatic meter reading facilities that allowed utility companies and municipalities to have access to household installed meters [36-40]. This facility was developed to include warning messages as well as being able to disconnect the user in cases where no payment is received, transmitting news messages or disaster-management messages, load-flow analysis and collecting of power line network characteristics, such as noise and interference data.

Different power line research topics have gained momentum in the last three decades. Researchers focused on different aspects and expanded their research field to include automatic controlling of intelligent devices, such as alarm systems, lighting, heating and air conditioning, as well as multimedia and traffic lights.

For a wider view on this topic, readers are referred to the references mentioned in section 2.11.

2.3 COMMUNICATIONS OVER POWER LINE GRID

Different research topics, theoretical analysis and experimental measurements have focused on wide aspects of the power line network and studied the power lines characteristics insofar as its use as a communication channel. The channel parameters are statistically described and measured, then channel capacity bounds are calculated [11, 41-46]. The outdoor and indoor power line networks have different environments and behaviours when used as communication channels since they both have large infrastructure that covers the majority of inhabited areas. Different overviews, measurements, analysis of the market, communication protocols, and different cables and topologies simulations on power line communications have been shown in [11] to give a clear understanding about the PLC channel.

The electric power network has a branching topology that is enforced by a physical layout of the electrical power cables, where signal attenuation is different in each branch [32, 47, 48]. Due to the nature of the LV network, multiple mismatched branches cause multiple reflections of the signal [48, 49], as the LV power line network is an unpredictable network where electricity consumers use the LV network in an uncontrolled manner. This causes sudden impedance fluctuations which make impedance matching impossible; therefore, the transmitted signal is partially or totally contaminated on the receiver side.

Reference [50] describes an analytical multipath model that shows complex transfer functions of typical power line networks using small sets of parameters. The measurement based model presented the required development and suitability of the PLC System for voice, Internet and data services. The model proved that there is a certain level of accuracy between the simulated and measured results which shows a possibility to carry out the investigations as well as evaluating and comparing the performance for different network topologies and study the impact on the power line network's performance by means of simulations.

Radio frequency interference creates long error bursts. This, as well as cross-talk and impulsive noise make communications on the power line network quite difficult. In [51], it is shown that the transmission of television services and high quality video is a challenging task on the power line network due to the "horrible channel". However, a promising solution for video distribution over PLC is proposed/set out in [51].

From a communication theory point of view, if the signal-to-noise ratio (SNR) is below a certain threshold, a practical communications system will experience transmission problems. This can occur on the PLC channel as a result of interference and impairments on the channel, such as signal attenuation and degradation, and interference sources along the signal path.

Various loads connected to the electric wires of the power line can also decrease signal quality on the communications channel. In this case, light sources are one of the main loads that have a notable influence on the power line when used as a communication channel. Light sources can affect the signal quality and cause signal attenuation and degradation. This can happen, as the amount of interference injected by the power electronics driving the light source exceeds a certain level which causes the communication signal to attenuate or gets distorted. Detailed explanation about the influence of the indoor and outdoor lamps on the power line network, as well as their effect on the communication network is given in Chapters 4, 5, 6 and 7.

2.4 INSTRUMENTS AND EQUIPMENT FOR COMMUNICATION ON THE PLC GRID

Researchers have been studying several methods for communication over the power line and designing different mechanisms to link the networks to each other. In fact, they have gone so far as to design a method that allows contactless communication on the power line grid as in [52]. Other research has studied the coupling circuits that play an important role on the power line network. Coupling circuits can be designed in different ways as in [53-56] and are essential for the power line research community and can also be considered one of the main components used when performing measurements on the power line network. They are considered as special filters that allow low frequency and high frequency communication signals to pass through them while filtering (blocking) the 50Hz power waveforms.

Five different power line adapters from four different manufacturers were tested by Jensen [57] in her experimental studies of the noise recovery ability of in-house power line equipment. Jensen's experimental tests were carried out in an isolated power line network as a further development of the benchmarking tests suggested in [58, 59]. In her approach, several steps were followed in the suggested testing method, such as measuring the throughput of the communication line on the power line grid and introducing white noise on the grid for more than 60 seconds, as well as measuring the throughput as a function of time until it is at the same level as before the introduction of noise, and introducing noise again to the power line grid by repeating the procedure. The studies showed the performance of the adapters during the noisy period and during the recovery process.

A Line Impedance Stabilization Network (LISN) has the ability to filter noise from an AC input when conducting measurements on the power line network. The measurement side is thus free of any noise generated within the power line network which allows for an accurate assessment of the noise generated by the device under test (DUT). The LISN can also supply a noisy load to the DUT. The characteristics of the LISN can be found in EN 50065-1 [60]. This is illustrated in the later chapters of this thesis.

2.5 NOISE, INTERFERENCE AND CHANNEL RESPONSE CHARACTERISTICS

Noise is one of the main research concerns for the power line network as it has the ability to hinder or stop any communications on any network. It can be classified as the "sum of noise waveforms produced and emitted to the lines from appliances connected to the wiring system of the power line grid" [61]. Reference [62] divides the noise on the power line into four classes: i) continuous coloured noise; ii) continuous tone jammers; iii) periodic impulses synchronous to mains; and iv) impulsive noise not synchronous to mains. Hooijen [12] stated during his measurements period on background, impulse, narrowband and synchronous noise that the signal attenuation levels ranged from 40–100 dB/km. These results can highly affect any transmitted bits or packets on the power line network. Background noise and synchronous noise on low frequencies up to 250kHz were studied in [63] and measurement results were presented.

Philipps [14, 44, 64] considered the noise effects for the broadband power line communications in his approach. The noise model used was based on a piece-wise constant power spectral density and studied the transfer function characteristics. The approach also considered measured impedance at different locations and models for in-building power line communications, a statistical channel model (transfer function and noise) at higher frequencies up to 30MHz. Philipps's approach included measurement results from a few hundred power line channels where noise was modelled as a sum of disturbances with different characteristics.

Reference [65] presented a detail study about the time and characteristics of the noise, as well as properties of background and impulsive noise. Different noise models were presented, for example, time behaviour of asynchronous impulsive noise where the noise scenario in power line channel was dominated by narrowband interference and impulsive noise. Reference [66] and [67] also discussed the results based on frequency and time domain measurements.

Impulsive noise within the indoor power line network was analysed in [68]. The study focused on the statistical properties of impulsive noise with the aim of creating an optimised method for transmission. It studied the sub-classes of pseudo frequency noise and presented a statistical analysis of the classes on the power line communications, such as distribution of the pseudo frequency and the interarrival time, as well as distribution of the pulse duration and other pulse characteristics, and finally, the amplitude distribution of the noise.

Impulsive noise is one of the main sources of interference which causes signal distortions leading to bit errors in data transmission. Many research papers focused on the behaviour of the noise model on the receiver side. Tilch *et al.* [69] proposed an innovative modeling approach that is applied to impulsive noises which are henceforth studied directly at their sources outputs. The study pointed out that the form of an impulsive noise pulse does not depend on the device that generates it, but on its in-device source; it also mentioned some advantages for measuring the impulsive noises at source, e.g. the ability to correlate with noise generators in an easy way with less noises. Additional studies by Tilch and others showed that noise at the receiver would be simply the noise model at source filtered by powerline channel block [70, 71].

Mathematical models of noise in power line network were described in [72-77]. In [61], the model defined for noise on power lines is a coloured Gaussian random process whose variance is a time and frequency dependent function, and with proposed approximations to express the variance function. The study described the procedure to find the parameters of the model from the measured noise waveform and showed an example for a waveform of noise generated by the model. Zimmermann and Dostert [73] stated that the power line channel does not represent an additive white Gaussian noise environment. They also presented comprehensive analysis of the time behaviour of impulsive noise in different environments and derived a statistical model of the time behaviour of random impulsive noise based on a partitioned Markov chain, which is suitable for implementation in computer-based communication system simulations.

2.6 EMI, EMC AND THE PLC CHANNEL

Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) adhere to some power line characteristics and share some regulations with the PLC community. EMC and EMI radiations can interfere with the transmitted signals on the power line grid as in the EN 50065-1 European Standard [60], hence, the power lines act as radiating antennas on low and high frequency data signals; therefore, the radiations can compete with or exceed the maximum allowable PLC signal levels. Standards that illustrate limits on the conducted EMI described by VDE, CISPR, IEC and FCC are referenced in [78, 79].

Power quality issues for low frequency loads, correlated with EMC and EMI which appear at urban transportation systems were described in [80] where aspects of power definitions for harmonic and unsymmetrical or non-sinusoidal regimes from three-phase circuits were presented and the obtained data were compared using the power quality standards IEEE 519/1992 and 1459/2000. The obeying of quality standards and some aspects, which are not considered in the specialised literature, concerning the corresponding EMC and EMI issues were discussed. The study presented some conclusions on approaching EMC and EMI at low frequencies, with an extension over 2kHz and the relation with the IEC 61000-4-30 standard.

An investigation of field line effects on near fields from high frequency broadband power line communications (BPL) and an examination of the emission level to determine the significance of radiation from BPL sources on power lines was described in [81]. The investigation showed that the emitted fields from vertical BPL feed wires and a vertical grounding wire on the pole could not be neglected relative to the fields emitted from the power lines that are being excited by the BPL source. Hence, the power lines are much longer than the vertical wires. Vertical currents in general tend to radiate more when placed over a conducting medium.

A practical approach to reduce the electromagnetic power field radiations by controlling the frequency band of the PLC system was proposed by [82] by developing a software code that allows the representation of radiation at a point depending on the wavelength, the length of the antenna and coordinates of the observing point. The approach could express analytically the radiation emitted by considering the potential vector at any observing point in space. The mathematical model in [82] described a few formulas for calculating the electromagnetic field of the antenna, such as:

$$\overrightarrow{A_k}(s) = \frac{\mu}{4\pi}\vec{k}\int_{\frac{-L}{2}}^{\frac{L}{2}} \frac{I(s,Z_o)e^{-\gamma(s)R(Z_o)}}{R(Z_o)}dZ \tag{2.1}$$

where $\overrightarrow{A_k}$ is the antenna vector, μ is the permeability, $\vec{k}$ is a spatial wave (frequency) vector, Z_o is the characteristic impedance, γ is a propagation constant, and $R(Z_o)$ is the distance from a considered point on the infinitely thin antenna to the observation point. Rickard's patents [83, 84] previously proposed several technical solutions to reduce and alleviate the electromagnetic emissions in an outdoor network.

Three types of EMI filters were described by Schlicke and Weidmann in [85]. The miniaturised ceramic filter that permits considerable size reduction for high frequency low-pass filters, and capacitors for medium frequency filtering, "lossy" filters that work unconditionally into all interface impedances, as well as active EMI filters that offer a possible approach to obtain reasonable size where low frequencies have to be filtered under strong power-bias conditions. An EMI filter design study for high frequency power converters was proposed in [86]. The filter parameters were calculated according to the following formula:

$$f_c = f_{sw}.10^{\left[\frac{Att}{40}\right]}, \tag{2.2}$$

where f_c is the cutoff frequency, f_{sw} is switching frequency, and *Att* is the required attenuation.

2.7 NARROWBAND, FCC, AND BROADBAND PLC

Researchers divide the PLC into different classes:

1. Ultra-Narrowband Power Line Technology (UNB-PLC) that achieves a low data rate of 100 bps and falls in the ultra-low frequency range of 0.3kHz – 3kHz.
2. Narrowband Power Line Technology (NB-PLC) which operates between the frequency range of 3kHz – 500kHz and includes the European Standard CENELEC band 3kHz – 148.5kHz [87], the US Federal Communications Commission (FCC) band with a frequency ranges 10kHz – 490kHz and the Japanese Association of Radio Industries and Businesses (ARIB) band that falls in the frequency range 10kHz – 550kHz. These frequency ranges include the traditional Very Low Frequency (VLF), Low Frequency (LF) and the Medium Frequency (MF) bands. The FCC has set a maximum field level of 30 µV/m at a horizontal distance of 30 meters from the nearest active power line and considers the technology a current-carrying system where the primary mode of operation should be conduction and not radiation [88].

   Narrowband PLC is usually divided into Low Data Rate (LDR) single-carrier systems that can achieve a few kilobits per second kb/s data rate and High Data Rate (HDR) multicarrier systems with an achievable data rate of up to 500 kb/s.
3. Broadband Power Line Technology (BB-PLC) that operates at 1MHz – 250MHz frequency range thus its technology operates at both the traditional High Frequency (HF) and Very High Frequency (VHF) bands.
4. Ultra-Wideband Technology (UWB) which plays an important role in the frequency range 3.1 – 10.6 GHz as defined by the FCC as in [89].

The European Committee for Electrotechnical Standardisation (*Comité Européen de Normalisation Electrotechnique*) CENELEC published the standard EN 50065-1 in 1992 [87]. This standard allowed for data to be transmitted within the LV network and determined the operation limits in the frequency range 3kHz – 148kHz with signal amplitude equal to 116, 120 and 134 dB (µV) [90]. This frequency band was further sub-classified into four different bands as shown in Table 2.1.

Table 2.1: "CENELEC Band Categorisation"

Band Code	Frequency Range (kHz)	Maximum allowed Transmission Level, dB (µV)	Utilisation (Access Protocol)	Usage Areas
–	3-9	134 dB	No protocol	Energy providers and utility
A	9-95	134 dB at 9kHz 120 dB at 95kHz	No protocol	Energy providers
B	95-125	116 dB	No protocol	Energy providers' customers
C	125-140	116 dB	Carrier Sense Multiple Access (CSMA) using frequency of 132kHz	Energy providers' customers with media access protocol
D	140-148.5	116 dB	No protocol	Energy providers' customers with no restrictions

2.8 POWER ELECTRONICS CONVERTERS AND RECTIFIERS

Converting electric energy from one form to another is called power conversion. Converting between alternating current (AC) and direct current (DC), changing a voltage, current or frequency is also part of power conversion. Some of the light sources that will be studied and described in this thesis do have power converters or conversion systems that are used to convert the electric energy, regulate voltage and covert AC to DC.

Power converters widely used can be classified into different types:

i. AC to AC, such as transformers, cycloconverters, voltage converters and voltage regulators.
ii. AC to DC, such as rectifiers, switch-mode supplies and mains power supplies.
iii. DC to AC, such as inverters.
iv. DC to DC, such as voltage and linear regulators, and DC-to-DC converters.

There are also other specialised types of converters, e.g. rotary converters, resonant converters and cascade converters.

Rectifiers are used to convert alternating current into direct current that flows in one direction. They are widely used in the modern lighting industry and are mainly found serving as components of DC power supplies. In [91, 92], the authors suggested the development of a unified theory of rectifiers and discharge lamps, and involved some analytical calculations of a harmonic emission. The study showed that discharge lamps can be represented by single-phase rectifiers. Lee and Cho [93] described a control method of an electric ballast inverter for a 70 watt metal halide lamp with a synchronous rectifier. The described method prevents the inverter from having “ringing problems” and “overshooting” on the inverted lamp current. Another study proposed a Class-DE rectifier for fluorescent lamps with electronic ballasts in [94], and a new design of electric ballast for xenon lamps with a half-wave rectifier was proposed in [95]. The diode bridge rectifier that converts AC to DC for LEDs and fluorescent tubes was studied in [96]. The study showed that the rectifier is a source of flicker for the lighting sources due to high frequency inter-harmonics. The flicker responses of the lamps were analysed. In [97], Daugherty illustrated the problems caused by using silicon controlled rectifiers (SCRs) to control lighting in theatres and studios.

A new class of universal bi-directional power converter with high power density and lifetime was proposed by Amirabadi in [98]. The study showed that the proposed converter can interface with any phase configuration, number of loads and sources, as well as output any form of frequency, voltage and amplitude.

2.9 VISIBLE LIGHT COMMUNICATIONS (VLC) AND POWER LINE COMMUNICATIONS (PLC)

Using light sources for communications is a new great achievement. Fluorescent tubes transmitting signals at about 10 kbps and LEDs at 500 Mbps are the most suitable lamps for data communications as a visible light communication (VLC) medium that can potentially reach up to 800 THz. High speed data transmission using VLC is described in [99-102]. In power line communications, VLC has recently gained momentum due to the applications’ cooperative interaction and synergy, implementation feasibility and cost efficiency. VLC can be considered as complementary to PLC since the lighting devices share the existing power line wiring system infrastructure. VLC has attracted researchers to investigate possible communications using light sources, with a high level of reliability and stability, extending the reach of transmitted signals over the power line channel. For the past decade, several researchers have studied visible light communications and its relation to light sources and PLC. An overview of VLC technology was given in [103]. Kavehard and Amirshahi showed that the power line and visible light technologies can use white LEDs to provide broadband network access to households while maintaining low cost lighting. This is illustrated in [104]. In 2011, the Technology, Entertainment and Design conference held a live demonstration of video transmission using an LED lamp that transported information wirelessly using the visible light spectrum [105]; this could be considered a quantum leap in the communications field.

Recently, visible (LED) light has been used in a Global Positioning System (GPS) as in [106]. The proposed system receives the light by an image sensor and an accuracy of 1.5m was achieved. For indoor applications, a positioning technique of transmitting signals using visible white LED light was proposed in [107]. Other research topics that proposed using LED light for positioning and localisation are found in [108, 109]. A visible light LED localisation system was also discussed in [110]. The localisation method used four LED lights and proved that it could locate the target within 5cm. A novel visible light based hybrid positioning system was described in [111]. The hybrid design proposed a long-range indoor localisation system using Zigbee wireless testing infrastructure. Hybrid systems that involved visible spectrum, colour shift keying (CSK), RF and PLC were also described in [112].

A networking protocol and physical layer study of LED-to-LED VLC was performed in [113]. The study focused on the usage of narrowband communications and coloured LEDs, as well as elimination of LED flickering and detection of using an efficient collision medium access protocol.

An experimental test that complies with the standards of CENELEC C and D bands was performed for a low cost bridging interface between VLC and PLC in [111]. The test presented a low data rate transmission solution and used orthogonal phase shift keying (OPSK). A low-complexity FSK study for the in-house integration between PLC and VLC that involved LED lights and Markov modelling was presented in [115], and a PSK-CSK study for the integration between PLC and VLC, as well as cascaded PLC-VLC channel using CSK technique was described in [116, 117].

2.10 LIGHT SOURCES AND THE POWER LINE GRID

In Chapter 1 of this thesis we have given a short overview of some problems that the existing light sources might cause to the power lines when used as a communication medium. In this section we will try to illustrate some of the research topics that focused on the different aspects of light sources and their relation to the power line channel.

2.10.1 Outdoor Lighting

Reference [118] presented a design for an electric ballast for use with a high pressure sodium (HPS) lamp. An investigation into the reliability of the power line communications grid, its properties and the characteristics of electronic ballast of the HPS lamp was given in [119] and [120]. Generally, electric ballasts cause interference to the power line channel. This is explained in Chapters 4 and 6. Different issues about HPS lamps were discussed in [121]. The study gave an overview of the HPS lamp network as a street light and discussed the structures of controllers, wave trap coil and carrier frequency of the HPS lamp network over PLC, as well as solving the network's security problems of the lamp. Maizonave *et al.* [122] implemented an intelligent system to control street lighting with electronic ballasts. They stated that the ballasts can communicate with each other using the network of the power lines and the system can give accurate information about energy billing, and is also able to control luminosity and gives a better power factor.

An implementation of 'zero power wake-up' system to reduce consumption of energy was introduced in [123]. The simulation based study showed that using the following parameters of transmission cable can reduce energy consumption of street lights when using the power line as the communication network:

$$R = \sqrt{\frac{\mu_r \mu_o}{\pi \sigma a^2}} \left[\frac{d/_{2a}}{\sqrt{(d/_{2a})^2 - 1}} \right], \tag{2.3}$$

$$L = L_{in} + L_{ex} \,, \tag{2.4}$$

where μ_r is relative permeability, μ_o is vacuum permeability, σ is conductivity, a is radius of the conductor, d is distance between two conductors, L is the inductance, L_{in} is internal inductance and L_{ex} is external inductance. Then L_{in} can be represented as

$$L_{in} = \frac{R}{2\pi f} \qquad \text{and} \qquad L_{ex} = \frac{\mu_r \mu_o}{\pi} \cosh^{-1}\left(\frac{d}{2a}\right),$$

and then

$$C = \frac{\pi \epsilon_r \epsilon_o}{\cosh^{-1}\left(\frac{d}{2a}\right)} \,, \tag{2.5}$$

where C is the capacitance and G is the conductance as in 2.5 and 2.6.

$$G = 2\pi C \tan(\delta) \tag{2.6}$$

The characteristic impedance Z_o of the power line is defined as:

$$Z_o = \sqrt{\frac{R + j\omega L}{j\omega C}} \,. \tag{2.7}$$

A simulation tool based on narrowband PLC for street lighting was derived in [124]. The power line network was chosen to support the smart lighting system. Spice simulation software was used to design a smart lighting system and the results were compared with lab experimental measurements.

A network performance laboratory study of the connection between aviation, ships and HomePlug power line communications using halogen lamps was described in [125]. Other studies have proposed a new method to link the aviation ground lighting system to the power line communications, such as in [126]. The proposed method resulted in creating a model that is integrated to build a complete PLC link model.

2.10.2 Indoor Lighting

In this chapter, we previously defined the converters and introduced the reader to the different types of rectifiers and power converters. LED lamps are considered as semiconductor light sources and require a rectifier or AC-DC type converter in order to deliver visible light. LED lamps are powerful and efficient light sources, and the present market is moving towards replacing the old classic lamps with LED lamps. A PLC technology prototype that is called P-BUS for general LED lighting system is described [127]. The technology described the master and slave controllers, the ancillary devices and the DC-DC modules for LED lamps. A novel lighting study to design a DC-LED lighting system with high efficiency, more lumens/watt, and more lifetime expectancy was described in [128].

In Kiedrowski's approach [129], lamps act as communication nodes on the PLC channel and can be divided into three parts: light sources, power line modems, and power converters. The approach further indicated that a proposed modelling method can be used in low-voltage network for street lights supplying any structure of the electric power network. Experimental measurements were performed for two touch dimmer lamps in [130] where the sensitivity of the lamps was dependent on the amplitude and the frequency of the signal bursts. The results of the measurements showed that the lamps cause interference to the PLC network and the lamps' operation was disturbed by the injected signal burst. The measurements also showed that different devices using the power line cables cause interference problems to the tested lamps.

Other research studies paid attention to other light sources, for instance [131] investigated the circuitry design of a control platform for fluorescent lamps and [132] that discussed the impact of CFL lamps on power quality, as well as the harmonic emissions obtained from using LEDs, CFLs and other energy efficient lighting as in [133-136].

It is important to mention that in many countries around the world, the European Conformity or Conformité Européenne (CE) standard that was initiated in the European Economic Area (EEA) in 1985 should be followed by manufacturers when designing any modern light source within the EEA.

2.11 DISCUSSION

Several studies of light sources and different technological approaches were illustrated in this chapter. An overview of the PLC channel and its relation to the lighting technology, EMC and VLC technology was presented. Noise, interference and channel hindrances were also presented and discussed. Further studies on LED lamps and other light sources were done by [137-139].

For more information on light sources and their harmonic emissions on the power line communications channel, we refer the reader to [19, 140-147]. This will be discussed in the next chapters. For detailed discussions and deeper knowledge on the technical field of PLC, the reader is advised to refer to [1, 148-154].

Chapter 3 – Experimental Set Up

Summary:

The setup of the measurements and the experimental measurement procedure, as well as the instruments used for the duration of the measurement procedure are illustrated in Chapter 3. This chapter includes a detailed study of the light source components as well as the characteristics of the different light sources used during the measurement procedure.

3.1 INTRODUCTION

Measurement preparations and set-ups were conducted according to the specific needs and characteristics of each measured lamp. The preparation of measurements for indoor lights was slightly different from that of outdoor lights, but both share most of the measurement devices and procedures.

3.2 UTILISATION OF INSTRUMENTS AND DEVICES

Each measured lamp was supplied with 220VAC through an isolation transformer and LISN. The isolation transformer was included, as the LISN causes an earth-leakage current to flow with resultant tripping of the supply. Floating the LISN rectifies this fault phenomenon. The LISN as used in this set-up, has two functions:

- Firstly, it filters out noise from the AC supply. The measurement side (current probe and measured lamp) is therefore clean from any noise on the power line. An accurate assessment of the noise produced by the measured lamp can therefore be made. A clean 50Hz 220VAC is supplied to the measured lamp.

- Secondly, it supplies a standardised noise load to the conducted interference created by the lamp. At higher frequencies (typically > 1MHz), the noise load impedance presented by the LISN (and seen by the lamp) is 50Ω.

Measurements and conclusions in this section were made for two regions of the emission spectrum:

- Narrowband PLC in the frequency band 3kHz – 150kHz: This is the frequency range of the so called CENELEC bands as defined by EN 50065-1 [60]. Measurement for this frequency band was made in the time domain and a Discrete Fourier Transform (DFT) was performed in order to obtain harmonics in the frequency domain. A Tektronix DPO7254 oscilloscope and a Tektronix TCP0030 current probe were used. It was assumed (by convention) that the Common Mode (CM) currents were negligible in this band, and that all interference was in Differential Mode (DM) – an assumption also used in EN 50065-1. The results were downloaded to a PC for processing.

- The frequency range used for Broadband PLC was 150kHz – 30MHz. It spans the range traditionally used to measure conducted emissions as per CISPR-16 [155]. In this case, measurements in the frequency domain were made directly using a Rhode & Schwarz FSH323 Spectrum Analyser plus an ETS-Lindgren 94111-1L 1GHz bandwidth current probe. Since interference on a PLC system occurs in DM, a special arrangement of cables pertaining to the current probe was used for measuring in this range. It cancels the CM current and measures only the DM.

3.3 LOW ENERGY LIGHT SOURCES

Light Emitting Diode (LED) lamps, Compact Fluorescent lamps (CFL), fluorescent tubes and plasma lamps are all (by convention) considered to be low energy lamps as they do not consume large amounts of energy and have relatively smaller dimensions as compared to high energy counterparts. They are mostly used for indoor purposes as explained in this chapter and Chapter 4.

The following figures explain the measurement set-up that we used during our experimental measurement campaign for the low energy indoor light sources.

3.3.1 LED and CFL Lamps

Fig. 3.1 shows the measurement set-up for measurements in the CENELEC band 3kHz – 150kHz range. Different LED and CFL lamps were used. Detailed explanations of lamp types are given in the later chapters.

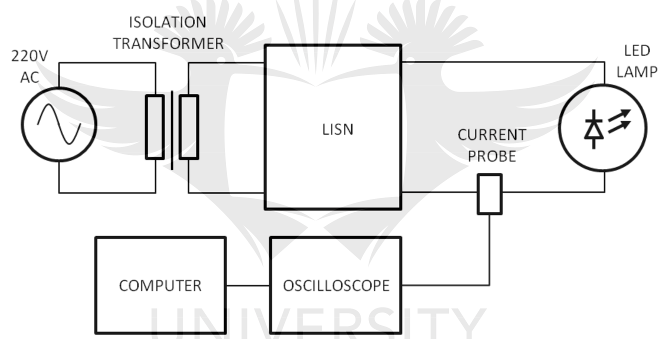

Figure 3.1: LED/CFL lamp: Measurement set-up for measurements in the 3kHz – 150kHz range.

Fig. 3.2 shows the measurement set-up for measurements in the broadband PLC spectrum with 150kHz – 30MHz range. The measurements are conducted in DM and the CM current has been neglected as in EN 50065-1.

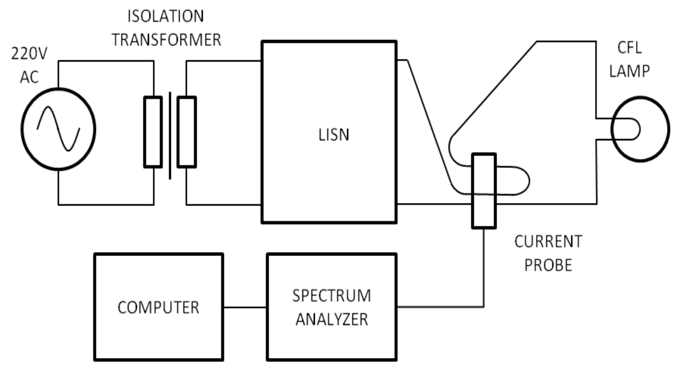

Figure 3.2: LED/CFL lamp: measurement set-up for measurements in the 150kHz – 30MHz range.

3.3.2 Fluorescent Tubes

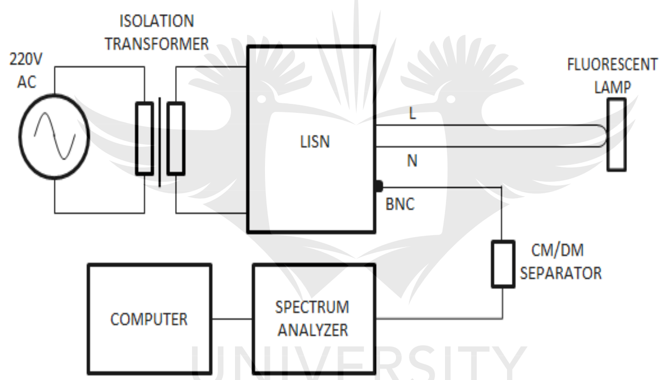

Figure 3.3: Fluorescent tube: measurement set-up for measurements in the 3kHz – 30MHz range.

Measurements for the full frequency range of 3kHz – 30MHz were made using a Rhode & Schwarz FSH4 Spectrum Analyser and CM/DM separator as shown in Fig. 3.3.

3.3.3 Plasma Lamps

As it is explained in Chapter 4, plasma lamps generally use two types of transformers: step-up and step-down transformers according to the lamp used. In Fig. 3.4 we show the measurement set-up when using the widely used step-up transformer that converts the received voltage to an average of 9000 volts.

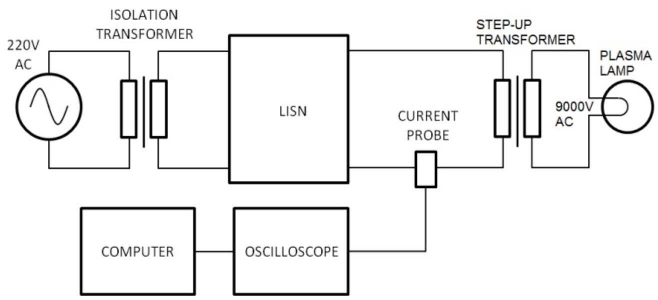

Figure 3.4: Plasma lamp: set-up for measurements in the 3kHz – 150kHz range.

3.4 HIGH ENERGY LIGHT SOURCES

Metal Halide Lamps (MHL), Mercury Vapor Lamps (MVL) and High Pressure Sodium Lamps (HPSL) are considered high energy electric and high power consumption lamps that produce visible light by an electric arc tube. High energy lamps are a class of high-intensity discharge (HID) lamp that contains a fused quartz element and a mixture of gases and are mostly used for outdoor purposes as mentioned in Chapter 6.

Fig. 3.5. gives an example of the measurement set-up for the high energy light sources when performing experimental tests and measurements. High energy light sources use

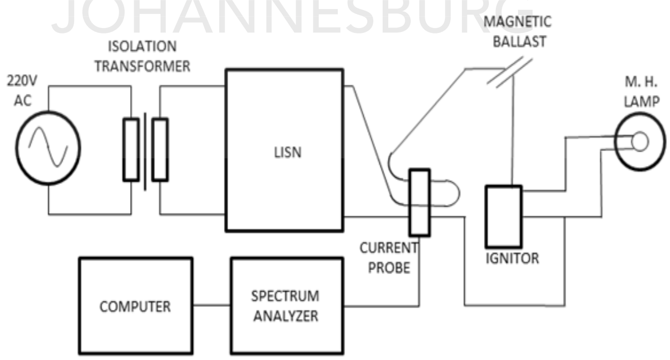

Figure 3.5: MHL/HPSL/MVL: set-up for measurements in the 3kHz – 30MHz range (Electromagnetic Ballast).

electromagnetic ballasts and igniters to start and control the lamp operating current flowing through the lamp after it has been started, as well as to maintain suitable voltage and current wave shapes.

Electronic ballasts are widely used for MH and HPS lamps and do not require igniters for startup. They have an "intelligent" function that switches the lamp off at its life end. This "intelligent" function exists in the electronic ballast only, as the ballast prevents the lamp from being a source of noise and disturbance on the power line system. This occurs especially when the lamp reaches the end of its life as it starts to switch on and off several times a day, causing the lamp to produce more interference in general and on the PLC signal. Fig 3.6 shows the measurement set-up for outdoor lamps when using electronic ballasts.

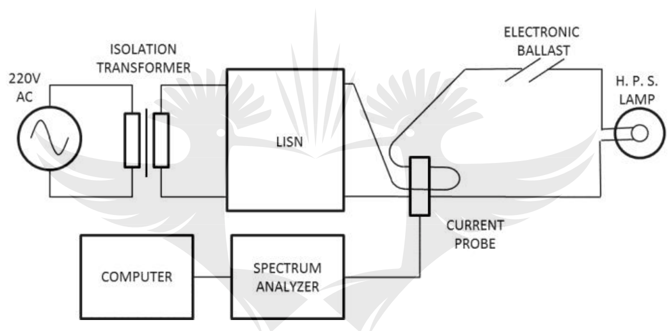

Figure 3.6: MHL/HPSL/MVL: set-up for Measurements in the 3kHz – 30MHz Range (Electronic Ballast).

3.5 DISCUSSION

In this chapter we have explained the way the measurements are conducted and the devices used for most of our measurement experiments. We have also studied the classes of light sources and the types of ballasts used by some of the lamps. The LISN functions, characteristics and usage were also explored.

Chapter 4 – Low Energy Light Sources

Summary:

Chapter 4 focuses on the different results obtained during the measurement process for the indoor lighting technology. Each light source has its own structure and characteristics, and injects an amount of noise into the wiring system of the power lines. Consequently, there exists a variation in results from one light source to another. This is explained in detail. It is also shown that in the low frequency, CENELEC band, there is a different level of interference than on the broadband spectrum, depending on the structure of the light source. In this section we investigate the noise and illustrate the background theory of the light sources. We also explain the way the light sources operate, and the inside structure of the light sources where electronic components are used to make the wide range of modern light sources.

4.1 INTRODUCTION

In this chapter we investigate the effects when electric lamps are seen as noise sources on the power line communications channel and their interference levels compete with signals from PLC devices. Generally, there are two types of lamps, low energy and high energy lamps. The low energy lamps are usually "indoor lamps" and the high energy lamps are "outdoor lamps". In this chapter, we will describe the low energy lamps and show the obtained results of our experimental tests.

4.2 LED LAMPS

There are two classes of LED lamps (active and passive) – depending on the noise generating electronics and that these have different influences in different parts of the emission spectrum**.** Two different measurement set-ups (depending on the interference band) were explained in the previous chapter. Time domain current waveforms for four different LED lamps are shown together with frequency domain results.

It is shown that in the CENELEC band: (3kHz – 150kHz) the interference level from all the LED lamps tested is significantly below the allowed maximum PLC signal levels and therefore poses no threat to the power line communications. In the band 150kHz – 30MHz however, PLC signals compete with Electromagnetic Compatibility levels and the S/N ratio can be equal to zero, but only if the lamps have active power electronic converters. It is also argued that from a PLC standpoint, passive LED driver circuits perform better. From a noise generation point of view, they have no high frequency noise components (in the 150kHz – 30MHz band) but have poorer power to light efficiency and functionality. This is a potential problem as the move in LED lighting will probably be to favour the higher efficiency power electronic converter driver types that interfere in the 150kHz – 30MHz band.

Lastly a case can be made that in the 150kHz – 30MHz band, PLC will always be at a disadvantage as it directly competes with device interference levels of similar magnitude.

4.2.1 LED Driver Types

In this section it is argued that, considering noise generation in LED lamps, there are two main classes of LED lamp drivers. The first and the simplest form is that of a passive RC divider network and rectifier (shown in Fig. 4.1) and the second that of an active rectifier with power converter as shown in Fig. 4.2.

In the typical configuration of Fig. 4.1, 220 VAC is divided down to a lower AC voltage through R1 and C1. It is then rectified to provide DC for the LEDs. R2 and C2 constitute a low pass filter while R2 also acts as current limiting for the LEDs. No high frequency switching is performed in the divider and rectifier type LED lamp drivers. It is therefore expected that this type of circuit will not produce high frequency noise but only lower frequency harmonics associated with the rectifier action.

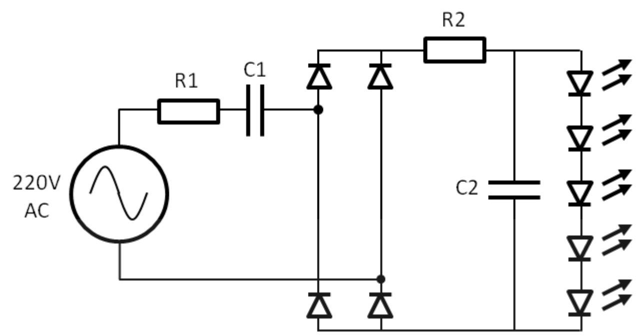

Figure 4.1: RC divider and rectifier type LED lamp and driver.

The second type of LED lamp driver is of the type shown in Fig. 4.2. In this type the 220VAC input is rectified and filtered (by C). This high voltage DC is then converted and current limited by an active high frequency switching power electronic converter. Although there are different topologies for this kind of converter (which falls beyond the scope of this thesis) it is sufficient to say that this circuit will produce high frequency switching harmonics in the current drawn from the supply at frequencies such as 40kHz, over and above the lower

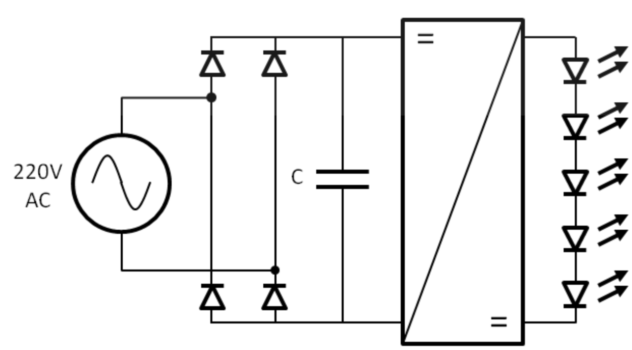

Figure 4.2: Rectifier and converter type LED lamp and driver

network harmonics due to the rectifier action.

Fig. 4.3 shows measured line current waveforms for four LED lamps. Three of these lamps are of the divider/rectifier type. They are 4W, 2W and 0.84W lamps. These lamps have similar waveforms but vary in amplitude due to wattage differences. The fourth lamp is of the rectifier/converter type and consists of a lamp made up of three 1W LEDs. Its time domain current waveform is different from the rest.

4.2.2 Harmonics – CENELEC Bands

In order to determine what effect the harmonics of an LED lamp has on the power line communications channel, the currents in Fig. 4.3 must be represented in the frequency domain. This is done by performing a Discrete Fourier Transform (DFT) on exactly one period of data from Fig. 4.3 Performing a DFT on one cycle of data yields the harmonics (or frequency domain components) that make up the time domain waveform.

The DFTs of Fig. 4.3 are shown in Fig. 4.4. The DFTs were performed for each of the four waveforms in Fig. 4.3 with the addition of a fifth analysis which is the harmonics of the current of all the lamps combined (turned on simultaneously). The fundamental for each lamp is at 50Hz. The "all lamps combined" fundamental is the largest as can be expected, since all the lamps combined draws the largest amount of current. The harmonics (starting in tens of mA's at the fundamental) roll off to the tens of µA's around 20kHz which is the noise floor.

In order to compare the current harmonics to typical power line channel signal voltages, the current magnitudes in Fig. 4.4 must be multiplied with typical power-line channel impedances for each of the harmonic frequencies. This power line channel impedance can be approximated by using the values of the LISN that is used for measurement (Figs. 3.1 and 3.2) despite the fact that input impedance of PLC channels are very frequency selective. The LISN characteristics are specified in EN 50065-1.

Fig. 4.5 gives the results when the "all lamps combined" harmonics (in voltage) are plotted against the CENELEC EN 50065-1 standards for maximum power-line communications signal and EMC levels.

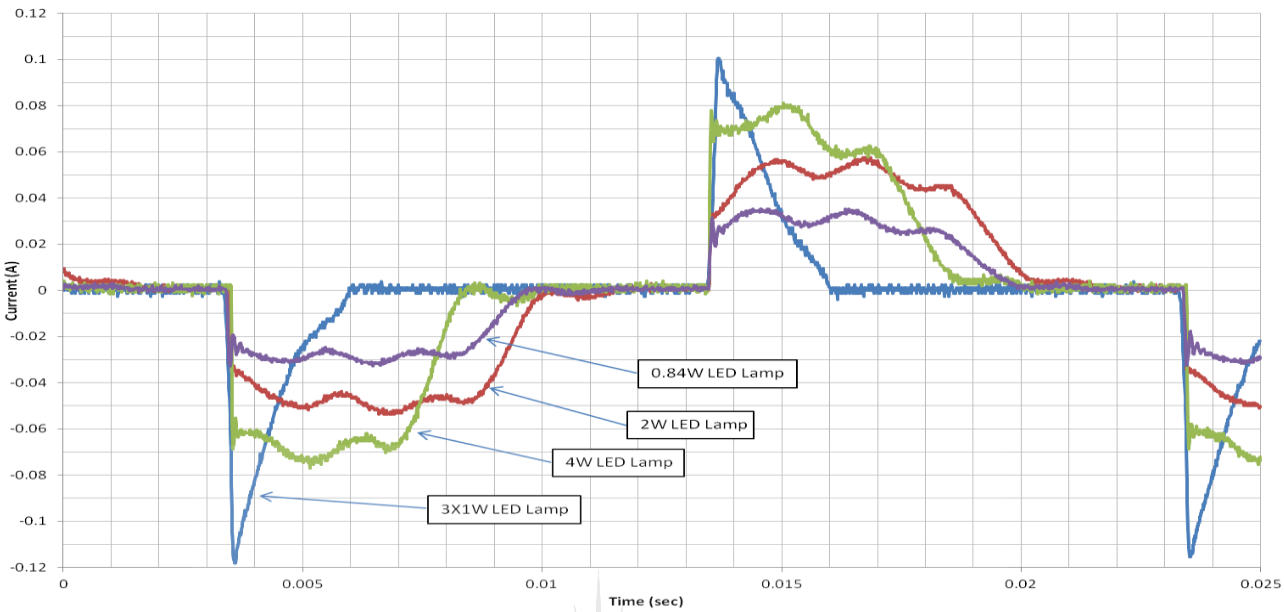

Figure 4.3: Time domain line current waveforms for four different LED lamps.

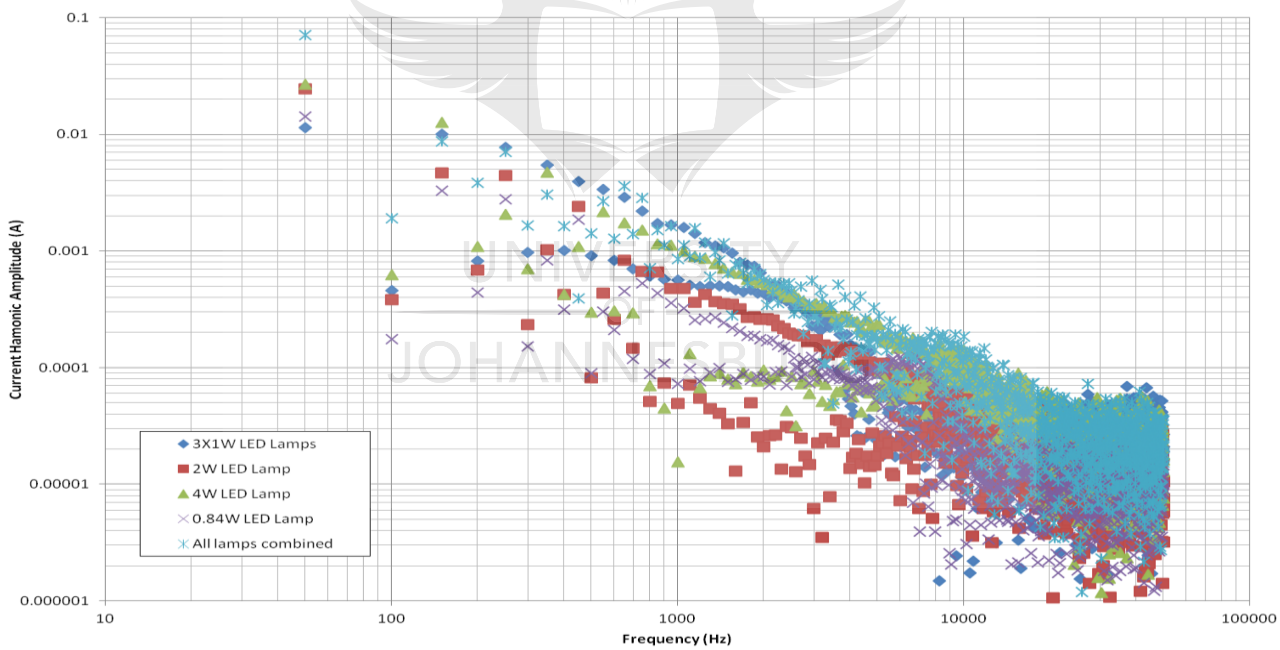

Figure 4. 4: Frequency domain line current harmonics (DFT) for the four different LED lamps shown in Figure 4.3. A fifth spectrum shows the harmonics when all the lamps are switched on simultaneously.

At 135dBµV (around 5V) the allowable wideband signal strength for a PLC signal is very high. It is around 60 - 70dB higher than the noise harmonics from the signal of all of the LED lamps tested together. The noise harmonics are also well below the allowable EMC limit as stated in EN 50065-1. It can therefore clearly be seen that in the CENELEC bands from 3kHz – 150kHz LED lamps are unlikely to interfere with the power line communications channel.

One period of the 50Hz power cycle were digitised at a sampling rate of 100kHz. A DFT was performed on 1000 points using a rectangular window to give Fourier components at 50Hz intervals.

4.2.3 Broadband Spectrum

In Fig. 4.3, the line current drawn by four different LED lamps are shown. Of those four only one (the 3X1W lamp) incorporates power electronics (the type shown in Fig. 4.2). In terms of noise in the Broadband PLC spectrum (150kHz – 30MHz) the 3X1W LED lamp is the only one generating noise in this part of the spectrum –due to the switching action of the power electronics converter. Fig. 4.6 shows the interference voltage from the 3X1W LED lamp versus the EMC average and peak/quasi-peak disturbance level limits in the band 150kHz – 30MHz. In the CENELEC bands from 3kHz – 150kHz there are dedicated maximum signal transmission levels. These do not exist in the 150kHz – 30MHz band and maximum signal transmission is assumed to be at the EMC limit levels. It can be seen in Fig. 4.6 that the interference voltage of the 3X1W lamp is close to and even exceeds (within experimental limits) the EMC limit in the beginning of the band. This can be expected as atypical manufacturer will only filter noise to the EMC limit in order to save on manufacturing costs. In stark contrast from the CENELEC bands, PLC signals in the 150kHz – 30MHz band have to directly compete with noise from other devices with power electronic converters and may have a zero S/N ratio at certain frequencies.

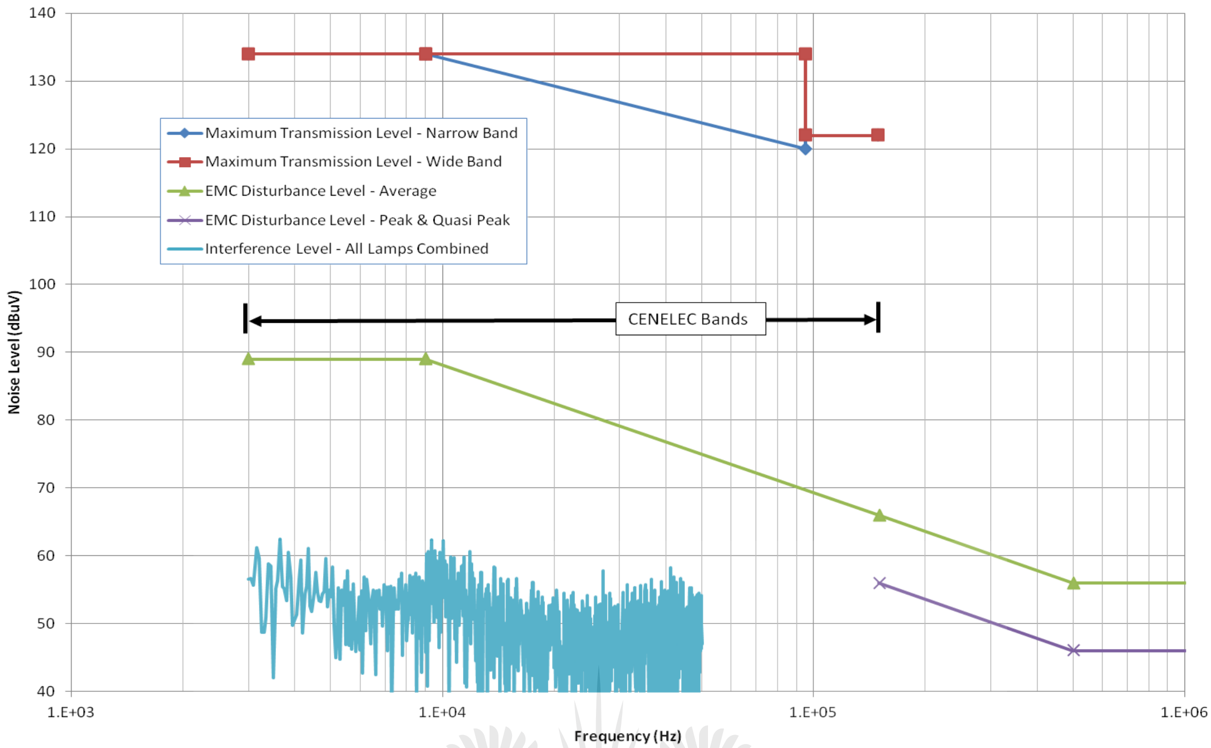

Figure 4.5: LED lamp: comparison of the harmonics of "all the lamps combined" with the EMC standards and maximum allowable PLC signal strength in the CENELEC band 3kHz – 150kHz.

There is no averaging for the used spectrum analyser; resolution bandwidth (RBW) = 10kHz and video bandwidth (VBW) = 10kHz.

4.2.4 Efficiency and Functionality

Comparing the passive divider/rectifier and active rectifier/converter circuits of Figs. 3.1 and 3.2, there are differences in power efficiency and functionality. The active circuit of Fig. 3.2 is more power efficient than that of Fig 3.1. The passive divider/rectifier has R1 and R2 where losses occur. In comparison only the losses of the power converter in Fig. 3.2 are of significance.

The active circuit of Fig. 3.2 can regulate for line voltage fluctuations. This provides a steady LED voltage which in comparison to the passive circuit of Fig. 3.1, will cause annoying fluctuations in the light output [156].

From both an efficiency and functional standpoint, the active LED lamp driver seems to be

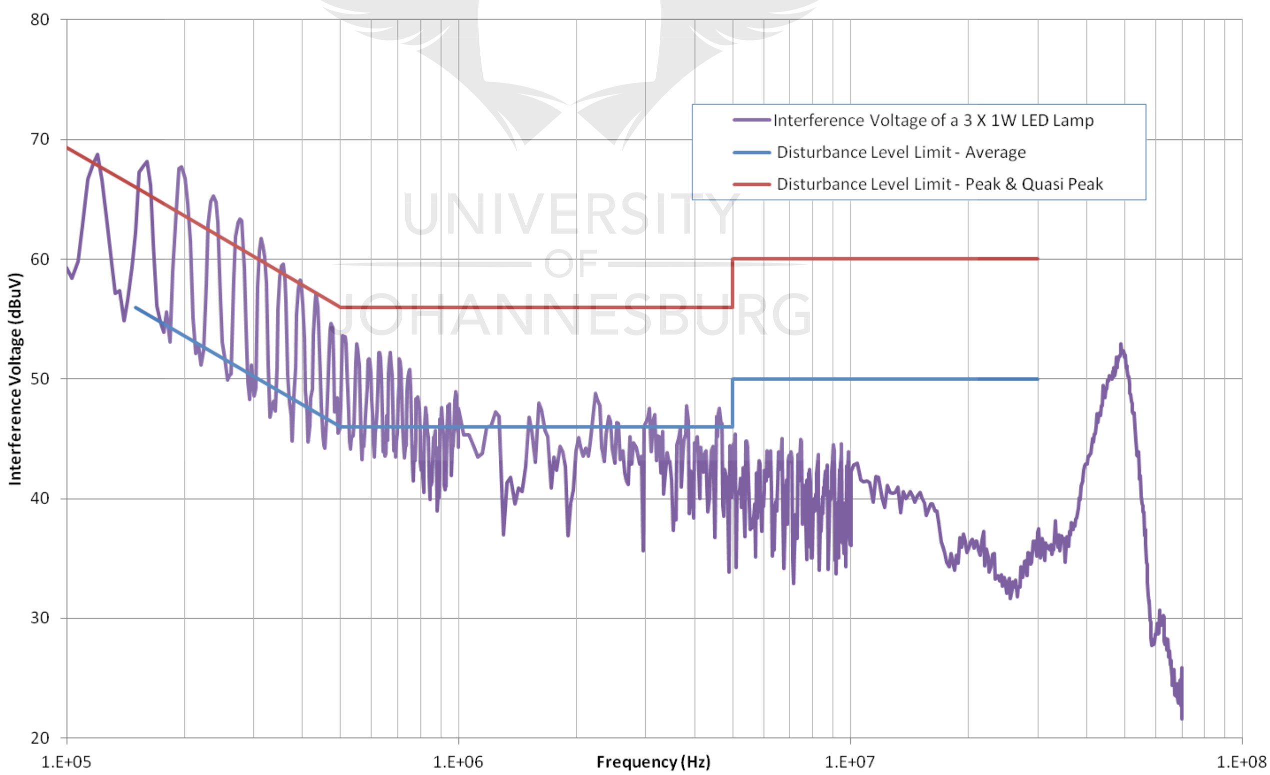

Figure 4.6: Interference voltage from the 3X1W LED Lamp versus the EMC average and peak/ quasi-peak disturbance level limits in the band 150kHz – 30MHz.

superior. From a PLC standpoint however, the passive driver is preferred as it does not cause noise (close to the maximum allowable PLC signal level) in the 150kHz – 30MHz band. The active LED lamps will only become a more favourable lighting solution (in PLC terms) if statuary signal limits are lifted in the 50kHz – 30MHz band.

4.3 CFL LAMPS

This section investigates the effects when compact fluorescent lamps are seen as interference sources on the wiring system of the power line communications channel. Two different measurement set-ups (depending on the interference band) are given.

The procedure of the measurements was made to comply with CENELEC narrowband rules in one case, and to serve the broadband signals in the other case [1].

Since compact fluorescent lamps range between high to low quality lamps, harmonics are more likely to be produced by the low quality ones. The main cause of the harmonics (in the CENELEC band) is the rectifiers that the CFLs use in their normal operation [157]. The cause of noise in the 150kHz – 30MHz band is a power electronics converter employed by all CFLs.

The parameters of the DFT and spectrum analyser employed to obtain the figures in this chapter were given in section 4.2.

4.3.1 CFL's Driver Structure

In this section we show that, considering noise generation in CFLs, there is a common structure in the CFL's drivers, which consists of an active rectifier with power converter and filter as shown in Fig. 4.7.

In the CFL the 50Hz, 220VAC input is rectified and filtered (by a capacitor C). This high voltage DC is then converted and current limited by an active high frequency switching power electronic converter. The circuit will produce high frequency switching harmonics in the current drawn from the supply, over and above the lower network harmonics due to the rectifier action. The filter between the rectifier and AC supply filters the high frequency

(150kHz – 30MHz) noise being produced by the converter. As it will be shown, manufacturers’ designs vary in the amount of this noise being filtered.

Figure 4.8 shows measured line current waveforms for four compact fluorescent lamps. A fifth trace shows the line current for all the lamps switched on at once. These lamps were manufactured by four different companies. The lamps have similar waveforms which vary slightly in amplitude due to differences in the brands.

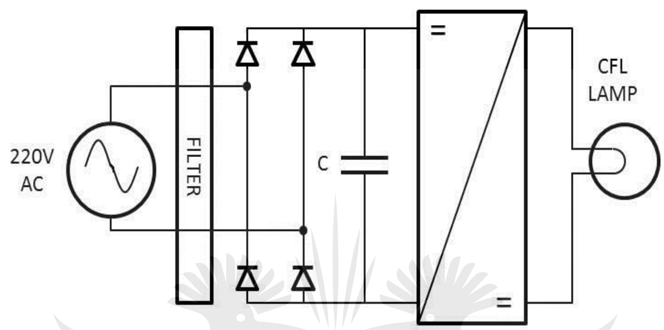

Figure 4.7: Rectifier and converter type CFL driver.

4.3.2 Harmonics – CENELEC Bands

In order to determine what effect the harmonics of the compact fluorescent lamp has on the power-line communications channel, the currents in Fig. 4.8 must be represented in the frequency domain. This is done by performing a Discrete Fourier Transform (DFT) on exactly one period of data from Fig. 4.8. Performing a DFT on one cycle of data yields the harmonics (or frequency domain components) that make up the time domain waveform.

The DFTs of Fig. 4.8 are shown in Fig. 4.9. The DFTs were performed for each of the four waveforms in Fig. 4.8 with the addition of a fifth analysis which is the harmonics of the current of all the lamps from the different brands combined (turned on simultaneously). This measurement of the fifth analysis was performed to show the interference that the CFL lamps cause to the power line channel. The fundamental for each lamp is at 50Hz. The “all lamps combined” fundamental is the largest as can be expected, since all the lamps combined draws the largest amount of current. The harmonics (starting close to a hundred mA at the fundamental) roll off to the tens of µA's around 20kHz which is close to the noise floor.

In order to compare the current harmonics to typical power-line channel signal voltages, the current magnitudes in Fig. 4.9 must be multiplied with typical power line channel impedances for each of the harmonic frequencies. This power line channel impedance can be approximated by using the values of the LISN that is used for measurement (Figs. 3.1 and 3.2). The LISN characteristics are specified in EN 50065-1.

Fig. 4.10 gives the results when the "all lamps combined" harmonics (in voltage) are plotted against the CENELEC EN 50065-1 standards for maximum power line communications signal and Electromagnetic Compatibility levels. The "all lamps combined" is the worst case noise for the lamps.

At 135dBµV (around 5V) the allowable wideband signal strength for a PLC signal is very high. It is around 40 - 60dB higher than the noise harmonics from the signal of all of the CFLs tested together. The noise harmonics are also well below the allowable EMC limit as stated in EN 50065-1. It can therefore clearly be seen that in the CENELEC bands from 3kHz – 150kHz, CFLs are unlikely to degrade the performance of PLC systems.

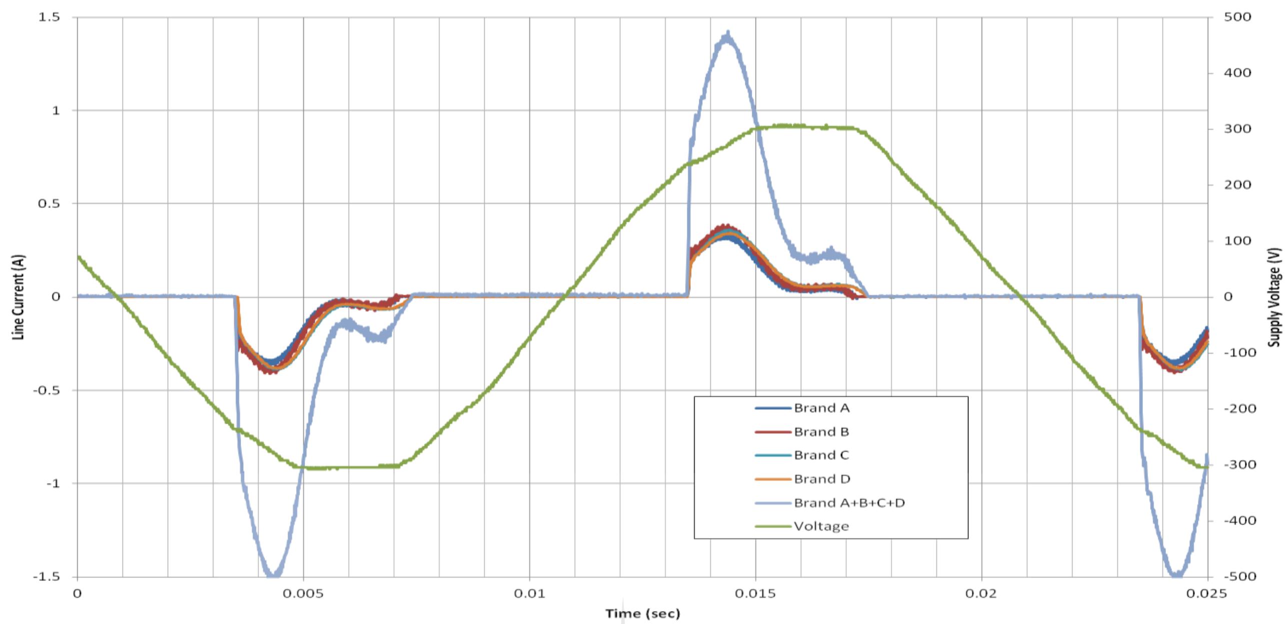

Figure 4.8: Time domain line current waveforms for four different compact fluorescent lamps. The voltage and line current with all the lamps switched on together are also shown.

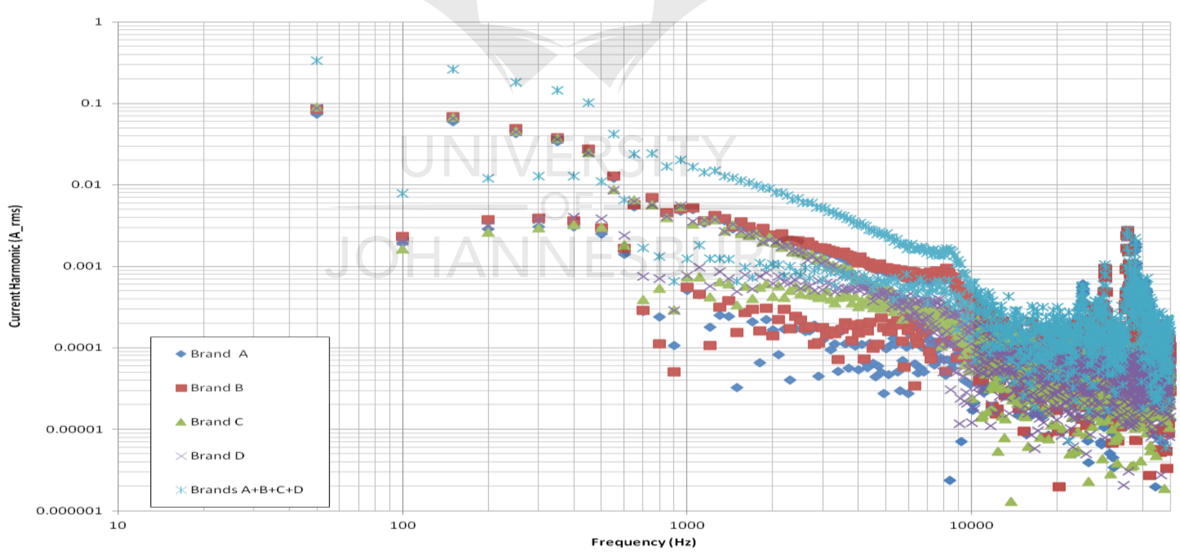

Figure 4.9: Frequency domain line current harmonics (DFT) for the four different CFL'S shown in Fig. 4.8 A fifth spectrum shows the harmonics when all the lamps are switched on simultaneously.

4.3.3 Broadband Spectrum

In Fig. 4.8, the line current drawn by four different brands of CFLs are shown. All those four incorporate power electronics (of the structure shown in Fig. 4.7). In terms of noise in the Broadband PLC spectrum (150kHz – 30MHz) the lamps generate noise in this part of the spectrum –due to the switching action of the power electronics converter.

The interference voltage from the CFL lamps versus the EMC average and peak disturbance level limits is shown in Fig. 4.11. It is shown that in the 150kHz – 30MHz band spectrum, the interference voltage level from the CFL lamps is close to the EMC limits at the beginning of the frequency band. The EMI filters included in the lamps are of inferior quality as manufacturers aim to reduce costs of electronic components included in the lamps, which results in filtering noise to the EMC limits only.

Reducing manufacturing costs of CFL lamps is thus a serious issue when the lamps are connected to electric power grid. Other connected devices, instruments and appliances to the network might also get affected.

4.3.4 Discussion

Four brands of “Energy-Savings” compact fluorescent lamps were tested for noise generation in the power line communications channel. This group of CFLs uses active power electronic converters to drive the lamps. They produce interference in the 3kHz – 150kHz band, but this poses low risk for PLC. Some of them do however produce interference in the 150kHz – 30MHz band. As the noise level and PLC signal level are governed by the same EMC standard, the CFLs can cause noise at the level of PLC transmissions, effectively drowning the communication signals. Unless this standard is revised and PLC signals allowed to exceed the EMC limit, power line communication signals will have to operate at very low signal to noise ratios, that is close to zero.

By comparing the results obtained from the CFL’s measurements to those obtained classical lamps, it was observed that using the CFL lamps result in having less harmonics and interference to the power line communications channel.

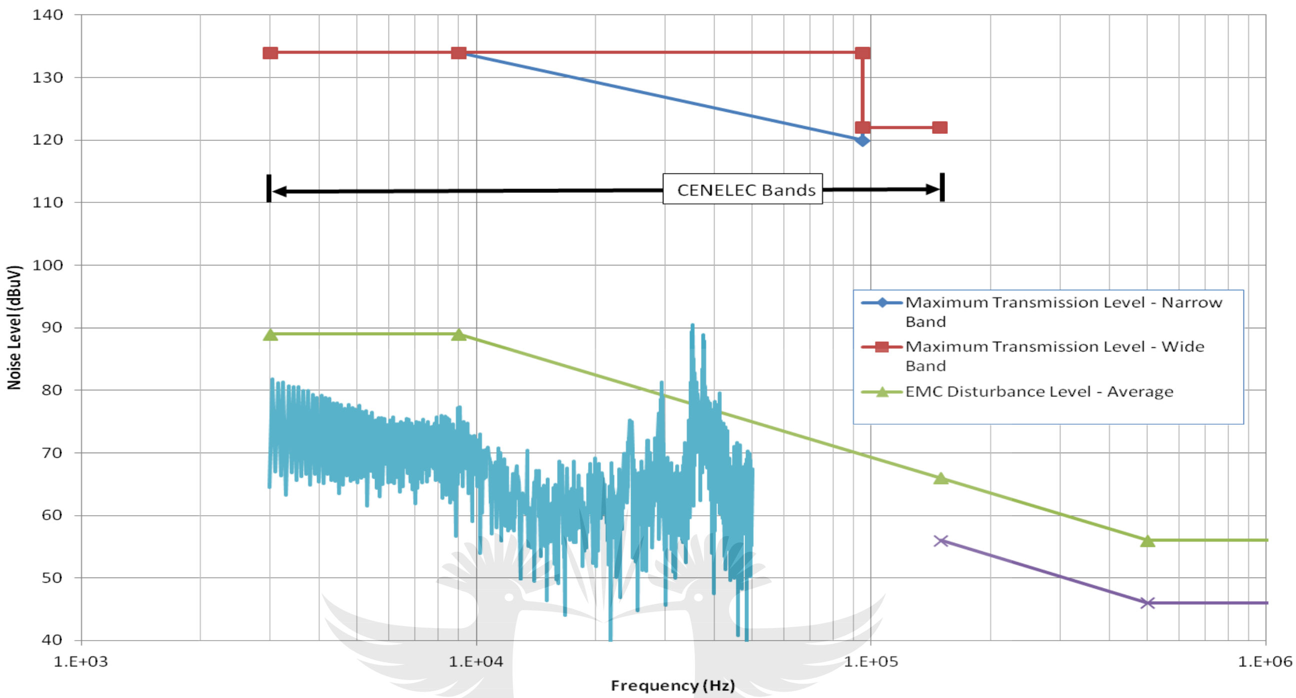

Figure 4.10: CFL lamp: comparison of the harmonics of “all the lamps combined” with the EMC standards and maximum allowable PLC signal strength in the CENELEC band 3kHz – 150kHz.

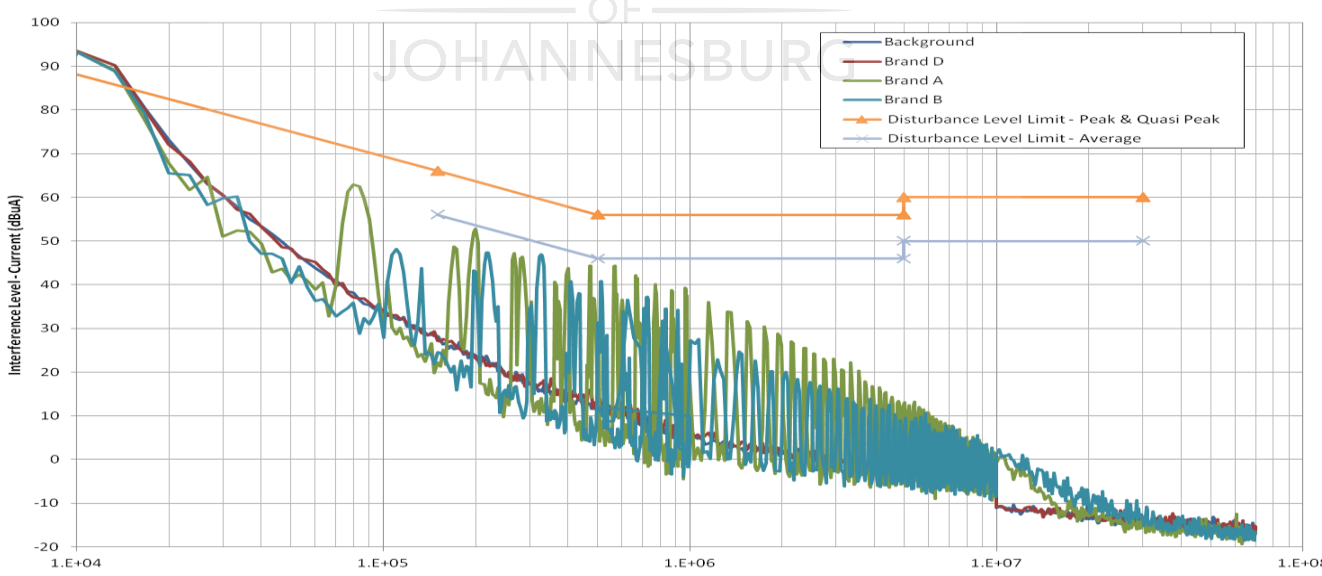

Figure 4.11: CFL lamp: high frequency, including the 150kHz – 30MHz band, spectrum results.

4.4 FLUORESCENT TUBES

The fluorescent lamp is a thermally sensitive light source and the average luminous output from a fluorescent lamp is 75 Lumens/Watt [158]. The lamp wattage characteristic changes with ambient temperature because the changing mercury vapor pressure within the lamp alters the voltage and current values, as well as their associated phase relationships.

Electronic ballast is a device intended to limit the amount of current in an electric circuit and it uses a half-bridge inverter and a boost DC-DC converter [159]. A familiar and widely used example is the inductive ballast used in fluorescent lamps, to limit the current through the tube, which would otherwise rise to destructive levels due to the tube's negative resistance characteristic.

Ballasts vary in design complexity; they can be as simple as a series resistor or inductor, capacitors, or a combination thereof or as complex as electronic ballasts used with fluorescent lamps and high-intensity discharge lamps. The electronic ballasts in fluorescent lamps are considered better than the electromagnetic ballasts since they provide a better efficiency (Lumen/Watt), they are smaller and lighter than the electromagnetic counterparts and they prolong the lamp's life [160].

However, fluorescent lamps with electronic ballasts do inject undesired noise into the power line communications channel.

It is shown that in the CENELEC band: (3kHz – 150kHz) the interference level from the fluorescent lamps is significantly below the allowed maximum PLC signal levels and therefore poses no threat to the power line communications. In the band 150kHz – 30MHz however, PLC signals compete with EMC levels.

We investigate the effects when fluorescent lamps with electronic ballasts are seen as interference sources on the wiring system of the power line communications channel. Two different measurement set-ups (depending on the interference band) are given.

The procedure of the measurements was made to comply with CENELEC narrowband rules in one case, and to serve the broadband signals in the other case. The power-line regulations were considered when performing related measurements.

For the parameters of the DFT and spectrum analyser employed to obtain the figures in this section, please refer to section 4.2.

4.4.1 Electronic Ballast Driver

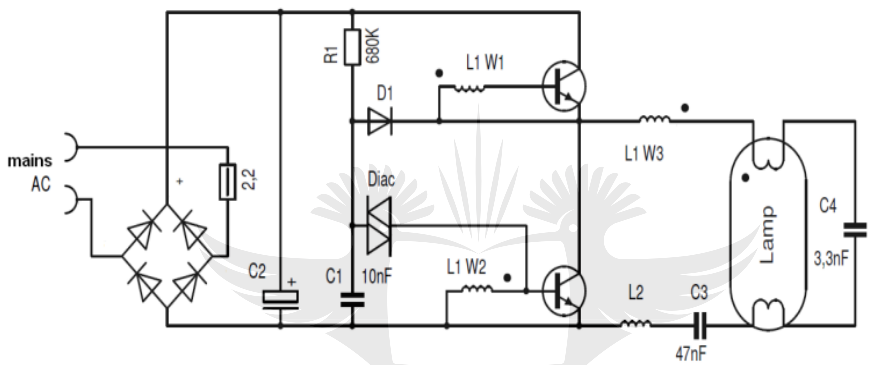

Figure 4.12: Electronic ballast fluorescent lamp driver (inverter).

In this section we show that, for noise generation in fluorescent lamps, there is a common structure of the electronic ballast fluorescent lamp drivers, which consists of different amplifiers and electronic components as shown in Fig. 4.12.

Fluorescent lamps require a ballast both to stabilise the current through the lamp, and to provide the initial striking voltage required to start the arc discharge. Those electronic ballasts employ transistors to change the supply frequency into high-frequency AC while also regulating the current flow in the lamp. Electronic ballasts typically work in rapid start or instant start mode, and are commonly supplied with AC power, which is internally converted to DC and then back to a variable frequency AC waveform.

4.4.2 Harmonics – CENELEC Bands

In order to determine what effect the harmonics of a fluorescent lamp has on the power line communications channel, a CM/DM-Separator is used in this type of measurements. This is done

to subtract the Differential Mode from the Common Mode as stated in [60]. The frequency domain harmonics (magnitude) for the waveforms in Fig. 4.13 were performed when having a steady-state noise measurement. The steady-state means that the 220VAC is on and the harmonics are continuously shown on the screen of the spectrum analyser. Another measurement was performed when applying switch on/off to the fluorescent lamp power button. It is the impulsive noise that occurs at a fraction of second (less than 2ms). This is also shown in Fig. 4.13.

No Specific EMC limits are included in Fig. 4.13 as they vary from product class to class.

The obtained harmonics (in voltage) are plotted against the CENELEC EN 50065-1 standards for maximum power line communications signal and EMC levels. At 135dBμV (around 5V) the allowable wideband signal strength for a PLC signal is very high. It is around 20 – 40dB higher than the noise harmonics from the signal of the fluorescent lamp. It can therefore clearly be seen that in the CENELEC bands from 3kHz – 150kHz, fluorescent lamps with electronic ballasts to a limited extent interfere with a power line communications channel at certain frequencies.

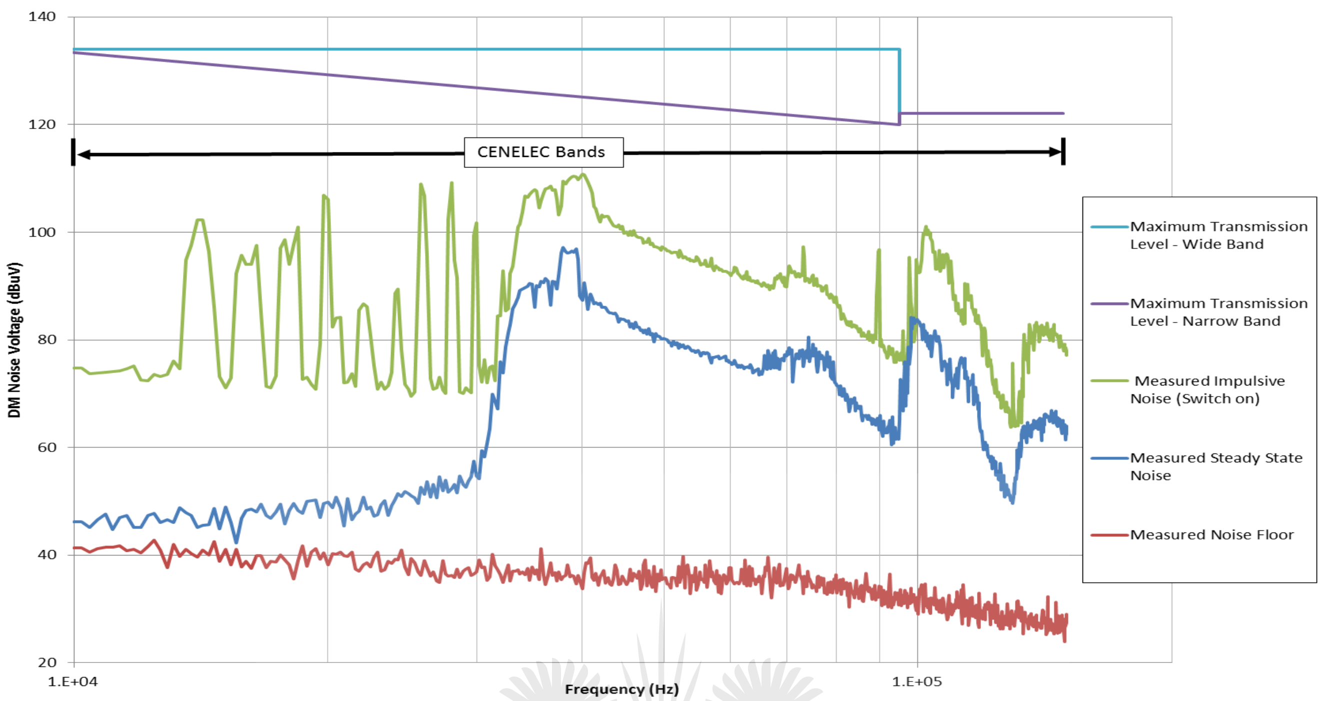

Figure 4.13: Fluorescent tube: frequency domain waveforms and harmonics for 3kHz – 150kHz range.

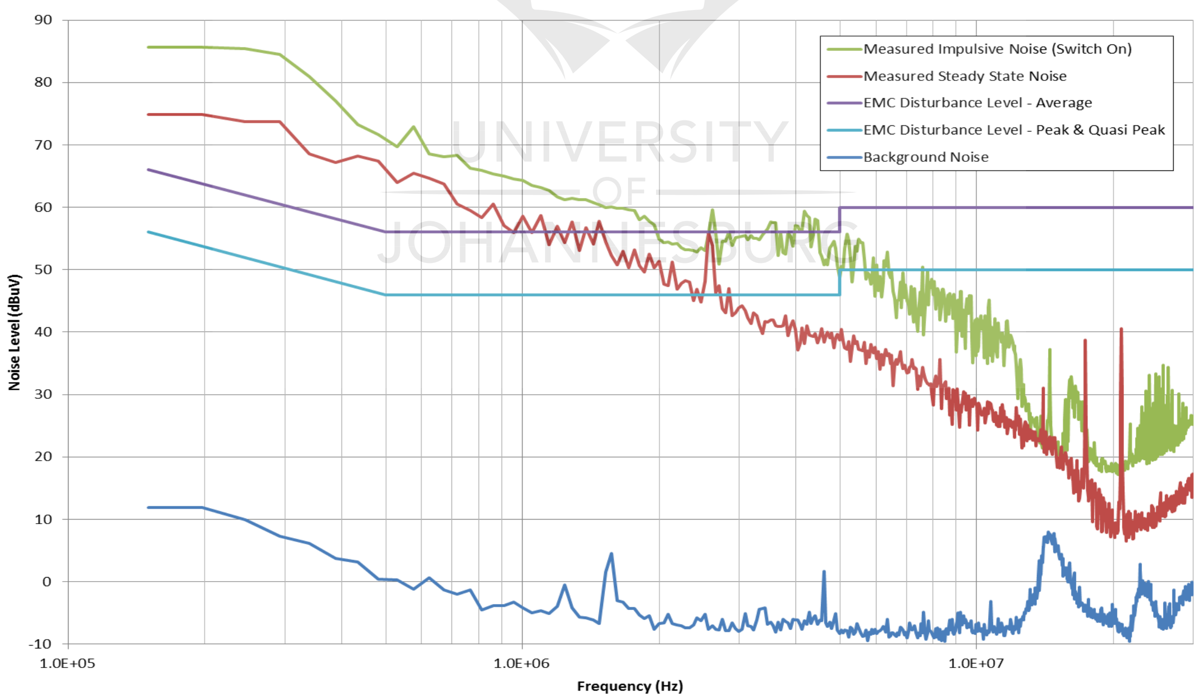

Figure 4.14: Fluorescent tube: frequency domain waveforms and harmonics for 150kHz – 30MHz range.

4.4.3 Broadband Spectrum

For this frequency range, a similar procedure of measurements to those of the CENELEC bands was performed to get the most accurate results possible. In terms of noise in the Broadband PLC spectrum (150kHz – 30MHz) the fluorescent lamps with electronic ballasts generate undesired noise in this part of the spectrum. This is shown in Fig. 4.14. The obtained frequency domain harmonics in this set of measurements, however, compete with the Electromagnetic levels.

The current harmonic signals shown in Fig. 4.14 clearly illustrate that the EMC disturbance level limits are exceeded. In the 150kHz – 30MHz band, the interference levels must be kept below the EMC maximum peak and quasi-peak limits as the power lines get affected by the perturbation signals caused by the fluorescent tubes. At around 5MHz, the signal levels compete with the EMC maximum allowable levels, where at 10MHz – 30MHz the PLC system is less affected, therefore, communications can be more possible.

As a conclusion, the PLC signals in the 150kHz – 30MHz spectrum band have to compete with interference from most devices with electronic ballasts and may have a zero S/N ratio at certain frequencies.

4.4.4 Discussion

From a PLC standpoint, the fluorescent lamp with electronic ballast is preferred as it does not cause noise (close to the maximum allowable PLC signal level) in the 3kHz – 150kHz band. The fluorescent lamps will only become a more favourable lighting solution (in PLC terms) if statuary signal limits are lifted in the 150kHz – 30MHz band. However, by comparing the noise measurements in Fig. 4.13 to the measured noise floor, we describe the power-line communications channel as an affected channel.

In this section, details of an electronic ballast for 36W/220V rms 50Hz for fluorescent lamp are presented. Several measurements have been conducted to illustrate the effects of the fluorescent lamps with electronic ballasts on the power line communications channel. It has been demonstrated that the fluorescent lamps do inject conductive noise into the PLC channel.

Fluorescent lamps produce noise in the 3kHz – 150kHz CENELEC bands, but this interference level is 20dB to 40dB lower than the allowable PLC signal level and therefore poses no risks for the communications over a power line channel. Fluorescent lamps also produce noise in the 150kHz – 30MHz band as the noise level and PLC signal level is governed by EMC standards. Unless this standard is revised and PLC signals allowed to exceed the EMC limit, power line communication signals will have to function with signal to noise ratios near zero. This is critical as it is envisaged that the fluorescent lamps market will move towards other new and different types of lamps as they might be more energy efficient and offer higher functional performance than fluorescent lamps.

4.5 PLASMA LAMPS

The well-known plasma lamps design was invented during the 1970's by an MIT student named Bill Parker [161]; nevertheless, the original plasma lamps were first created by Nikola Tesla [162] while studying the effects of high frequency current discharged into low pressure gases contained by a glass tube.

Plasma lamps come in different constructive design and shapes, globes, domes, orbs and others, but they all work on the same basic principle. They can usually be found in the shape of a clear glass orb, containing a mixture of low pressure gases such as xenon, krypton and neon, although the gaseous mix is not preferential. The other glass shell houses a much smaller glass orb that has the role of the electrode. High frequency, high voltage alternating current is being pumped into the electrode with the help of a high voltage transformer.

The procedure of the measurements was made to comply with CENELEC narrowband rules in one case, and to serve the broadband signals in the other case.

The parameters of the DFT and spectrum analyser employed to obtain the figures in this chapter were given in section 4.2.

4.5.1 Plasma Driver Structure

There are two main classes of plasma lamp drivers. The first and the simplest form is the one that uses the step-up transformer, which consists of a 220VAC to 9000VAC transformer that powers the plasma lamp as shown in Fig. 4.15.

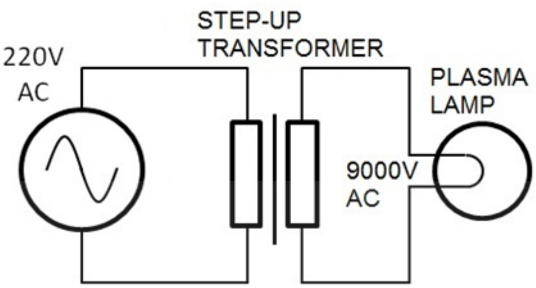

Figure 4.15: First class of plasma lamp drivers

The circuit of the second type of plasma lamps is basically 220VAC in a 25.2V step down transformer, into a full wave bridge rectifier, and a large filter capacitor, which gives over 25.2V DC at just under 2 amperes in the primary side of the circuit with no load. The capacitor is necessary as it charges during the peak of the AC cycle, and releases during the trough. This voltage charges the primary coil and consequently the ferrite core of the transformer, which induces a charge in the "feedback" coil, which turns off the transistors. When the transistors have stopped conducting, the power is rerouted through the resistors. The EM field in the ferrite core then collapses with no charge to support it, which induces a large high voltage spike in the secondary coil in the reverse direction (basic laws of inductors). The transistor then begins to conduct again because there is no longer any current in the feedback winding, which causes the DC input to oscillate and produce AC voltage, out from the secondary at a high frequency like 15kHz – 40kHz, and around 10kV – 25kV output. Diodes can be used as a safety device to keep high voltage induced in the primary coil from damaging the transistors (the system works without them, but they keep the structure from heating up. This is shown in Fig. 4.16.

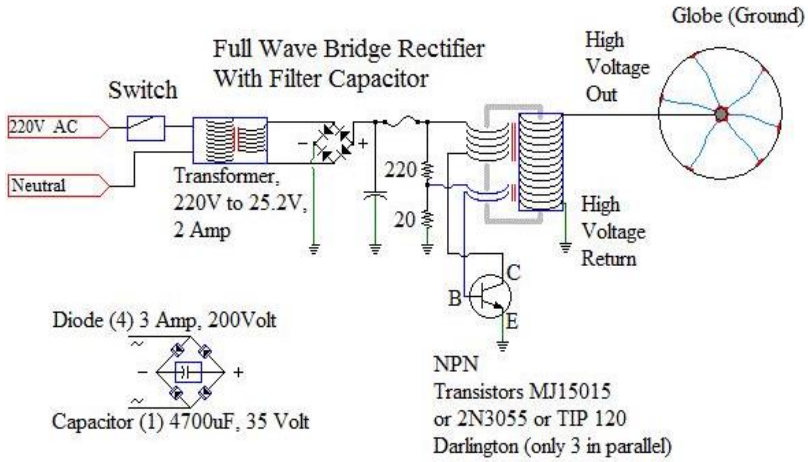

Figure 4.16: Second class of plasma lamp drivers designed using specialised software

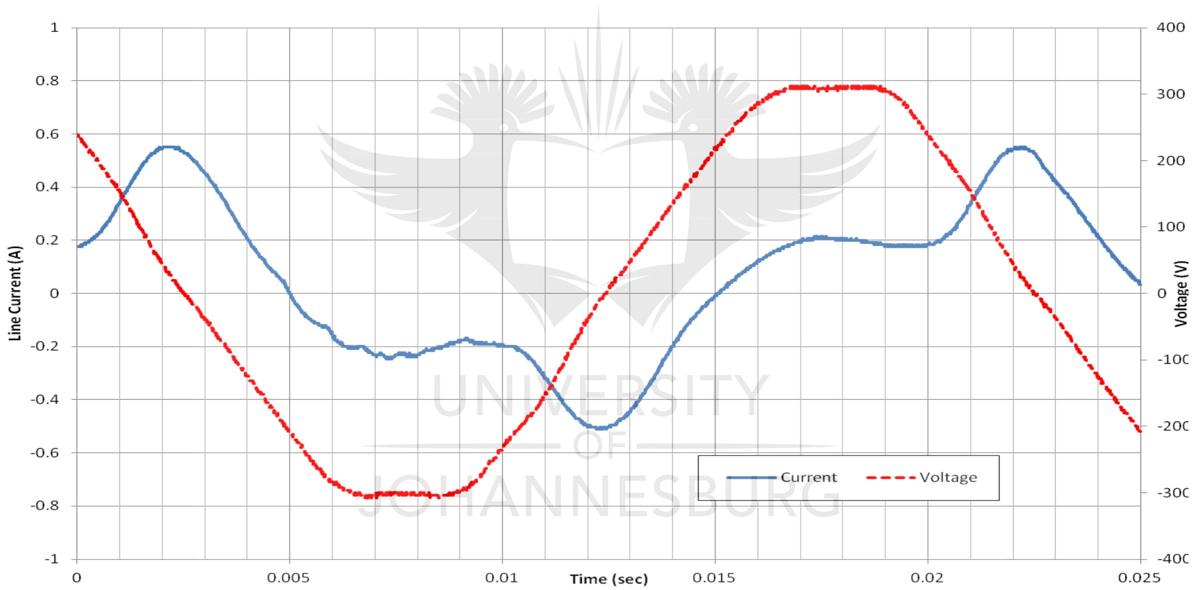

Figure 4.17: Time domain line current waveforms for the plasma lamp.

4.5.2 Harmonics - CENELEC Bands

Detection of the current harmonics for the waveform in Fig. 4.17 is shown in Fig. 4.18 after a DFT operation was performed. The current harmonics and interference signals are compared with the typical PLC signal voltages and the current magnitudes in Fig. 4.18 are multiplied with the PLC impedances for all harmonic frequencies. The PLC impedances can be approximated by using the values of the LISN that is used for measurements (Figs. 3.2 and 3.4).

In the 3kHz – 150kHz band, the current harmonics in Fig. 4.19 are plotted against the CENELEC EN 50065.1 standards for maximum PLC and EMC allowable signal levels. Significant differences in behaviour are observed when plasma lamps are connected to the wiring infrastructure of the PLC channel. Those differences can be clearly seen by performing a comparison with other types of lighting sources, such as LED and CFL lamps.

The interference signals are positioned below the maximum PLC and EMC allowable signal limits as stated in EN 50065.1.

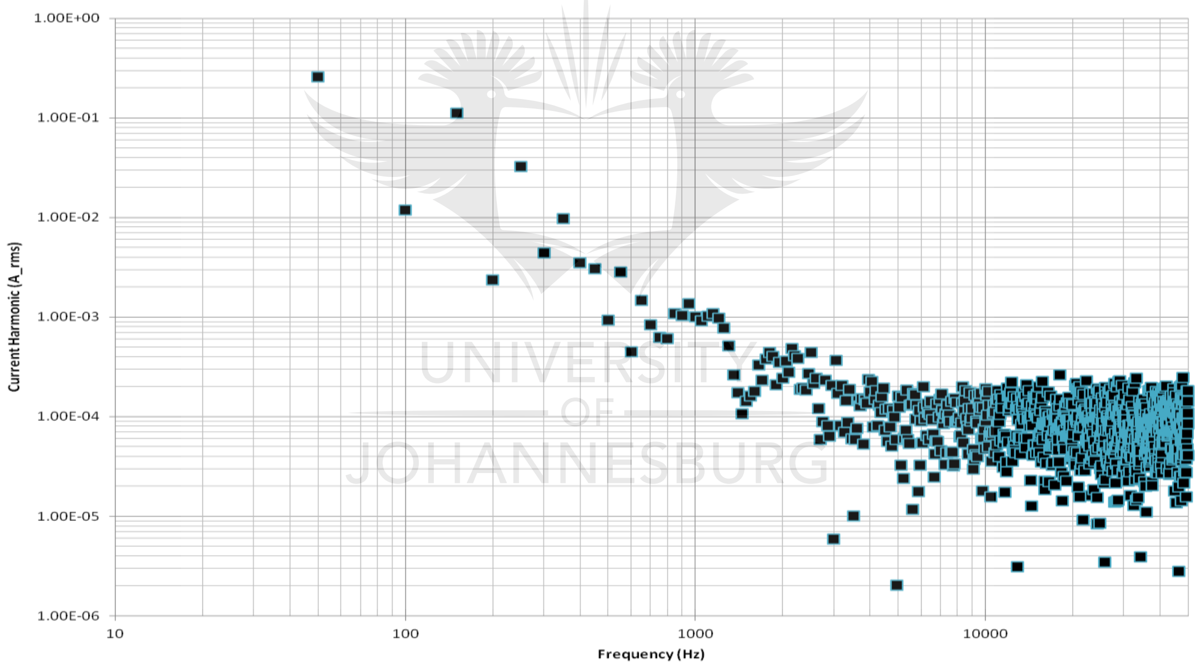

Figure 4.18: Frequency domain line current harmonics (DFT) for the plasma lamp shown in Figure 4.17

We can draw a conclusion that communications on the electric power grids are possible in this frequency band as the plasma lamps are unlikely to interfere with a power line channel. This is because the CENELEC band maximum limits are about 70dB higher than the plasma lamp's noise harmonics and interference.

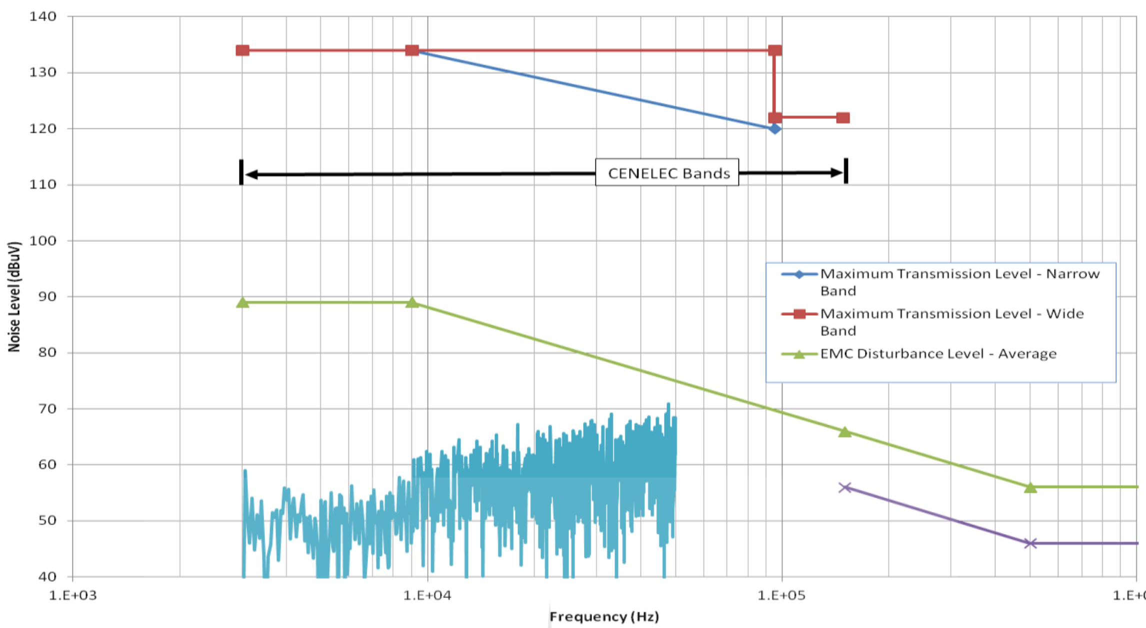

Figure 4.19: Plasma lamp: comparison of the harmonics with the EMC standards and maximum allowable PLC signal strength in the CENELEC band 3kHz – 150kHz.

4.5.3 Broadband Spectrum

As shown in Fig. 4.20, plasma lamps can affect the communications on the PLC channel in the 150kHz – 30MHz band spectrum. However, the results show that the noise levels in this frequency band are below the EMC maximum allowable interference limits and do not compete with them which makes chances of communications more possible.

Plasma lamps can be considered one of the “good” low energy lamps to the PLC network and can be recommended for indoor usage.

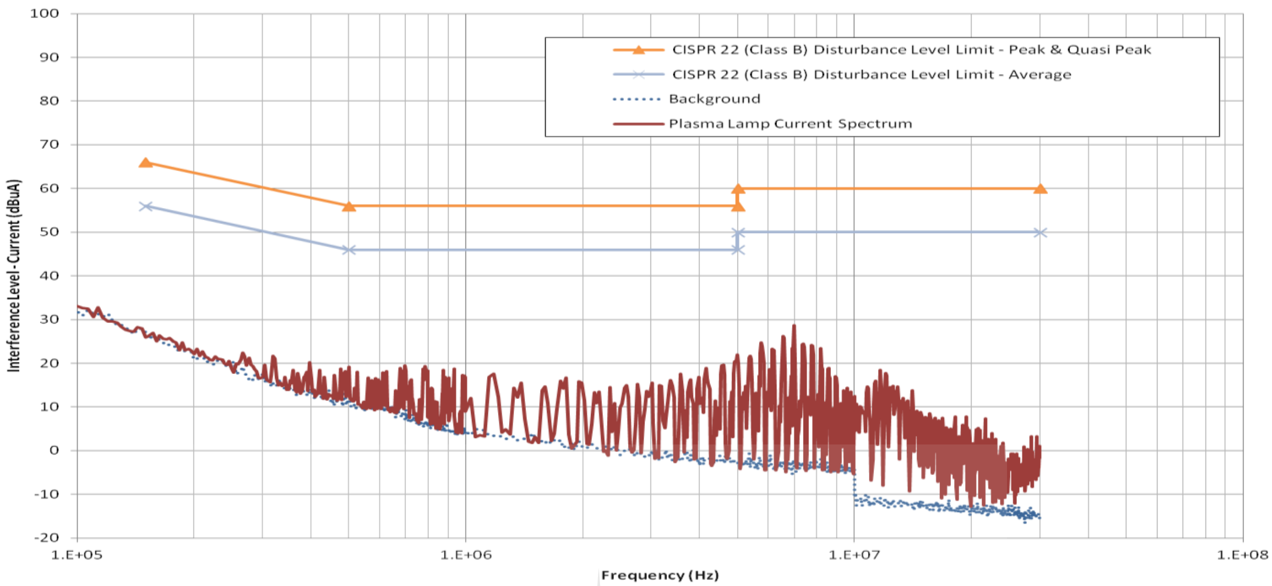

Figure 4.20: Plasma lamp: high Frequency, including the 150kHz – 30MHz band, spectrum results.

4.5.4 Discussion

We showed that there are two distinct classes of plasma lamps when considering noise generation in the power line communications channel. The plasma lamps produce noise in the 150kHz – 30MHz band where the noise level and PLC signal level is governed by the same EMC standard. They also produce noise in the 3kHz – 150kHz CENELEC bands, but this interference level is 60dB to 70dB lower than the allowable PLC signal level and therefore pose no risks for power-line communications.

Chapter 5 – Specialised Low Energy Light Sources

Summary:

A detailed comparison between Colour LED & CFL Lamps is shown and the related experiments are explained in Chapter 5. This chapter also shows how LED tubes negatively influence the data rate throughput of an indoor broadband PLC channel.

5.1 COLOUR LED & CFL

5.1.1 Introduction

For the past two decades several types of light sources have been dramatically developed to suit the market needs. Different types of modern lamps have been introduced to the market in addition to the existing "old fashion" lamps. In the previous chapters, several types of lamps used as lighting sources have been shown. Most of them are long life lamps and are seen as efficient and low cost lamps.

In this chapter, and for most accurate results of experimental measurements, we have conducted measurements that compare the levels of interference caused by colour modern light sources. The main colour low-energy indoor light sources that exist in the market, such as light emitting diodes (LEDs) and compact fluorescent lamps (CFLs), have been tested for noise generation on the PLC channel and the results are analysed and shown in this chapter.

Almost all the indoor light sources, such as LEDs and CFLs, inject undesired noise into the low voltage network [163]. This noise can have a detrimental effect on the power line network when used for communications. This can also have a strong and negative effect when using the smart-grid communications channel to control the automatic switching of lamps in small and large buildings and factories, as well as homes and shopping centres. It can be one of the power features and quality concerns in residential and industrial areas as the LEDs and CFLs are considered as serious interference sources on the low voltage PLC network [157].

The LEDs and CFLs differ in design, shapes, colours, output wattage and manufacturing quality. They can be warm, cool, bright white or daylight, with or without colours and day/night motion switching sensors. Colour LEDs can achieve efficacy of over 50 lumens per watt (lm/W) and colour CFLs range between 50 – 70 lumens per watt. LED lamps can be divided into two classes (active and passive). They can have different effects in all sections of the emission spectrum which completely depends on the noise generating electronics that are used as LED drivers. Colour CFLs range between high to low quality lamps, therefore, harmonics in the band 3kHz – 150kHz are more likely to be produced by the low quality ones and due to low cost filtering and the rectifiers that the CFLs use in their normal operation [60]. The cause of noise in the 150kHz – 30MHz band is the power electronics converter employed by all CFLs.

On the other hand, the frequency spectrum of various colours of light emitted by LEDs and CFLs in the field of power line communications lies between 750nm (red light) and 380nm (violet light) as per the equation:

$$c = f\lambda \tag{5.1}$$

where c is the speed of light (2.998×10^8m.s^{-1}), f is the frequency which corresponds to the wavelength denoted by λ can be used to convert the wavelength of light in the visible spectrum to a specific frequency band.

Rearranging (5.1) yields:

$$f = \frac{c}{\lambda} \tag{5.2}$$

which, when used, returns a frequency of 399.7 THz for red light and 788.9 THz for violet light.

Frequency Domain Harmonics:

A periodic signal, which is a signal that repeats itself after a specified period *T*, is related to the fundamental frequency (f_o) through the equation:

$$f_o = \frac{1}{T}. \tag{5.3}$$

Harmonics in the frequency domain occur at integer multiples of the fundamental frequency. This means that the frequency spectrum of a periodic signal will have spectral content at the fundamental frequency and the harmonics. The nature of the signal will dictate the amplitude of the content at each particular frequency.

5.1.2 Current Harmonics

Chapter 4 stated that the current harmonics (magnitude) produced by LED and CFL lamps are a serious challenge to the power line communications channel. The colour lamps also inject noise waveforms into the infrastructure of the PLC channel. When conducting measurements in the 4 CENELEC bands, the frequency domain waveforms were extracted from the obtained current harmonics by multiplying the later with the LISN impedance values.

The measurements were taken for three coloured LED lamps that were designed to operate at 220VAC and have power consumption rating of 1.2 watt each. Each lamp was tested a few times for accuracy and comparison purposes. Visible light is a portion of the electromagnetic spectrum that falls between ultraviolet rays and infrared rays, with an approximate wavelength of 390 – 700 nanometres (nm). The noise harmonics shown in Figs. 5.1 and 5.2 are well below the maximum allowable CENELEC band limits, which can, therefore, clearly be seen that in the band from 3kHz – 150kHz colour LED and CFL lamps are unlikely to interfere with the communications over the power line channel.

5.1.3 Broadband Spectrum

The broadband spectrum measurements were performed in a similar procedure to those of the CENELEC bands. Colour LED and CFL lamps do inject unwanted noise in the (150kHz – 30MHz) broadband PLC spectrum. This is shown in Figs. 5.3 and 5.4 However, harmonics from the colour LED lamps in Fig. 5.3 can be seen as less interfering with the power line channel in comparison with the results obtained from the measurements performed for the colour CFL lamps, where the PLC channel gets more contaminated as shown in Fig. 5.4 This is the worst scenario for PLC. The obtained frequency domain harmonics in Fig. 5.4 do exceed the highest allowed Electromagnetic disturbance levels.

In the CENELEC bands from 3kHz – 150kHz there are dedicated maximum signal transmission levels. These do not exist in the 150kHz – 30MHz band and maximum signal transmission is assumed to be at the EMC limit levels.

5.1.4 Discussion

Colour LED and CFL light sources were tested against noise generation on the PLC network. Both light sources produce conducted noise when connected to the existing infrastructure of the PLC channel which can be of a serious risk to the PLC channel.

For colour light sources with active power electronic converters, the SNR can be equal to zero where PLC signals compete with EMC “maximum” signal levels. This leads to performance degradation on PLC transmission.

Unless designers and manufacturers of colour LED and CFL lamps upgrade the quality of electronic components and rectifiers that lamps are made of, PLC will suffer hindrance of communications.

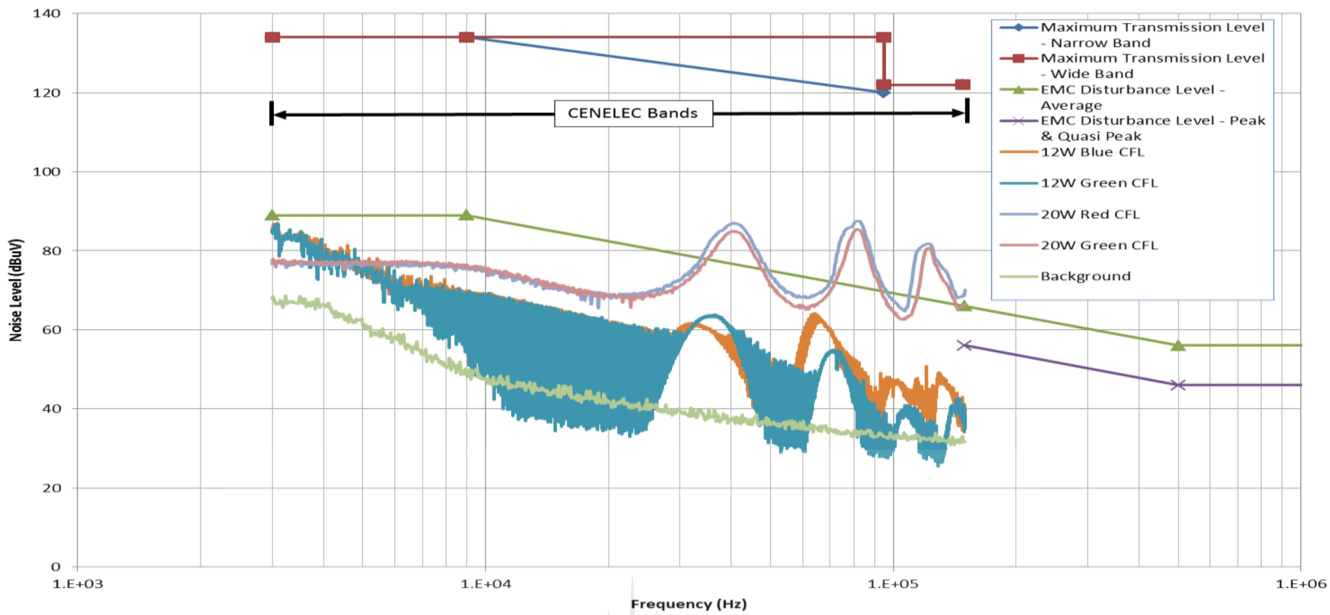

Figure 5.1: CFL frequency domain waveforms and harmonics for the 3kHz – 150kHz range.

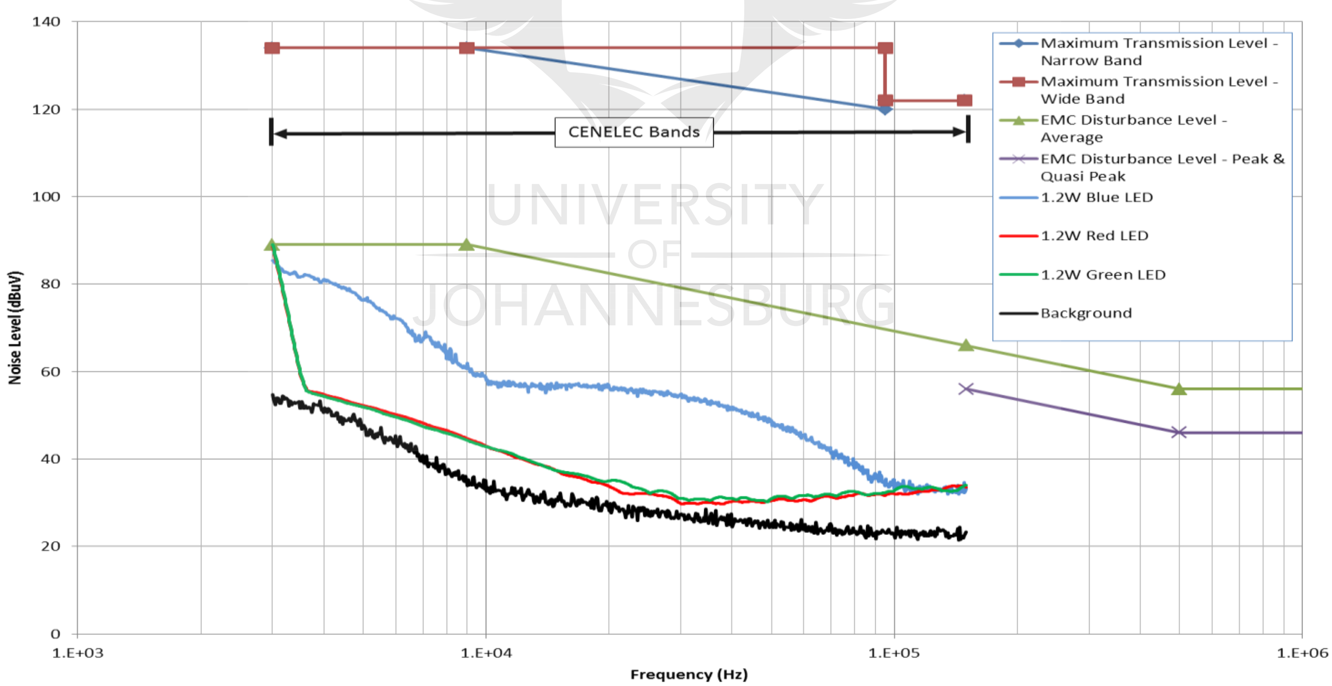

Figure 5.2: LED frequency domain waveforms and harmonics for the 3kHz – 150kHz range.

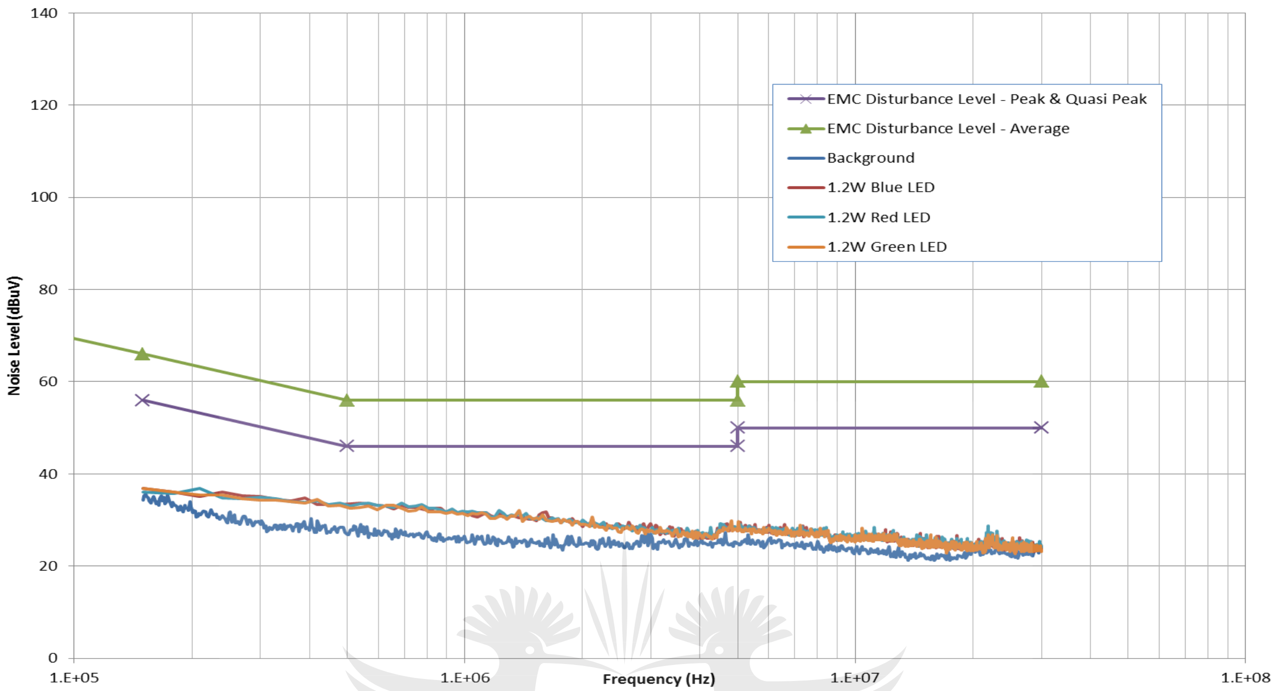

Figure 5.3: LED frequency domain waveforms and harmonics: 150kHz – 30MHz range.

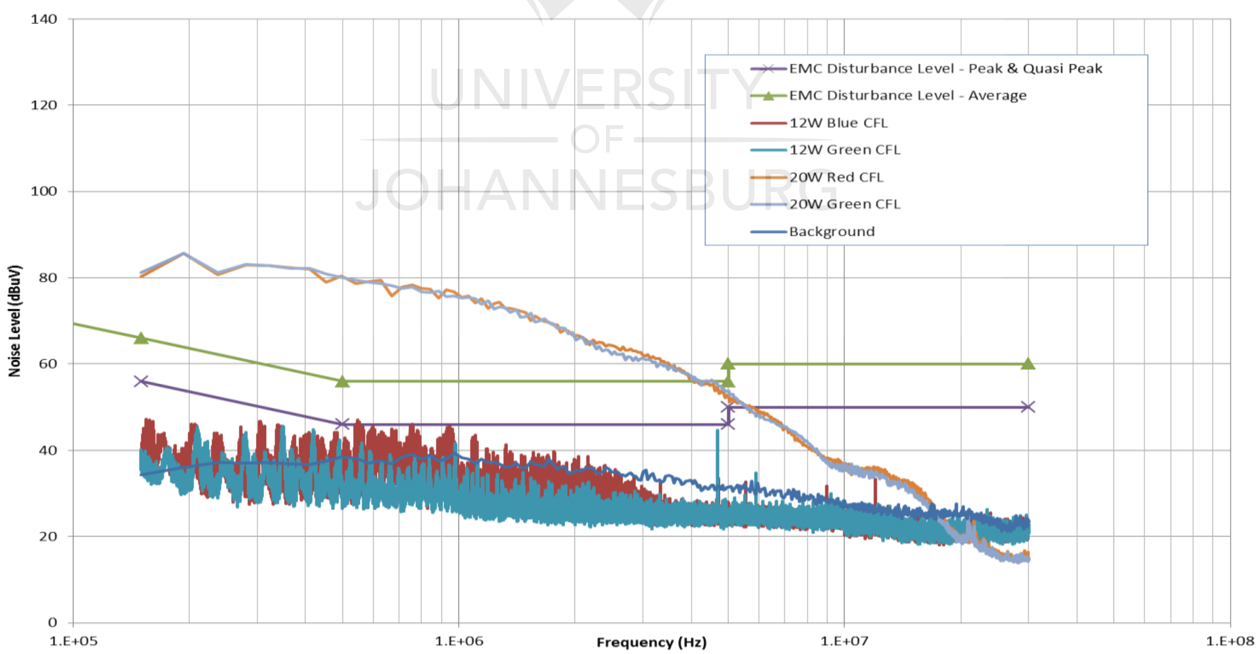

Figure 5.4: CFL frequency domain waveforms and harmonics: 150kHz – 30MHz range.

5.2 TRANSMISSION TESTS IN THE PRESENCE OF LED TUBES

5.2.1 Introduction

LEDs are grouped together to form the LED tubes. LED tubes negatively influence the data rate throughput of an indoor broadband PLC channel. This negative influence on the data rate is due to noise being generated by the tubes. Due to the power conversion in the LED tubes, electrical noise is produced just as with the previous lighting technologies where power conversion takes place. The negative effects of noise on the data rate or throughput on a PLC channel is measured in this section. The throughput in the presence of noise for a given signal strength, bandwidth and noise is given in its theoretical limit by the Shannon-Hartley theorem [164]:

$$C = B\log_2(1 + \frac{S}{N}) \tag{5.4}$$

Data rates (throughput) are measured between two PLC modems in the presence and absence of noise from LED tubes. Two sets of measurements are done; one with the modems in close proximity – a reference case and one with the modems communicating over a 30m power line. The latter is a more realistic or practical case.

A significant decrease (up to 50%) in throughput is observed due to the presence of noise from the LED tubes. This was measured for three different manufacturers of tubes. This result can have implications for designers wanting to use PLC near energy saving LED tubes.

Although (5.4) only applies to Gaussian channels, it shows the trend that if noise increases or channel bandwidth decreases, the feedthrough data rate also decreases.

The parameters of the DFT and spectrum analyser employed to obtain the figures in this chapter were given in section 4.2.

5.2.2 Set-up of Measurements

The measurement set-up consists of two PLC (Homeplug AV2) modems [165,166] communicating on an energized power network. Two PCs were used to communicate via the PLC network. 220VAC (50Hz) was supplied through a LISN. The LISN ensures that power from the mains is clean and it supplies standardised impedance (50Ω to chassis above 1MHz) to the network from the modem's side. An RF current probe connected to a spectrum analyser measures high frequency currents (typically above 1MHz). These currents flow through the impedance of the LISN and are a direct indication of the modems' transmission voltage and signal strength. The current probe is connected so that common mode current is cancelled and so that only Differential Mode (DM) current is measured. An LED tube is connected between the modems and injects noise into the network. Measurements were taken with three different LED tubes energised.

Two physical measurement set-ups were used. These are shown in Figs. 5.5 and 5.6. The only difference in the two set-ups is the distance between modems. In Fig. 5.5, the modems are next to each other (close proximity), while in Fig. 5.6 they are connected by 30m of power cable.

Measured throughput results were taken by transferring a 100MB file from one PC to another (both download and upload) and measuring the time it took. Throughput is then calculated in Mbps. This is done with software that is routinely used to determine upload and download speeds to servers. This was repeated five times to determine a spread of throughputs.

5.2.3 Results

Fig. 5.7 shows a spectrum of the modems polling. One trace is of a modem in close proximity (set-up as in Fig. 5.5) and another of the modem at 30m (set-up as in Fig. 5.6). The Orthogonal Frequency-Division Multiplexing (OFDM) [167,168] carriers can clearly be seen. Only the carriers are present as the modems are polling and no data is being exchanged. Exclusion bands in the Short Wave (SW) band can also be seen. Up to 27MHz the transmission voltages of the modems are high and are limited from 27MHz to around 68MHz.

The signal from the modem at 30m measures lower as the 30m power cable has an attenuating effect on the voltage (and therefore

current) being produced. Depending on the frequency, the attenuation of the 30m power cable is around 5dB to 10dB.

In this initial test, a deterministic spectrum of a periodic signal, namely the unmodulated carrier, is observed (i.e. only the sounding carriers before establishing data transmission) and, in later tests, a random data signal power spectral density is obtained, when transmitting data.

Fig. 5.8 shows the different noise spectra of three different LED tubes in the absence of any communication signal. The LED tubes are clearly different in their noise signatures. Brand A has the highest noise signature followed by Brand C in the lower frequencies and then Brand B. Brand A's noise level is at least 10dB to 20dB higher than the ambient.

Fig. 5.9 is the spectra of signals of modems communicating (that are in close proximity) while in the presence of additive noise from the LED tubes. This is different from the measurement of Fig. 5.7 as the OFDM carriers cannot be clearly seen. Instead, the spectrum is continuous over the bandwidths where data is being communicated. The Homeplug AV2 standard determines the maximum transmission signal strength and is higher from typically 2MHz to 27MHz than in the rest of the band up to about 68MHz.

Fig. 5.9 also represents the conditions under which the throughput measurements were made for the reference condition of the two modems in close proximity (Figs. 5.5 and 5.10). Results of the throughput measurements with the modems in close proximity are given graphically in Fig. 5.10.

With the two modems in close proximity (next to each other on the power line) the system typically achieves data throughput rates of 170Mbps to 190Mbps. This is done as reference as two modems next to one another is not used in practice. However, this will achieve maximum throughput. With the addition of noise from the LED tubes the data rates fall dramatically. For Brand A the throughput falls from 60Mbps to 70Mbps. For Brand B, 60Mbps to 75Mbps and for Brand C, around 80Mbps to 90Mbps. From a throughput and data speed point of view, performance is highest in the presence of Brand C. Brand C has a noise signature that is very close to ambient from around 50MHz with a virtual noise free band up to 70MHz. This most probably explains why the configuration with the Brand C LED lamp has the best throughput under noisy conditions. It is important to note that with the inclusion of lamps directly next to the modems, the throughput data rate drops to at least 50%.

With the two modems at 30m apart and the noise source at the one modem, the system typically achieves data throughput rates of 140Mbps to 185Mbps (Fig. 5.6 and Fig. 5.11).

With the addition of noise from the LED tubes the data rates also fall dramatically with 30m of power cable. For Brand A the throughput falls to 40Mbps to 65Mbps. For Brand B, 80Mbps to 130Mbps and for Brand C, around 85Mbps to 100Mbps. From a throughput and data speed point of view, performance is highest in the presence of Brand C, but paradoxically higher than the two modems in close proximity. The reason for this is not clear although it is important to note that with the inclusion of lamps and the modems 30m apart, the throughput data rate drops to at least 50% and in some cases even further.

5.2.4 Discussion

Data rates (throughput) were measured between two PLC modems in the presence and absence of noise from LED tubes. Two sets of measurements were conducted. One with the modems in close proximity – a reference case and one with the modems communicating over a 30m power line. The latter is a more realistic or practical case. In both cases (due to the noise caused by the LED tube power conversion) the throughput data rate dropped to at least 50% when LED tubes are included on the network. Although all three the LED tubes had Electromagnetic Compatibility markings on them (and it is therefore assumed that they conform to noise emission standards), they still influenced the data transmission rates of a PLC system on the same network. This has important consequences for system designers wanting to use PLC in the vicinity of LED tubes.

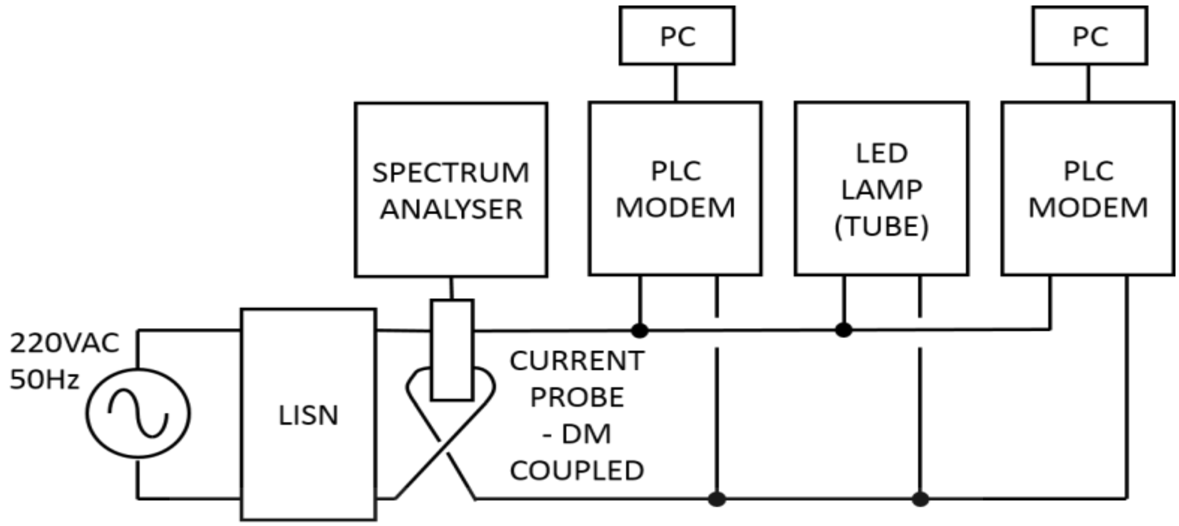

Figure 5.5: Measurement set-up with modems in close proximity.

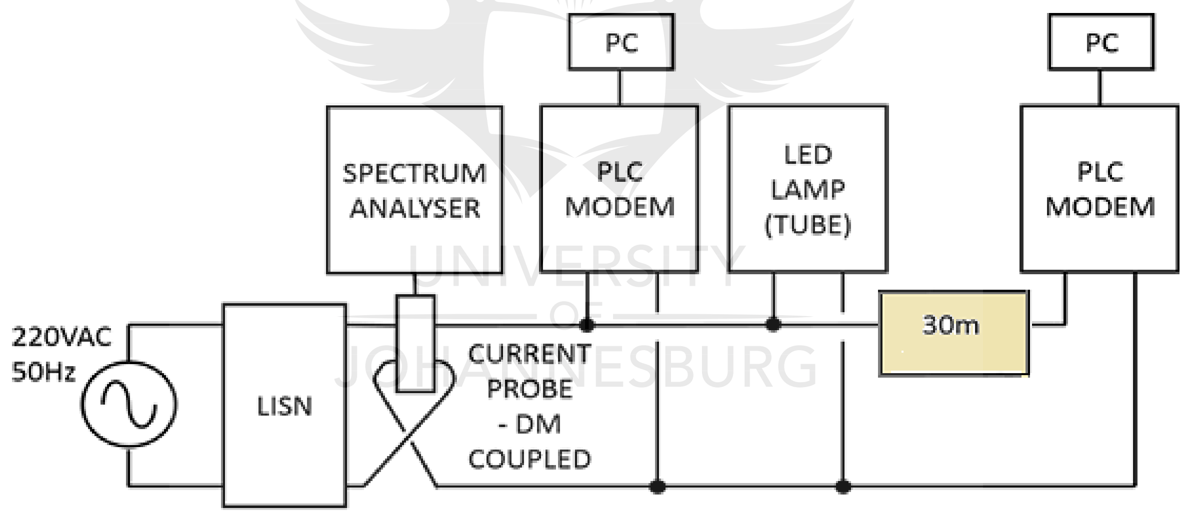

Figure 5.6: Measurement set-up with modems at 30m.

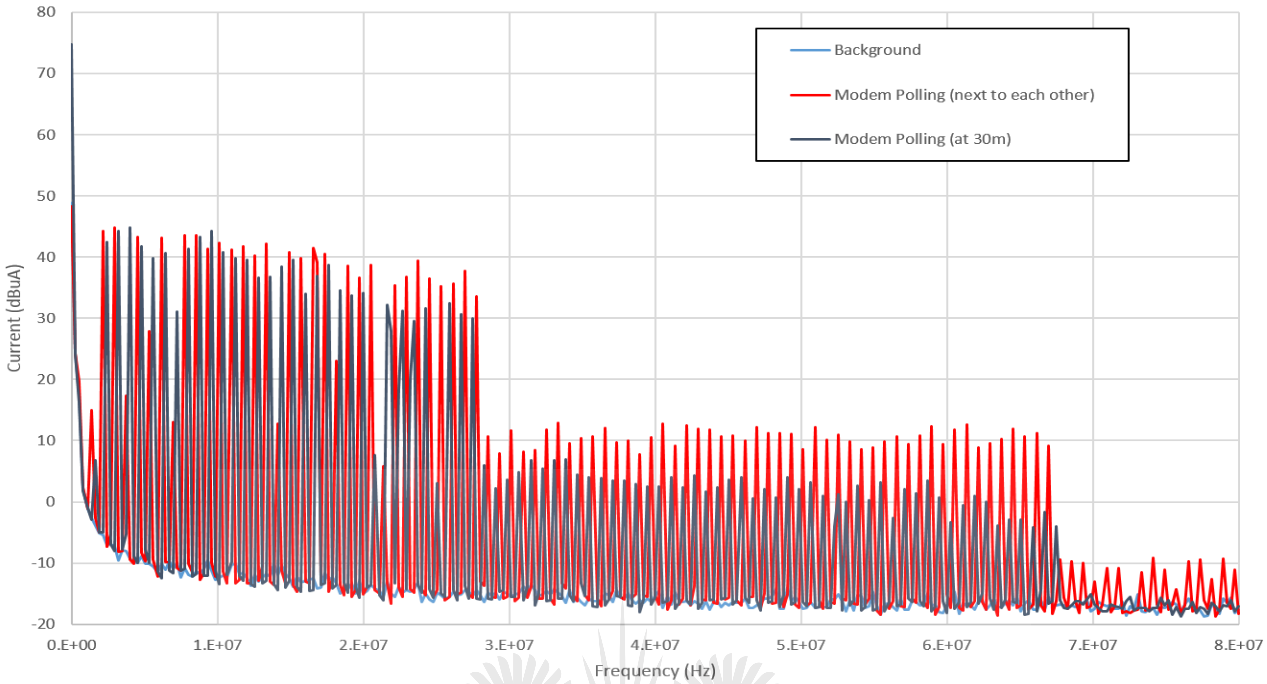

Figure 5.7: Spectrum of modems' polling. Modem in close proximity and at 30m.

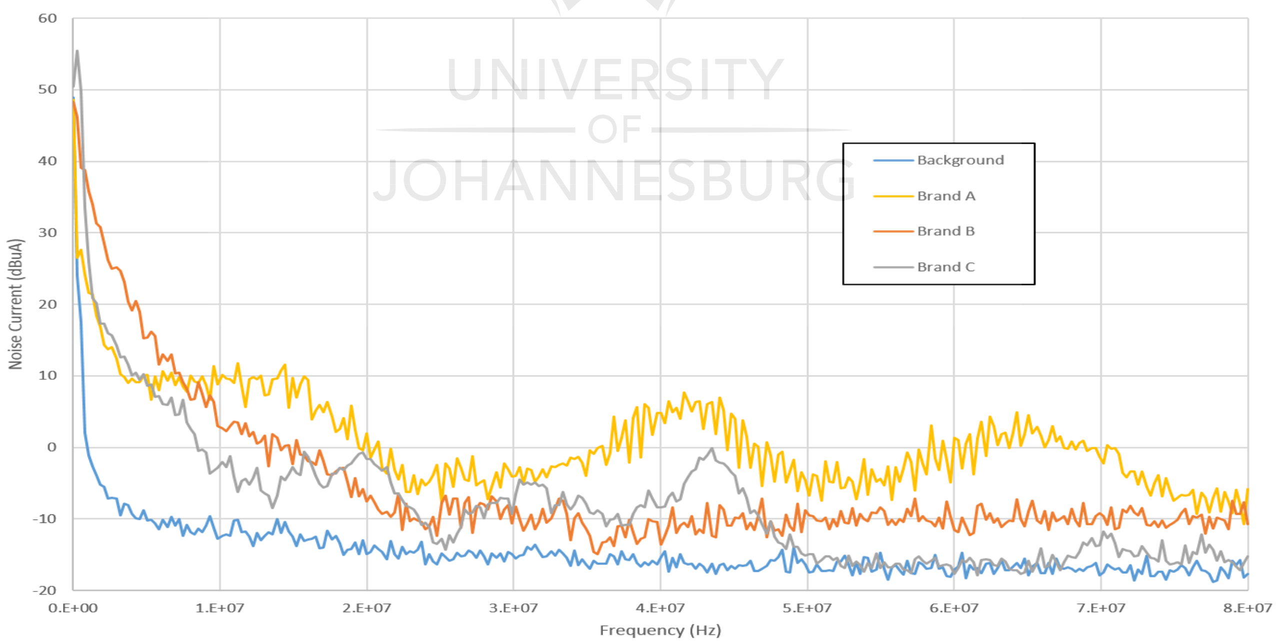

Figure 5.8: Noise spectra of different LED tubes.

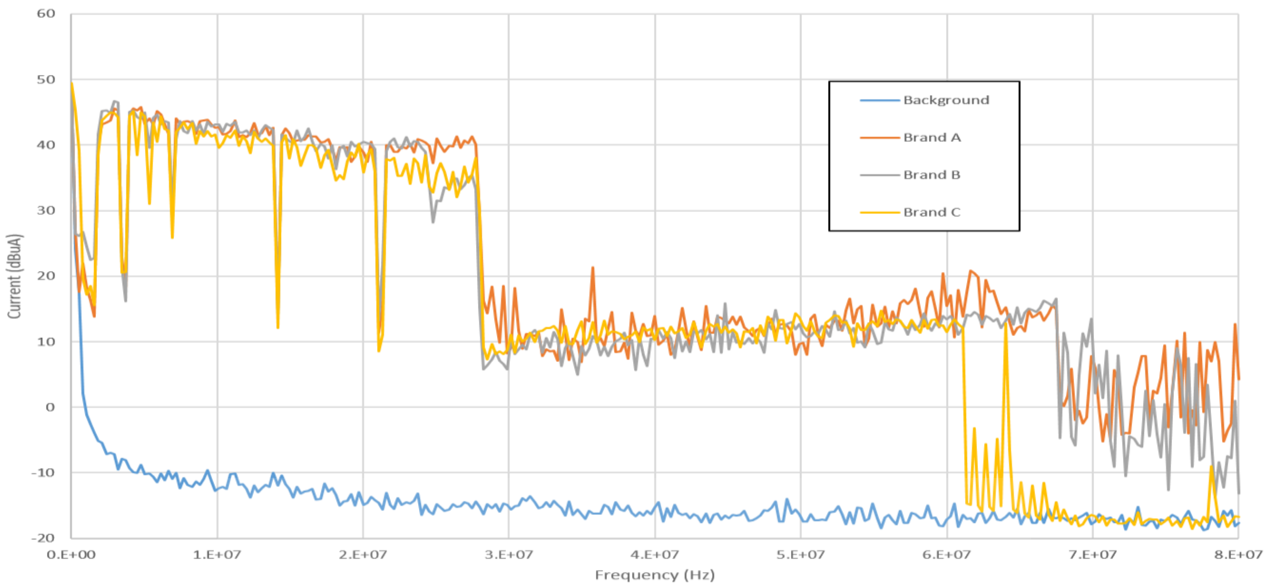

Figure 5.9: Spectrum of modems communicating in close proximity and in the presence of noise from the LED tubes.

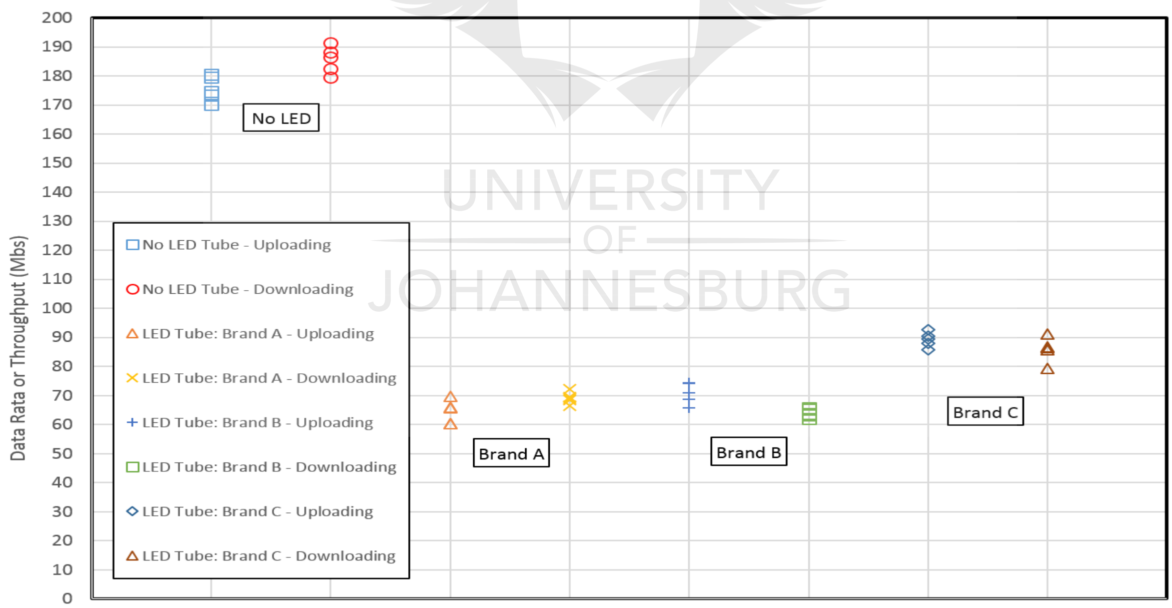

Figure 5.10: Throughput measurement results for modems in close proximity, with three kinds of LED tubes and without.

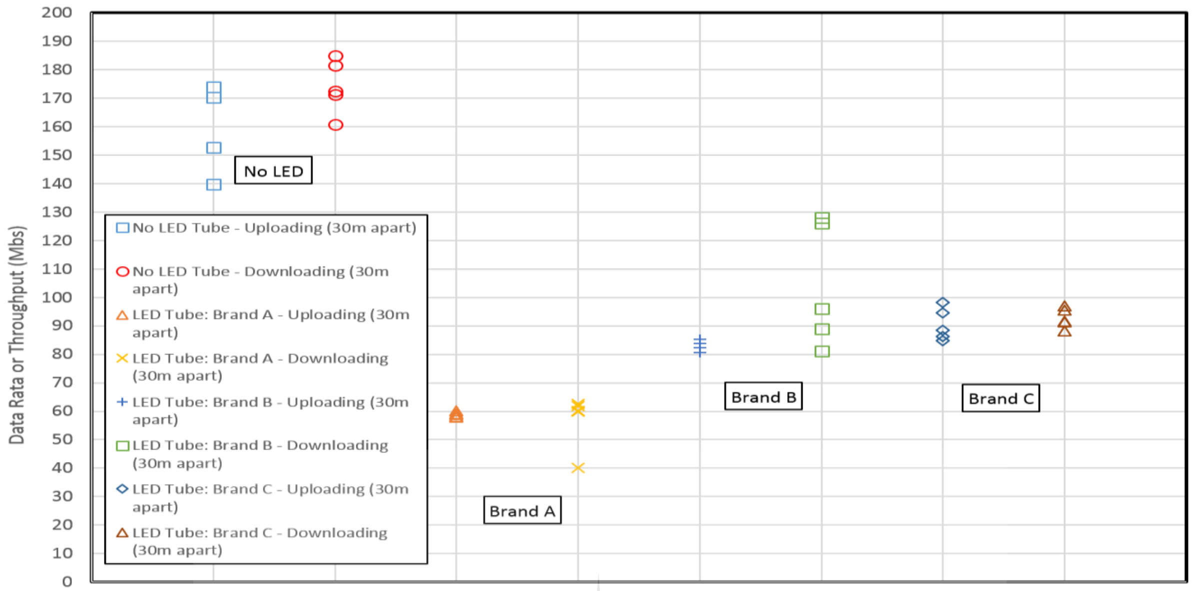

Figure 5.11: Throughput measurement results for modems at 30m, with three kinds of LED tubes and without.

Chapter 6 – High Energy Light Sources

Summary:

Chapter 6 focuses on the different results obtained during the measurement procedure for the high energy outdoor light sources. Each light source has its own structure and characteristics, and injects an amount of noise into the electric power grid. In this section we investigate the problem and illustrate the background theory of the outdoor light sources. We also explain the way the light sources operate, the inside structure of the light sources where electronic components are used to make the wide range of modern light sources, as well as the structure of the electric ballasts that are used to operate and ignite some of the light sources.

6.1 METAL HALIDE LAMPS

Metal halide lamps use igniters and electrical ballasts to start and regulate the lamp operating current flowing through the lamp after it has been started, as well as to maintain suitable voltage and current wave shapes. There are two main types of ballasts, electronic and electromagnetic ballasts that can have different names, such as probe-start ballasts, pulse-start ballasts, and solid-state ballasts.

An electrical ballast is a device intended to limit the amount of current in an electric circuit and it uses a half-bridge inverter and a boost DC-DC converter. A familiar and widely used example is the inductive ballast used in fluorescent lamps or metal halide lamps [159, 169].

Ballasts vary in design complexity: they can be as simple as electromagnetic ballasts or as complex as electronic ballasts used with metal halide lamps and high-intensity discharge lamps. The electronic ballasts are considered better than the electromagnetic ballasts since they provide better energy efficiency (Lumen/Watt), cause less interference to the low voltage network, they are smaller and lighter than the electromagnetic counterparts and they prolong the lamp's life [170]. Ballasts are also discussed in chapter 4.

However, metal halide lamps with electronic/electromagnetic ballasts do inject undesired noise into the electric power grid.

It is shown that in the CENELEC band: (3kHz – 150kHz) the interference level from the metal halide lamps is significantly below the allowed maximum PLC signal levels and therefore poses no threat to the power line communications. In the band 150kHz – 30MHz however, PLC signals compete with Electromagnetic Compatibility levels.

This section investigates the effects when metal halide lamps with electronic/electromagnetic ballasts are seen as interference sources on the wiring system of the smart-grid communication network. Two different measurement set-ups (depending on the ballast type) are given.

The procedure of the measurements was made to comply with CENELEC narrowband rules in one case, and to serve the broadband signals in the other case. The power line regulations were considered when performing related measurements.

For comparison purposes, most of the images in this chapter were moved to the end of the chapter.

6.1.1 Electrical Ballast Driver

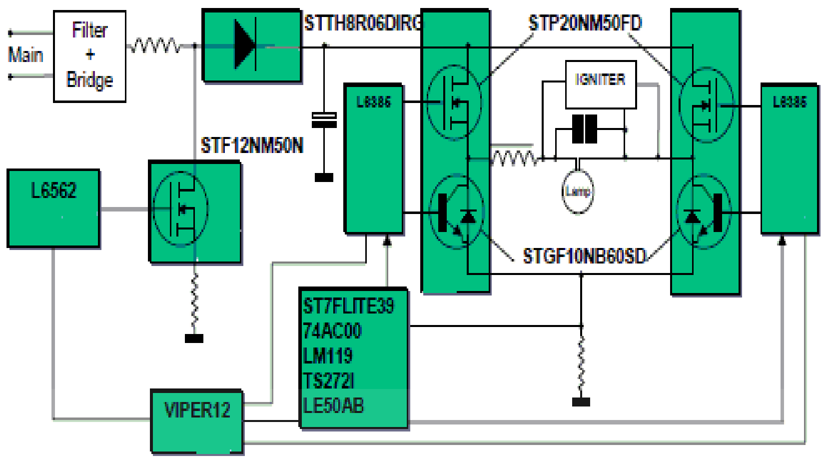

Figure 6.1: Electrical ballast driver (green shading is due to software output).

There is a common structure of the electrical ballast drivers used with the metal halide lamps, which consists of different amplifiers and electronic components as shown in Fig. 6.1.

Metal halide lamps require a ballast to start and regulate the starting of the lamps, and stabilise the current through the lamp, as well as to provide an appropriate sustaining supply voltage. Those electrical ballasts employ transistors to change the supply frequency into high-frequency AC while also regulating the current flow in the lamp. Electrical ballasts typically work in rapid start or instant start mode, and are commonly supplied with AC power, which is internally converted to DC and then back to a variable frequency AC waveform. However, metal halide lamps require a few minutes to warm-up and reach their full light output.

6.1.2 Harmonics - CENELEC Bands

Harmonics are seen as a serious challenge to the electric power system. In order to determine what effect the harmonics of a metal halide lamp have on the power line communications channel, a Tektronix TCP0030 current probe is used in this type of measurements.

Fig. 6.2 gives the results when the harmonics (in voltage) are plotted against the CENELEC EN 50065-1 standards for maximum PLC signal amplitude and EMC levels. The frequency domain harmonics (magnitude) for the waveforms in Fig. 6.2 are performed using an electronic ballast when having a steady-state (continuously on) noise measurement. The steady-state means that the 220VAC is on and the harmonics are continuously shown on the screen of the spectrum analyser. This is the so-called warm-up period, the time that the lamp needs to reach its full output. Another measurement is performed when applying switch-off to the metal halide lamp power button, and having the lamp switched on within a small period of time, typically a few seconds. This status is called the re-power or re-heat period. The obtained signal during this period can be categorised as an affected signal that partially affects the power line communications channel.

Fig. 6.3 shows the harmonic spectrum when using electromagnetic ballast for this type of measurements. Higher interference levels are noticed when performing the repower measurements, as well as when the lamp reheated itself and went on again. By comparing the obtained results from both types of ballasts, one can assume that the PLC channel gets more affected by the harmonics that were obtained from the electromagnetic ballast in this band.

6.1.3 Broadband Spectrum

This section presents the broadband spectrum measurements where a similar procedure of experiments and measurements to those of the CENELEC bands was performed. The metal halide lamps with electronic or electromagnetic ballasts do generate undesired noise in the broadband PLC spectrum (150kHz – 30MHz). This is shown in Figs. 6.2 and 6.3.

Fig. 6.4 shows the measurements that were performed using a metal halide lamp with electronic ballast on several stages. The PLC channel gets more infected when the lamp is switched on after it was switched off and a few minutes were allowed before it reheated itself.

A metal halide lamp with electromagnetic ballast was used for the measurements shown in Fig. 6.5. This is the worst scenario for power line communications, as the obtained frequency domain harmonics in this set of measurements compete with or exceed the Electromagnetic Compatibility levels.

Fig. 6.4 shows the interference voltage from the metal halide lamp versus the EMC average and peak/quasi-peak disturbance level limits in the band 150kHz – 30MHz. In the CENELEC bands from 3kHz – 150kHz there are dedicated maximum signal transmission levels. These do not exist in the 150kHz – 30MHz band and maximum signal transmission is assumed to be at the EMC limit levels. The EMC level is the maximum level at which PLC signals are allowed to be transmitted. For the 150kHz – 30MHz band therefore the signal to noise ratio (S/N) is low. This will affect the maximum theoretical PLC transmission capacity as can be seen from the Shannon theorem [164] that was presented in section 5.2.

6.1.4 Discussion

From a PLC standpoint, the metal halide lamp with electronic ballast is favourable as it does not cause noise (close to the maximum allowable PLC signal level) in the 3kHz – 150kHz band. The metal halide lamps will only become an acceptable lighting solution (in PLC terms) if statuary transmission signal limits are lifted in the 150kHz – 30MHz band. By comparing the noise measurements in Figs. 6.3, 6.4, and 6.5 to the measured noise floor, we can describe the power line communications channel as an affected channel.

This section studied the behaviour of the electronic and electromagnetic ballasts that are used with metal halide lamps. Several experiments and measurements have been conducted to illustrate the effects of metal halide lamps with electrical ballasts on the power line communications channel.

It has been shown that metal halide lamps produce noise and affect the 3kHz – 150kHz CENELEC bands, but this interference level is below the allowable PLC signal level and therefore poses no threat to the PLC channel.

For the broadband spectrum (150kHz – 30MHz), metal halide lamps however inject noise into the electric power grid, where the signal level is governed by EMC standards. This interference competes with the EMC levels and can be seen as a serious risk to the power line communications.

6.2 MERCURY VAPOUR LAMPS

To operate a mercury vapour lamp, one can also use an electric ballast (Fig. 6.6). Mercury vapour lamps can use electronic or electromagnetic ballasts, or can be self-ballasted. The self-ballasted lamps use a filament that is connected in series with the arc tube and this is the only kind of mercury vapour lamp that can be connected directly to the 220V mains without using an external ballast.

The ballast provides sufficient voltage to start the lamp and regulates the current to the lamp. During lamp starting, the ballast briefly supplies high voltage to establish an arc between the two lamp electrodes. Once the arc is established, the ballast reduces the voltage and regulates the electric current to produce a steady light output. Without a ballast to limit its current, a lamp connected directly to a high voltage power source would rapidly increase its current drawn. Within a second the lamp would overheat and burn out [159, 171].

Mercury vapour lamps with ballasts inject unwanted noise into the power line communications network (PLC).

The so called CENELEC band (3kHz – 150kHz) gets affected by the conducted interference that the mercury vapour lamp causes when connected to the wiring system of the smart-grid network. This noise is below the allowed maximum PLC signal levels and therefore is considered below the “risk” levels.

In case of the broadband spectrum (150kHz – 30MHz), the noise level competes with, or exceeds the EMC levels.

This section adheres to the CENELEC narrowband rules and serves the broadband standards and regulations too. An explanation is given regarding the operational mode of the electric ballasts used with the mercury vapour lamps and to the measurements set-up as well.

6.2.1 Electrical Ballast Driver

Electronic ballasts are rarely used for mercury vapour lamps and are not readily found in the market since they can be a source of interference and give a shorter life to the mercury vapour lamp. Electromagnetic ballasts are widely used in most countries that have the mercury vapour lamp as a main outdoor lighting source. The main advantage for using the electronic ballast rather than electromagnetic ballast is the "intelligent switching" that the electronic ballast has. It is a function that allows the electronic ballast to turn off the mercury vapour lamp when it comes to the end of its life, as the electronic ballast recognises this condition and switches off the lamp. This enables easy identification of a defective lamp and prevents the lamp from being a "heavy" source of interference and disturbance to the power line communications channel and other devices such as radio receivers [172].

Fig. 6.7 shows the circuit of an electric ballast used for mercury vapour lamps. The ballasts consist of different electronic components, such as, resistors, capacitors and inductors.

Ballasts are required to regulate and start the mercury vapour lamps, and to provide sufficient voltage and stabilise the current through the lamps.

Electric ballasts are supplied with 220VAC power which is internally converted to DC then back to a variable frequency AC waveform.

6.2.2 Harmonics - CENELEC Bands

The mercury vapour lamps with electric ballasts do, unfortunately, also inject undesired noise into the wiring system of the power line channel. As stated before, this can negatively affect the transmission over the communications channel. During the measurements period, a current probe is used in order to determine the current harmonics that the mercury vapor lamps cause in the PLC channel.

For discussion on the behaviour of the narrowband signal on the low voltage network, we refer to Figs. 6.8 & 6.9. The conducted measurements in the so-called CENELEC band (3kHz – 150kHz) show a small amount of harmonics (in voltage) which increases and, therefore, can be clearly seen during the warm-up period (typically 3 – 4 minutes) that the lamp needs to become stable after an operation of switching off and on again. In fact, the obtained harmonics pose no threat to the low voltage network as they can be classified as an allowed signal considering CENELEC EN 50065-1 and EMC levels.

The mercury vapour lamp produces an amount of interference when it reaches its full output. This happens when the warm-up period is passed. The signals from Figs. 6.8 and 6.9 that can be seen at around 100kHz – 140kHz are considered "friendly" harmonics as they are way below the maximum allowed signal level. However, in the worst scenario, the harmonics can hinder the transmission or receiving of bits and/or packets on the power line communications channel.

Measurements are conducted for three other mercury vapour lamps in order to test the behaviour of the harmonics in the CENELEC band. One of the lamps has been in operation for three months and the other two have been operating for five years and seven years respectively. The results show that the oldest two lamps have a slight different behaviour than the newer lamps. They produce more interference in the CENELEC band, but this remains below the maximum allowed signal level.

6.2.3 Broadband Spectrum

In this type of measurements, the broadband spectrum measurements are conducted to show the effect of the mercury vapour lamp on the PLC channel when it is connected to 220V where a similar procedure of measurements to those of the narrowband is followed. The broadband spectrum (150kHz – 30MHz) where the measurements are performed shows different levels of harmonics (in voltage) as the lamp produces an amount of interference when it gets stable after the warm up period of several minutes.

Figs. 6.10 and 6.11 illustrate the level of interference when the lamp is "on", where it can be considered below the EMC disturbance level on peak and quasi-peak measurements level. The level of interference increases dramatically when the lamp is switched off and on again. For this type of measurements, this can be the worst scenario for the PLC channel, as the levels of interference compete with or exceed the maximum allowed electromagnetic levels.

This warm-up period can be of a serious risk to the power line channel as it produces a level of disturbance that can affect the communications over the wiring system on the PLC channel.

In the CENELEC bands from 3kHz – 150kHz there are dedicated maximum signal transmission levels. These do not exist in the 150kHz – 30MHz band and maximum signal transmission is assumed to be at the EMC limit levels.

In the broadband spectrum, the tests of the aging lamps are repeated as for the ones in the CENELEC band. The signal is almost stable in comparison with the obtained signal from the new lamps. The seven years old lamp shows a small change in the output signal, but this causes no difference to the infected power line channel.

6.2.4 Discussion

Mercury vapour lamps have been used in lighting applications and are more energy efficient than other outdoor light sources. Besides the fact that they are not suited to render the human skin colour well – as they are not used in retail stores, hospitals, schools and other commercial applications – they produce interference to the power line communications channel. They will only become a more favourable lighting solution (in PLC terms) if statutory signal limits are lifted in the 150kHz – 30MHz band.

The smart-grid when relying on PLC will need a more favourable light source when used to control the automatic switching of lamps in public places. The light emitting diodes can be one of the solutions for the future market as it causes less interference to the low voltage network.

The mercury vapour lamp is also one of the light sources that produce conducted noise when connected to the wiring system of the power line communications channel. This noise can be of a serious risk to the PLC channel if it exceeds the allowed maximum EMC noise levels as in the broadband spectrum range of 150kHz – 30MHz.

It has been shown that the level of noise in the CENELEC band (3kHz – 150kHz) is below the allowable PLC signal level and, therefore, it is “safe” to use the mercury vapour lamp in this frequency range.

6.3 HIGH PRESSURE SODIUM LAMP

The high pressure sodium lamp operates with an arc tube and contains a mixture of xenon, mercury and sodium. It is supplied with 220VAC in series with an electric ballast in order to provide a constant current and sufficient voltage to start the lamp [29].

When the lamp comes to the end of its life, it faces the “cycling” period, that is usually caused by a loss of sodium gas in the arc, which causes the lamp to switch on and off several times a day. Using a simple electromagnetic ballast during the cycling period results in injecting more noise into the PLC channel since it cannot control the lamp from being an interference source; however, the new electronic ballasts (see Fig. 6.12) are more “intelligent” and can extinguish the lamp and prevent it from being a source of interference to the power line communications channel [173].

High pressure sodium lamps with ballasts inject undesired noise into the power line communications channel (PLC).

In case of CENELEC band: 3kHz – 150kHz, the noise level does not exceed the allowed maximum interference levels. Therefore, the high pressure sodium lamp with electronic or electromagnetic ballasts can be considered as a noise friendly lighting source.

6.3.1 Electrical Ballast Driver

In general, the electronic ballasts are seen as serious noise sources to the power line system, rather than the electromagnetic ballasts since they contain complex electronic components and circuits. However, this does not highly affect the communications on the CENELEC band.

Electronic ballasts are widely used for high pressure sodium lamps because of the “intelligent” function that switches the lamp off when it becomes old. This “intelligent” function exists in the electronic ballast only, as the ballast prevents the lamp from being a source of noise and disturbance on the power line system, especially when the lamp reaches the end of its life as it starts to switch on and off several times a day; this causes the lamp to produce more interference on the PLC channel.

The electromagnetic ballast is simple in design, as it mainly contains a laminated transformer, where igniters are usually added to the circuit (see Fig. 3.5) in order to start the lamp, to assist in providing sufficient voltage and correct the power factor.

6.3.2 Harmonics - CENELEC Bands

The interference that the high pressure sodium lamp with electric ballast produces can affect the so called CENELEC bands; however, the signal levels measured is below the allowed maximum signal levels. Figs. 6.13 and 6.14 show the noise levels in dBμV which are represented in the frequency domain. This is done by performing a Discrete Fourier Transform (DFT) on one cycle of data which yields the harmonics that make up the time domain waveform. In order to compare the obtained current harmonics to a typical power line channel signal voltages, the current magnitudes must be multiplied with typical power line channel impedances for each of the harmonic frequencies. This power line channel impedance can be approximated by using the values of the LISN that is used for measurements (Figs. 3.5 and 3.6). The LISN characteristics are specified in EN 50065-1.

The conducted measurements in CENELEC bands show that when using electromagnetic ballast, as in Fig. 6.13, the level of noise is relatively small and communications can still be made on the power line wiring system. The results from the high pressure sodium lamp with electronic ballast are shown in Fig. 6.14. The amount of interference differs, and the lamp is not stable. However, this amount of interference can still be considered safe against the CENELEC band standards.

The high pressure sodium lamps need no warm-up period when applying switching off and on again to their power buttons. They can reach the full output in less than a second; therefore, slight interference can be recorded in that period. This is a “unique” case, as most of the high energy outdoor lamps that use ballasts to start, need a warm-up period of several minutes in order to reach their full output. The turn-on operation records an amount of interference in Figs. 6.13 and 6.14. This happens when the power button is switched on and the lamp starts.

6.3.3 Broadband Spectrum

Fig. 6.15 shows the results that are obtained when conducting measurements in the broadband spectrum of 150kHz – 30MHz. The interference voltage from the high pressure sodium lamp with electromagnetic ballast is plotted against the EMC maximum disturbance levels. It is seen that the interference levels do compete with or exceed, in some cases, the allowed maximum EMC levels. During the turn-on operation, the noise is, then, called risky on the PLC system; therefore, it is safer to communicate over the power line channel when the lamp reaches its full output, typically after one second of switching the lamp on.

In Fig. 6.16, experimental measurements using the electronic ballast of the high pressure sodium lamp are conducted in the 150kHz – 30MHz band. In this band, the power line signals need to compete with other interference signals caused by other devices, therefore, it can have a zero signal-to-noise ratio at certain frequencies.

As shown in Fig. 6.16, the current harmonic levels do exceed the electromagnetic allowable levels which may hinder the communications on the power lines. At around 3MHz – 20MHz, the signals become less "noisy", which gives more opportunities for friendly communications on the network.

6.3.4 Discussion

In this section, the high pressure sodium lamps that use electromagnetic and electronic ballasts to start the lamps were tested for noise generation in the power line communications channel.

The lamps produce interference in the 3kHz – 150kHz band, but this poses no risk for PLC. However, they produce interference in the 150kHz – 30MHz band which can have a detrimental effect on the PLC channel.

The PLC signal levels are governed by the same EMC standards. Unless these standards are revised and PLC signals are allowed to exceed the EMC limits, power line communication signals will have to compete with zero signal to noise ratios.

Further measurements showed that the high pressure sodium lamp needs no warm-up period and can reach its full output in one or two seconds. This is different from all major outdoor light sources, as they require a few minutes to warm-up when they are repowered.

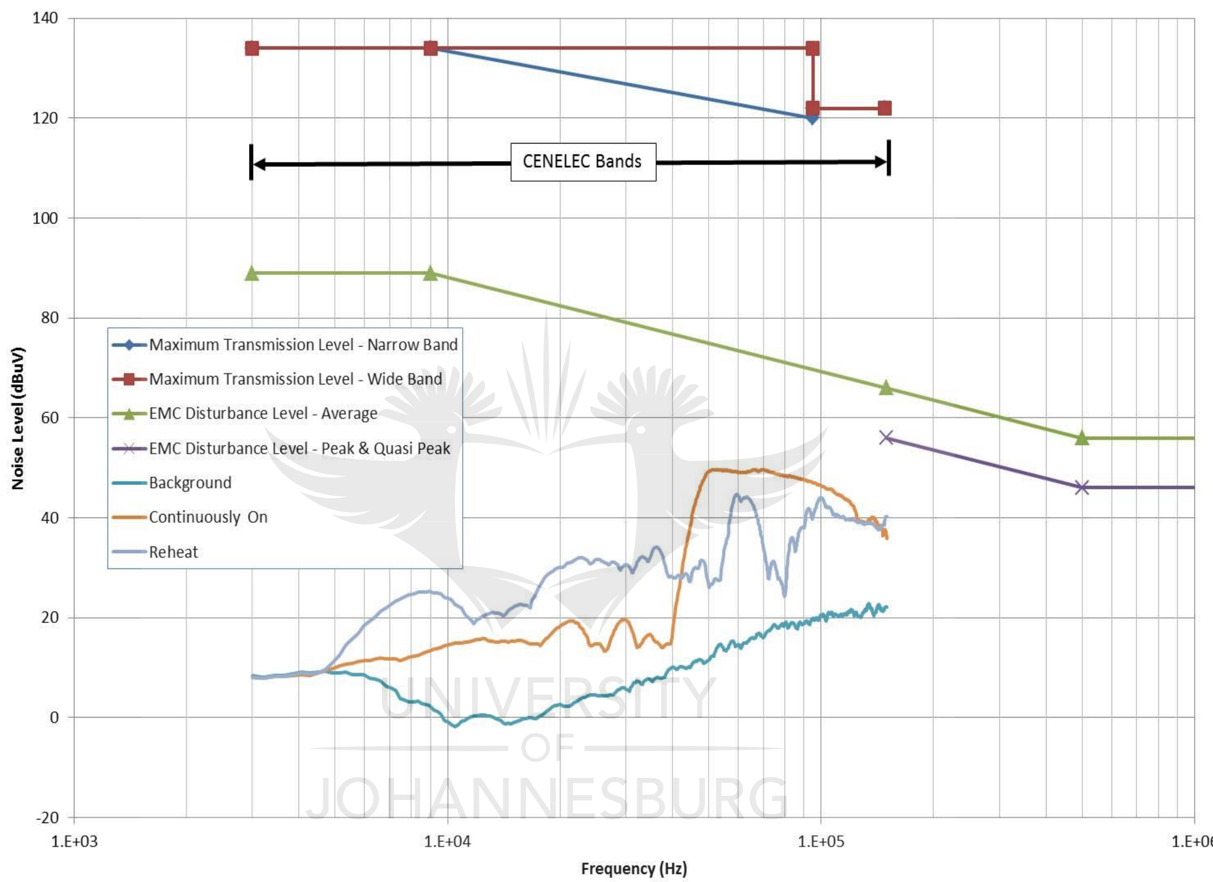

Figure 6.2: Metal halide lamp: frequency domain waveforms and harmonics for 3kHz – 150kHz range (Electronic Ballast).

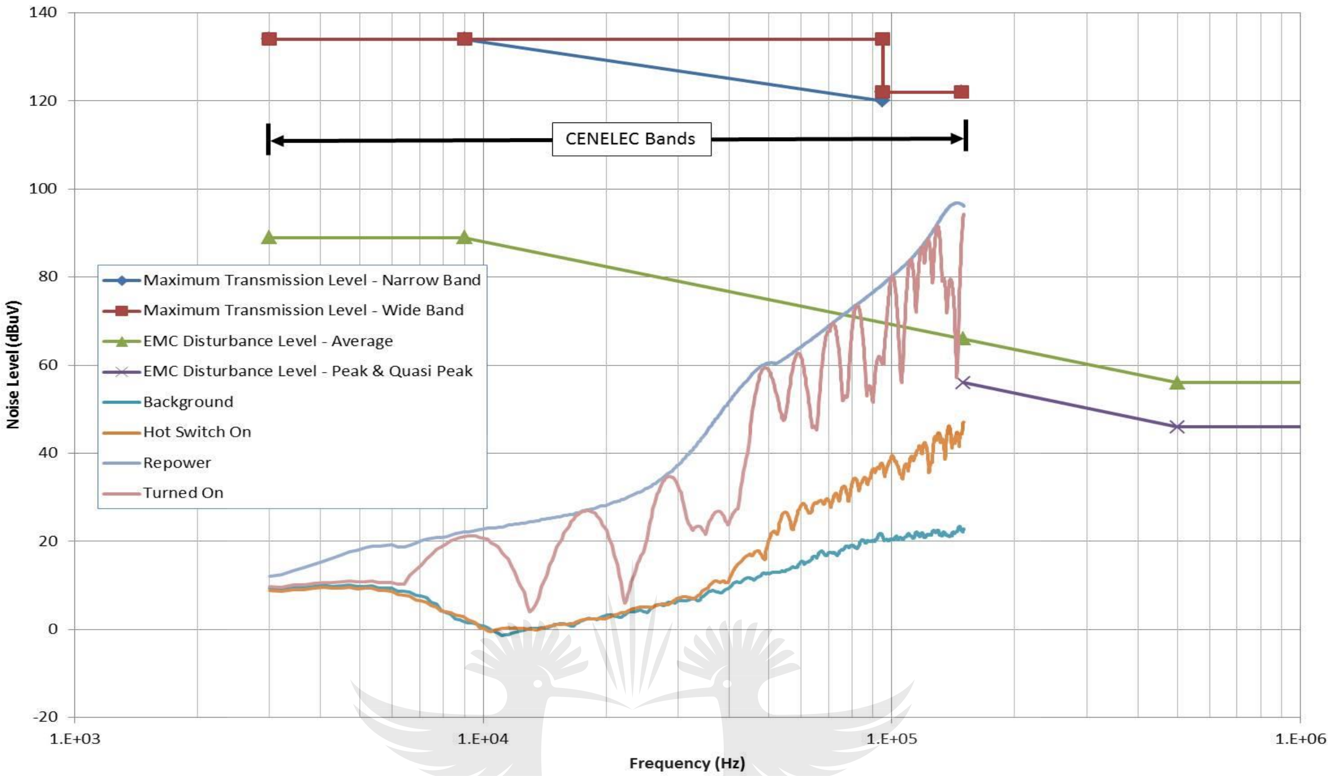

Figure 6.3: Metal halide lamp: frequency domain waveforms and harmonics for 3kHz – 150kHz range (Electromagnetic Ballast).

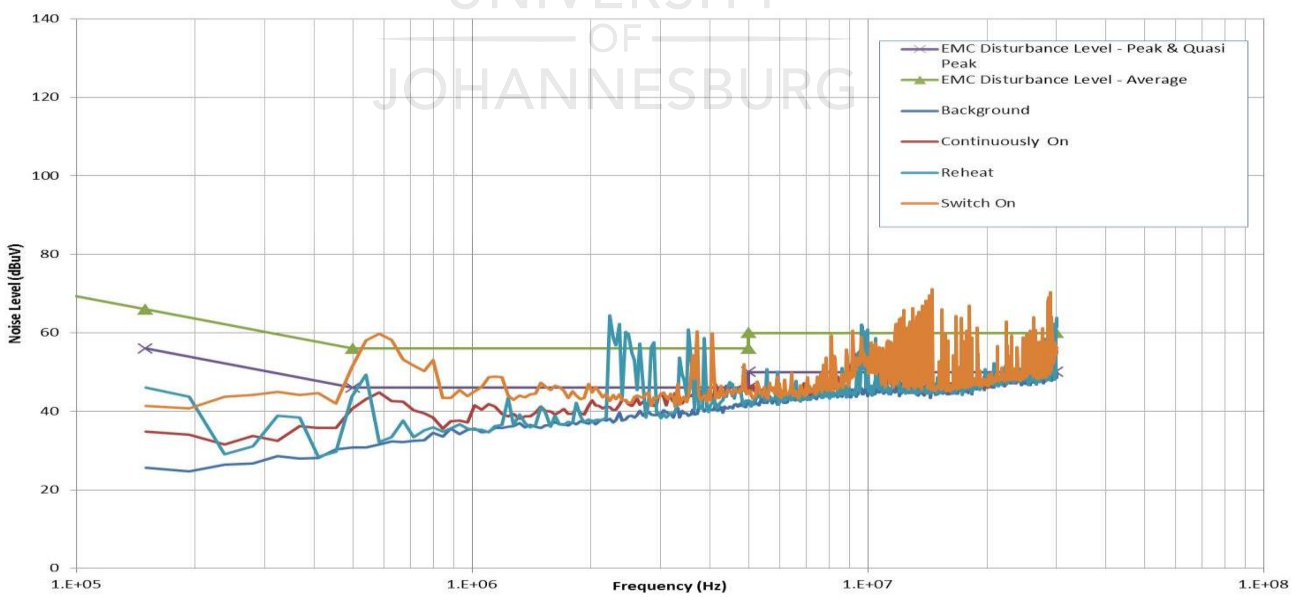

Figure 6.4: Metal halide lamp: frequency domain waveforms and harmonics for 150kHz – 30MHz range (Electronic Ballast).

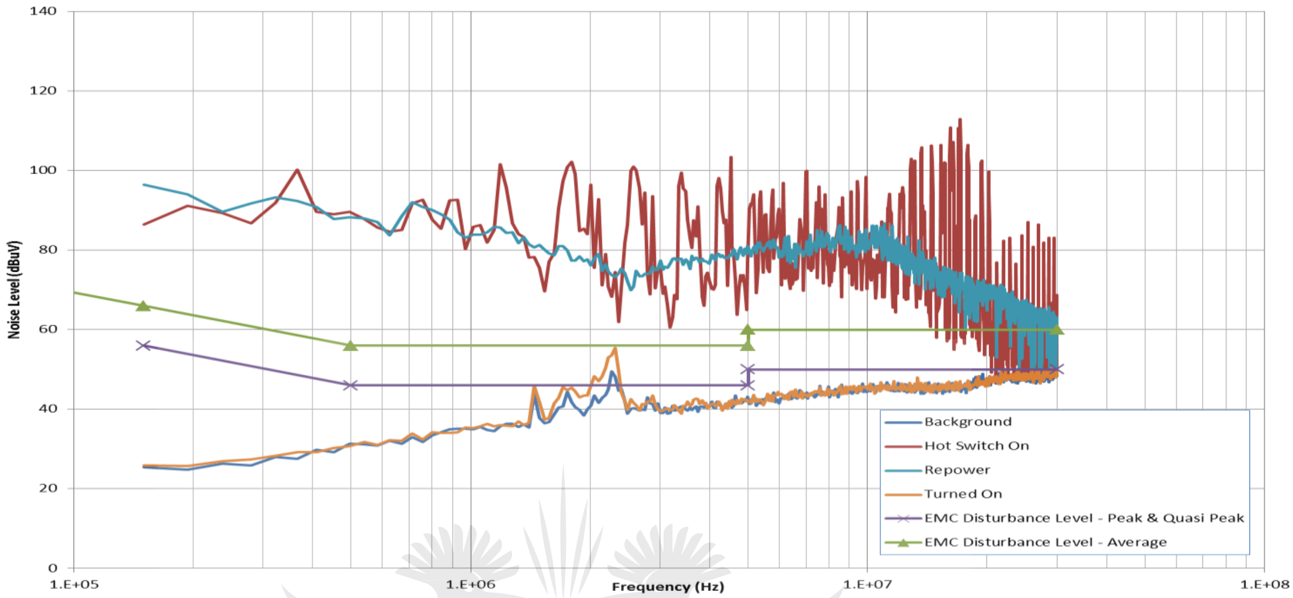

Figure 6.5: Metal halide lamp: frequency domain waveforms and harmonics for 150kHz – 30MHz range (Electromagnetic Ballast).

Figure 6.6: Electronic ballast used with mercury vapour lamp.

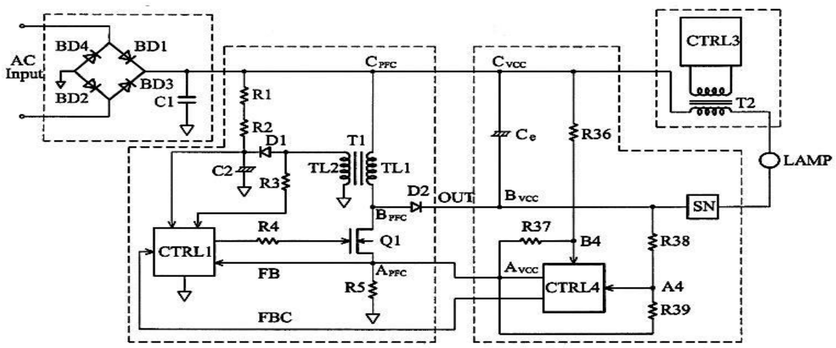

Figure 6.7: Electronic ballast driver for mercury vapour lamp.

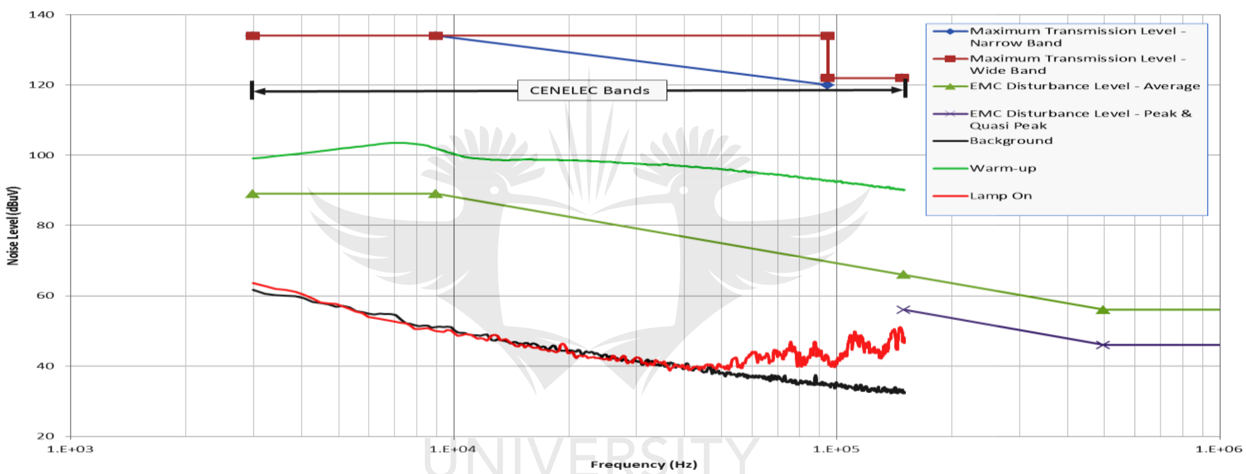

Figure 6.8: Mercury vapour lamp: frequency domain waveforms and harmonics for 3kHz – 150kHz range (Electronic Ballast)

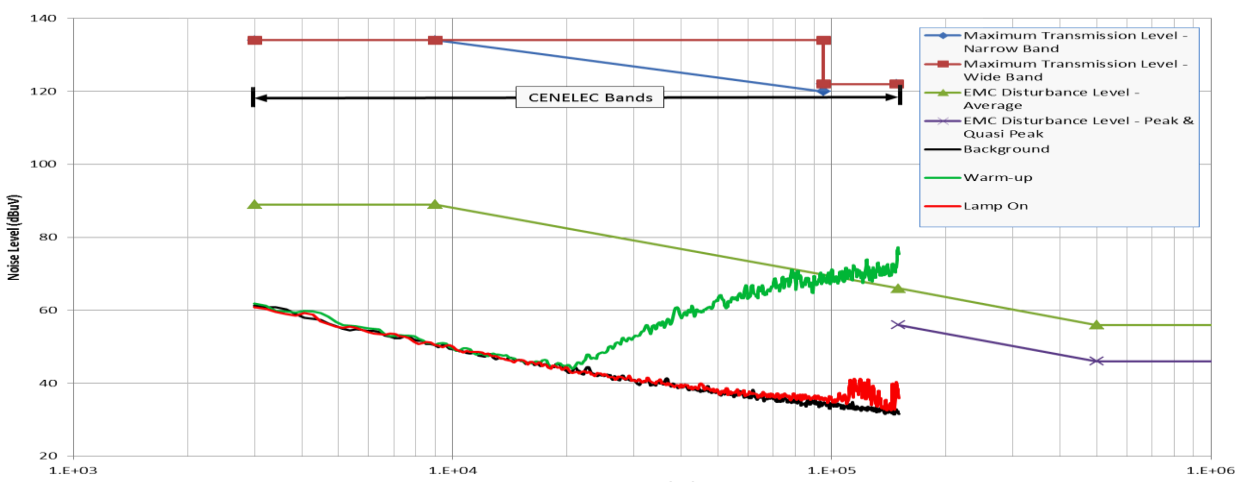

Figure 6.9: Mercury vapour lamp: frequency domain waveforms and harmonics for 3kHz – 150kHz range (Electromagnetic Ballast).

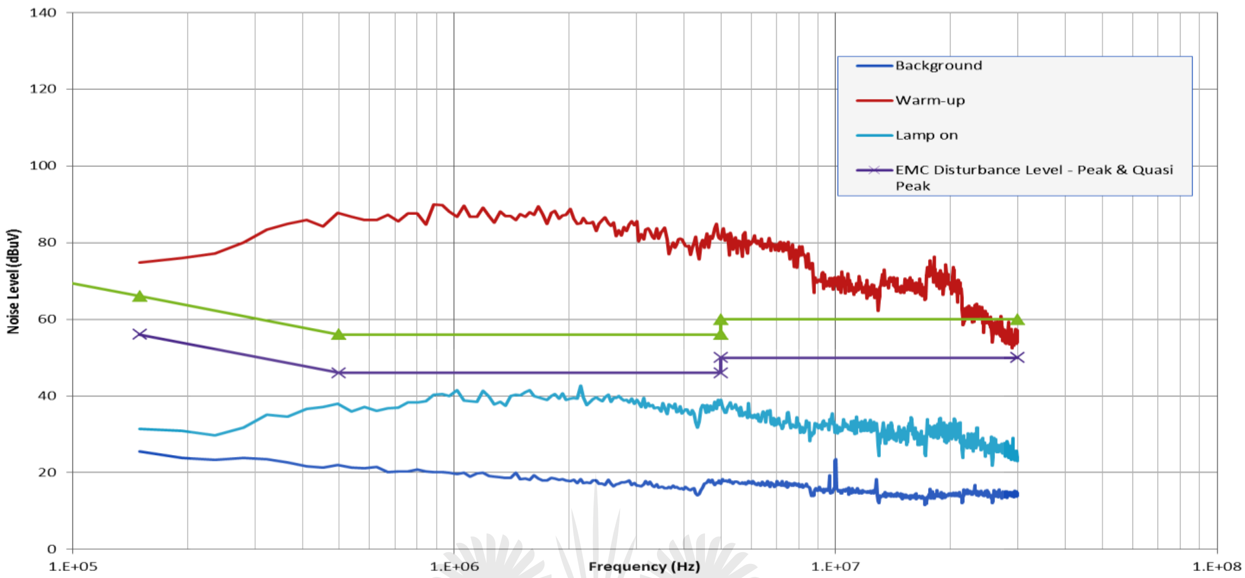

Figure 6.10: Mercury vapour lamp: frequency domain waveforms and harmonics for 150kHz – 30MHz range (Electromagnetic Ballast).

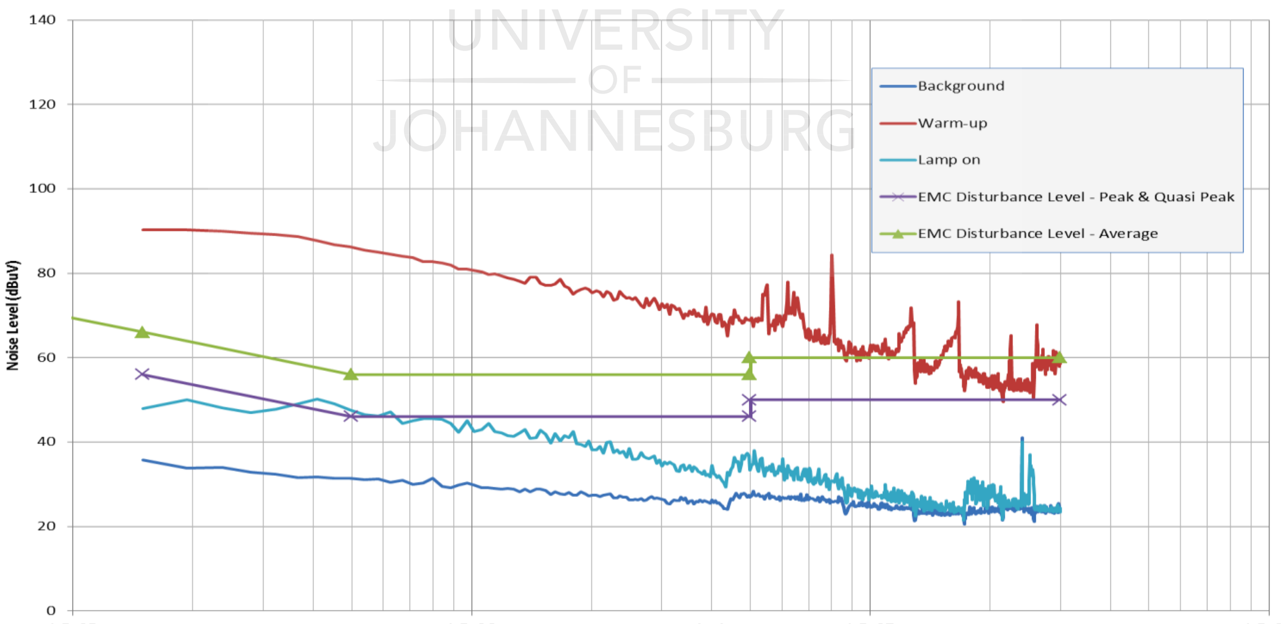

Figure 6.11: Mercury vapour lamp: frequency domain waveforms and harmonics for 150kHz – 30MHz range (Electronic Ballast).

Figure 6.12: Electric ballast used with high pressure sodium lamp

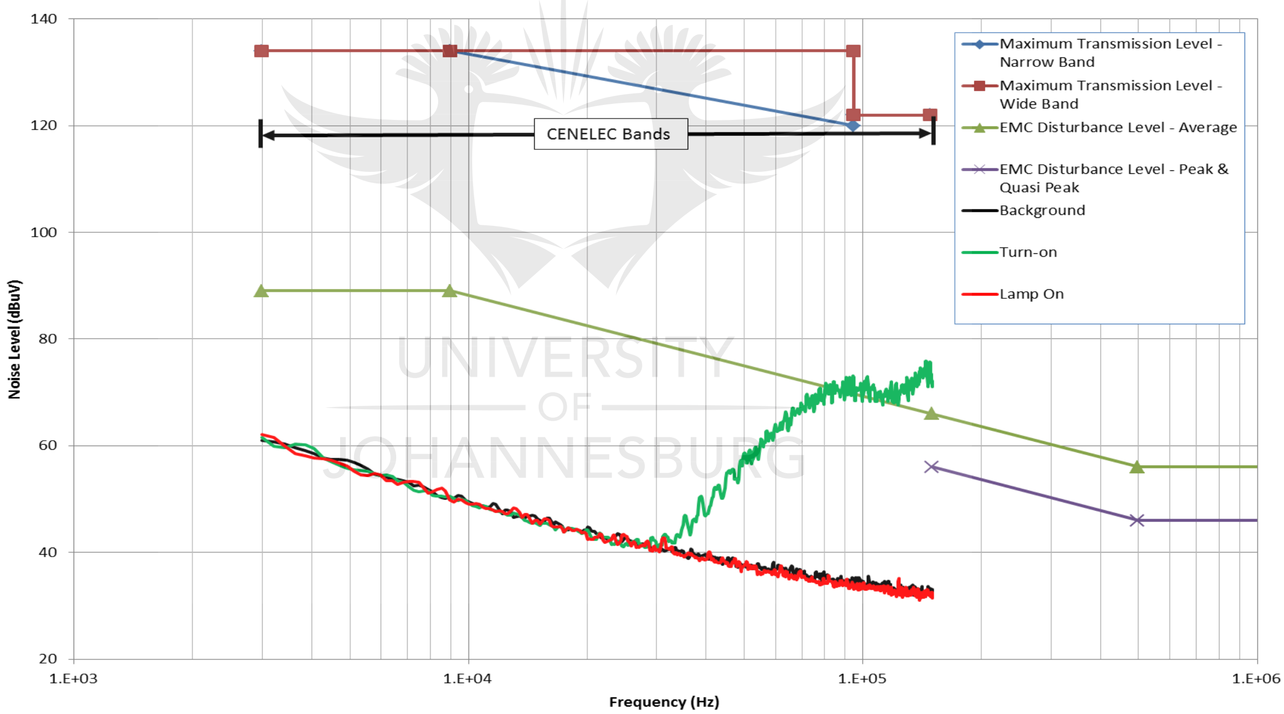

Figure 6.13: High pressure sodium lamp: frequency domain waveforms and harmonics for 3kHz – 150kHz range (Electromagnetic Ballast).

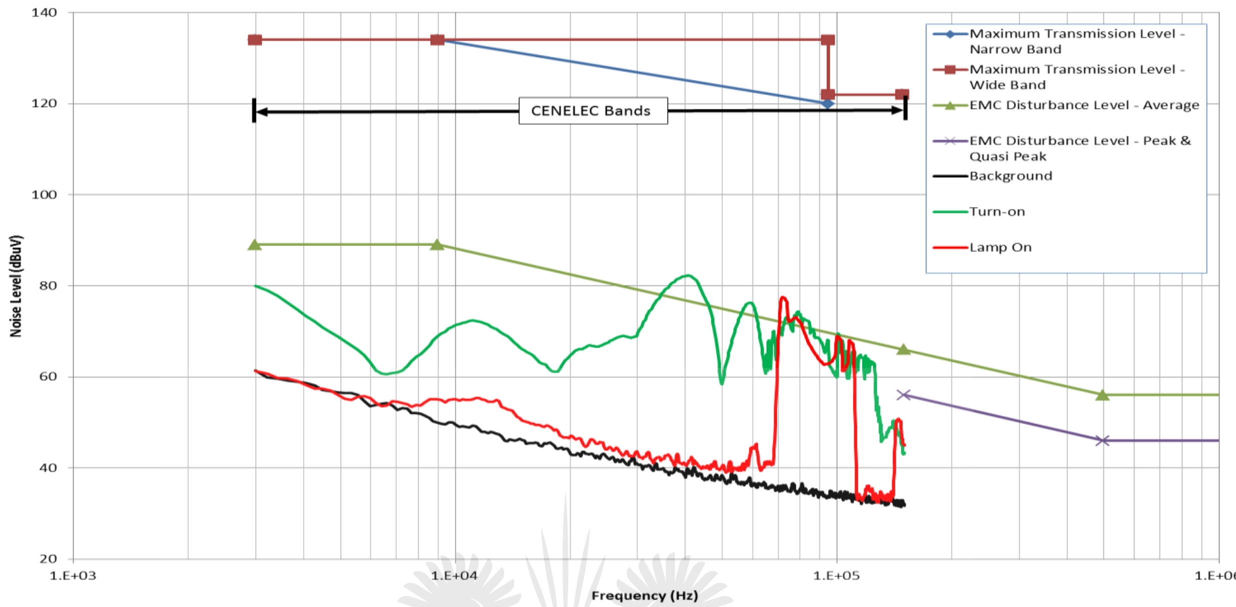

Figure 6.14: High pressure sodium lamp: frequency domain waveforms and harmonics for 3kHz – 150kHz range (Electronic Ballast).

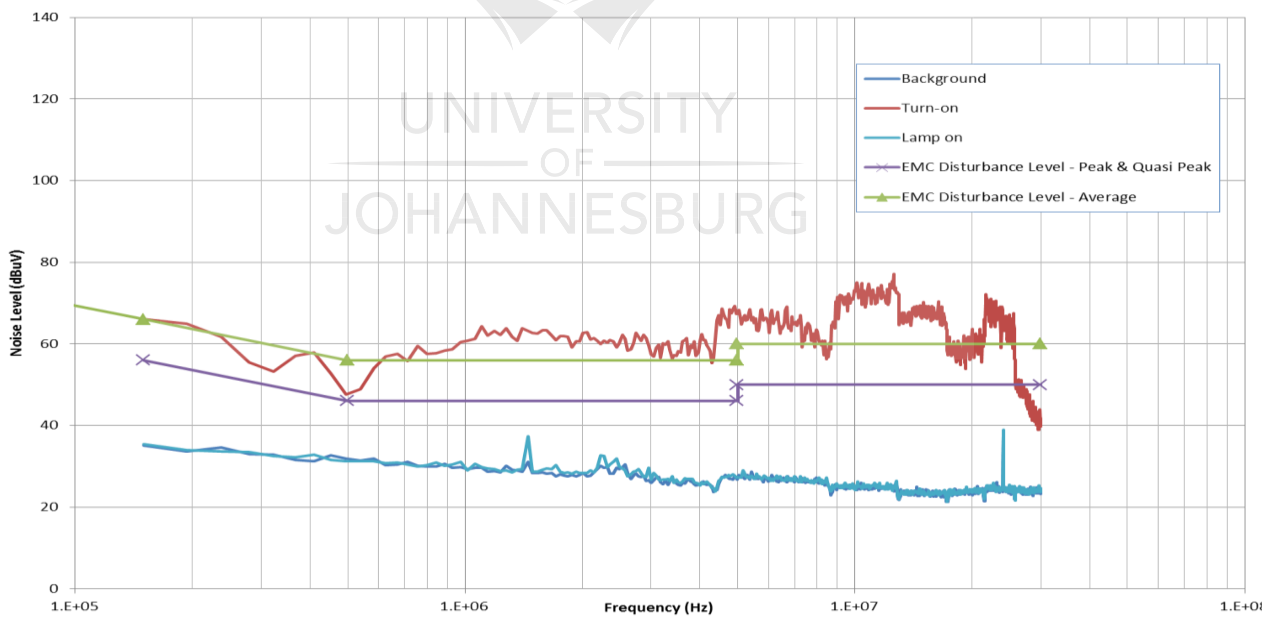

Figure 6.15: High pressure sodium lamp: frequency domain waveforms and harmonics for 150kHz – 30MHz range (Electromagnetic Ballast).

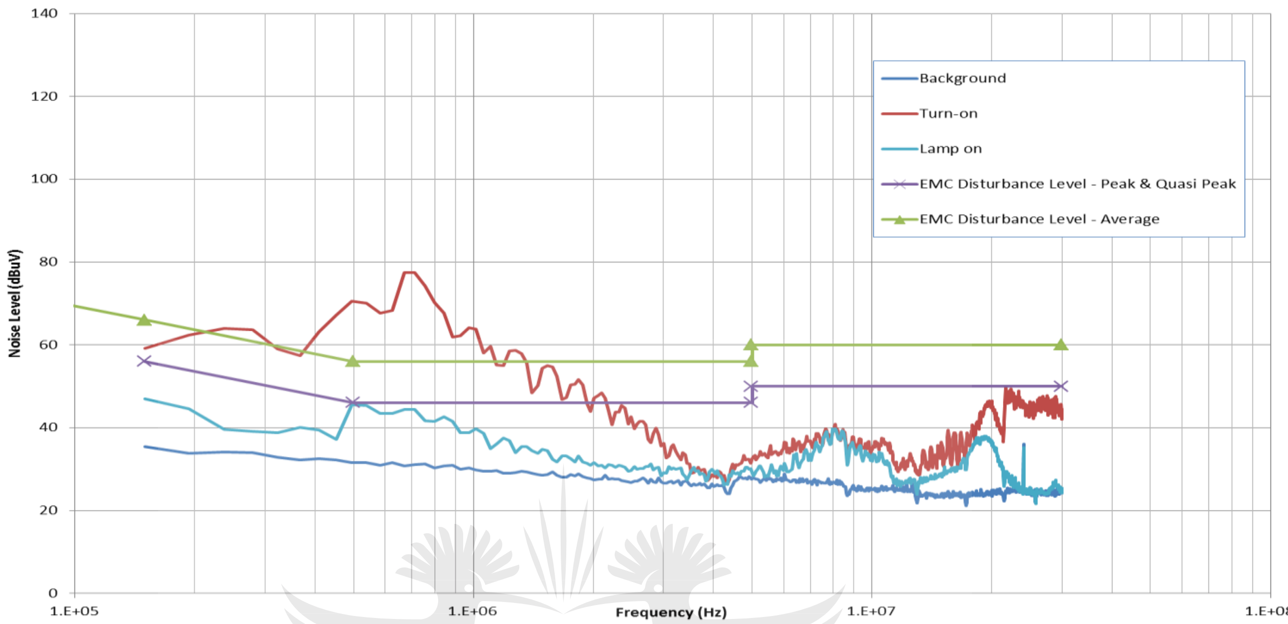

Figure 6.16: High pressure sodium lamp: frequency domain waveforms and harmonics for 150kHz – 30MHz range (Electronic Ballast).

Chapter 7 – Usage of the Bridge Rectifier in Lighting Technology

Summary:

Analysis of a bridge rectifier, high frequency converters and mathematical analysis, as well as simulation results are given in Chapter 7. This is to verify that the practical measurements are accurate and the results are valid. Within this chapter, we shall be also summarising the key result from previous chapters and attempt to use this to place attention on the structure of a general lighting model for future studies of lighting technology.

7.1 INTRODUCTION

Bridge rectifiers are widely used for lighting sources and can be considered the backbone of the LED lamp structure. The main structures of the LED lamps that contain diode bridge rectifiers with filter capacitors was studied [19]. These rectifiers inject pulse currents which cause the input current to create undesirable harmonics and cause distortion to the voltage waveform. This distortion hinders communication on the PLC channel [174].

Many countries that use LED lamps or LED tubes as a lighting source require that the LEDs comply with regulations on EMC emissions issued by their governments. However, there are a number of other countries with LED manufacturers that do not comply with regulations which leads to producing LED lamps and tubes that have impact on the power lines when used as a communication medium [175].

LEDs produce high frequency current harmonics depending on their design [19], and the existing switching waveform of the DC-DC converters that cause high conducted and radiated emissions. This results in having emissions that hinder the communications over the PLC channel, as well as interference with radio communications via radiated emissions and may cause a "premature" failure to the LED lamp itself [176].

LED lamps consist of a full wave bridge rectifier, DC-DC converter, DC "link" storage capacitor, and in some cases, a passive EMI filter to smooth the current harmonics that the DC-DC converter produces in the storage capacitor. In many cases, LED lamps do not contain an EMI filter or have an inadequate EMI designed filter to save costs.

In this chapter, we derive and investigate an analytical model with a full range of measurements that cover different output wattages of LED lamps. The diversity of current harmonics caused by the LED lamps is also studied. Furthermore, a simulation analysis about the bridge rectifier is illustrated.

7.1.1 Circuit analysis of the Bridge Rectifier

Full wave bridge rectifiers make use of four diodes while the centre tapped rectifiers use only two diodes. The main difference between the two rectifiers is the maximum voltage *Vs(max)* in the circuit of the full wave bridge rectifier where only two diodes conduct during each of the two AC half cycles in the transformer circuit; on the other hand, the maximum voltage *Vs(max)* in the centre tapped rectifier is represented only on each AC half cycle of the secondary winding of the transformer circuit.

For peak currents, the voltage in the rectifier is represented as $vs = Vs(max)\ Sin\ \omega t$ and the diode is presumed to act as a forward resistance (R_F). The current that flows through the load resistance (R_L) is represented as

$i_1 = 0$

where

$$I_{max} = \frac{Vs(max)}{R_F}\ Sin\ \omega t \tag{7.1}$$

and $i_2 = i_1$.

This condition applies on the first AC half cycle, where the condition of the current in the second AC half cycle changes to $i_1 = 0$ and $i_2 = 0$.

Since the DC voltage is averaged over the period T of the output voltage, it can be represented as

$$V_{DC} = \frac{1}{T}\int_0^T V_L(t)dt\ , \tag{7.2}$$

and the r.m.s. voltage can be defined as

$$V_L = \sqrt{\frac{1}{T}\int_0^T V_L^2(t)dt}\ . \tag{7.3}$$

The ratio of both DC and r.m.s. voltages is the form factor

$$FF = \frac{V_L}{V_{DC}}\ . \tag{7.4}$$

If the load is resistive, the current can be represented as

$$i_L(t) = \frac{V_L(t)}{R_L}\,, \tag{7.5}$$

$$I_{DC} = \frac{V_{DC}}{R_L}\,, \tag{7.6}$$

and

$$I_L = \frac{V_L}{R_L}\,. \tag{7.7}$$

In case of load resistance, the total flowing current includes both i_1 and i_2 currents which can be represented as $i_1 + i_2 = i = I_{max}\ Sin\ \omega t$ for a full AC cycle. The current that flows through *(R_L)* is then represented as

$$I_{max} = \frac{Vs\ (max)}{(2R_F + R_L)}\,. \tag{7.8}$$

The AC output current for the full wave bridge rectifier is then represented as

$$Idc = 1/\pi \int_0^{\pi} i_1\ d\,(\omega t) = \frac{1}{\pi}\left[\int_0^{\pi} I_{max}\ \ Sin\ \omega t d(\omega t)\right] = \frac{2I_{MAX}}{\pi}\,. \tag{7.9}$$

The output current does not change through R_L in both sides of the AC cycle, and the magnitude of DC current *Idc* is equal to the AC current value which is gained by integrating the current i_1 between *0* and π or the current i_2 between π and 2π.

The DC output voltage in the circuit can be represented as

$$V_{DC} = I_{DC}\mathrm{R_L} = 2/\pi\ I_{max}\mathrm{R_L}\,, \tag{7.10}$$

where the RMS value of the current that flows through R_L is represented as:

$$I2_{rms} = \frac{1}{\pi \int_0^{\pi} i_{1,2}\, d\,(\omega t)} = \frac{I2_{MAX}}{2} \text{ or } I_{rms} = \frac{I_{max}}{\sqrt{2}}. \tag{7.11}$$

The ripple factor in output voltage of the bridge rectifier is known as the ratio of the residual AC component to DC component, and the ripple factor of the half wave rectifier is twice as in the full wave rectifier. It is used to describe the quality of the rectification. The passive filters on the rectifier are used to reduce the harmonic content (ripple factor) of the voltage and current at the output of the bridge rectifier.

The ripple factor can be expressed by

$$RF = \frac{\sqrt{V_L^2 - V_{DC}^2}}{V_{DC}} = \sqrt{FF^2 - 1}. \tag{7.12}$$

At full wave rectifier, the rectified output voltage is represented as

$$K_f = \frac{I_{rms}}{I_{avg}} = \frac{\left(I_{rms}/\sqrt{2}\right)}{(2I_{max}/\pi)} = \frac{\pi}{2\sqrt{2}} = 1.11, \tag{7.13}$$

which means that the ripple factor $\gamma = 1.11^2 - 1 = 0.482$. This leads to the fact that, in the full wave bridge rectifier, the residual ripples are relatively low, where in the half wave rectifier, the residual ripples are very high. Since the efficiency of the full wave rectifier is twice the efficiency of the half wave rectifier, a basic filter is needed to get a constant DC voltage in the electronic circuit of the bridge rectifier. Analysis of the LED bridge rectifier will be shown in more details in Chapter 7.

7.1.2 Light Emitting Diodes (LEDs)

LED lamps or LED tubes can be either active or passive in terms of manufacturing classes as discussed in [19]. Both classes of LEDs can create current harmonics if not filtered. Fig. 7.1 shows a block diagram of the internal structure of an LED lamp with EMI filter and Fig. 7.2 shows the structure without being filtered. LEDs can have diverse impacts in all areas of the outflow range of spectrum which totally relies on the interference creating hardware that are utilised as LED drivers.

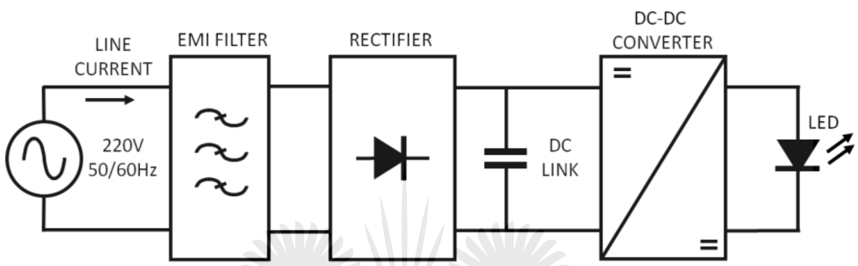

Figure 7.1: EMI filter and DC-DC converter with rectifier type LED lamp driver.

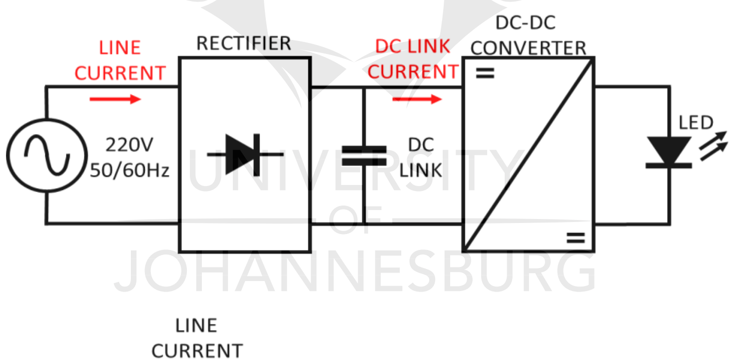

Figure 7.2: Modulation of the line current in the absence of the EMI filter.

7.2 MEASUREMENT SET-UP

Fig. 7.3 shows the measurement setup of the conducted experiments that include the 3kHz – 150kHz CENELEC band, as well as the broadband spectrum with the frequency 150kHz – 30MHz. A special arrangement is followed to perform the measurements in Differential Mode

(DM) as the Common Mode is excluded according to EN50065-1. Line Impedance Stabilisation Network and isolation transformer are used in the measurements as the LISN supplies a "clean" 50Hz 220VAC sinewave but causes earth leakage current to flow, where the isolation transformer is utilised to float the LISN, as it rectifies this fault condition.

The current harmonics made by the LED lamp are shown by the spectrum analyser and processed by a PC.

One LED lamp brand is chosen to conduct the measurements on, and then it is compared with other brands for more accuracy.

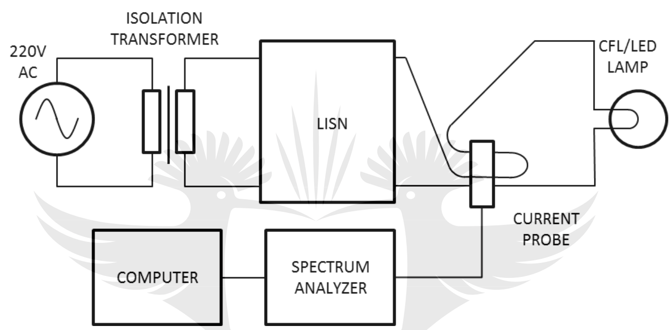

Figure 7.3: Set-up for measurements in the 3kHz – 150kHz range and 150kHz – 30MHz range.

7.3 HARMONICS - CENELEC BANDS

Electric wiring of the PLC network is usually characterised by a certain impedance *Z*, and electric devices such as LED lighting technology can fall between 10Ω and 1kΩ. This can be categorised as an absolute value of the internal components of the bridge rectifier in an LED lamp, such as resistors and capacitors. When an LED lamp is connected to the wiring system of the PLC network, it typically modifies the impedance on the electric wires. This results in having current harmonics and interference as shown in Figs. 7.4 and 7.5.

Losses of data are more likely to occur while transmitting over the wiring infrastructure of the power line network. One of the main reasons for those losses is the current harmonics that LED lighting sources inject into the PLC network which can interfere with the transmitted/received data. LEDs produce harmonics that affect the communications on the PLC CENELEC bands. However, this interference has no major effects on the CENELEC band as it falls below the band's maximum allowed signal levels.

Fig. 7.4 shows the obtained results on the CENELEC band. It is clearly seen that the most "noisy" lamp is the 20W FS200 that exceeds the CENELEC band maximum limit levels.

The current harmonics (magnitude) will then be represented in frequency domain waveforms. This is done by performing a Discrete Fourier Transform (DFT) and multiplying the current harmonics with the LISN impedance values that are used for measurements (Figs. 3.1 and 3.2) to get the voltage values.

Tests on LEDs from Chapter 4 differ from those in this chapter as the LED measurements conducted in this chapter are to get the best and worst values for curve fitting purposes.

7.4 BROADBAND SPECTRUM

Similar to those of CENELEC band measurements, a set of measurements that covers the frequency band 3kHz – 30MHz was performed to show the impact of the LED lamps on this frequency range. Harmonic noise is usually quantified by SNR and measured in decibels (dB). In this case, harmonic noise is made out of multiple frequencies produced by LED lighting technology when connected to the PLC network and considered as multiples of the line frequency, i.e. the 50Hz frequency yields odd harmonics of 150Hz, 250Hz, 350Hz, and so forth.

From the EMC viewpoint, LED lamps generate electrical perturbations and harmonics that can be conducted via the wiring system of the power lines, or are induced and emitted in the radio environment [176].

Fig. 7.5 shows the worst scenario for the PLC network. LEDs produce interference in this frequency band and this can have a serious impact on the data transmission of the power lines. This is an infected channel and the highest allowed EMC levels are exceeded.

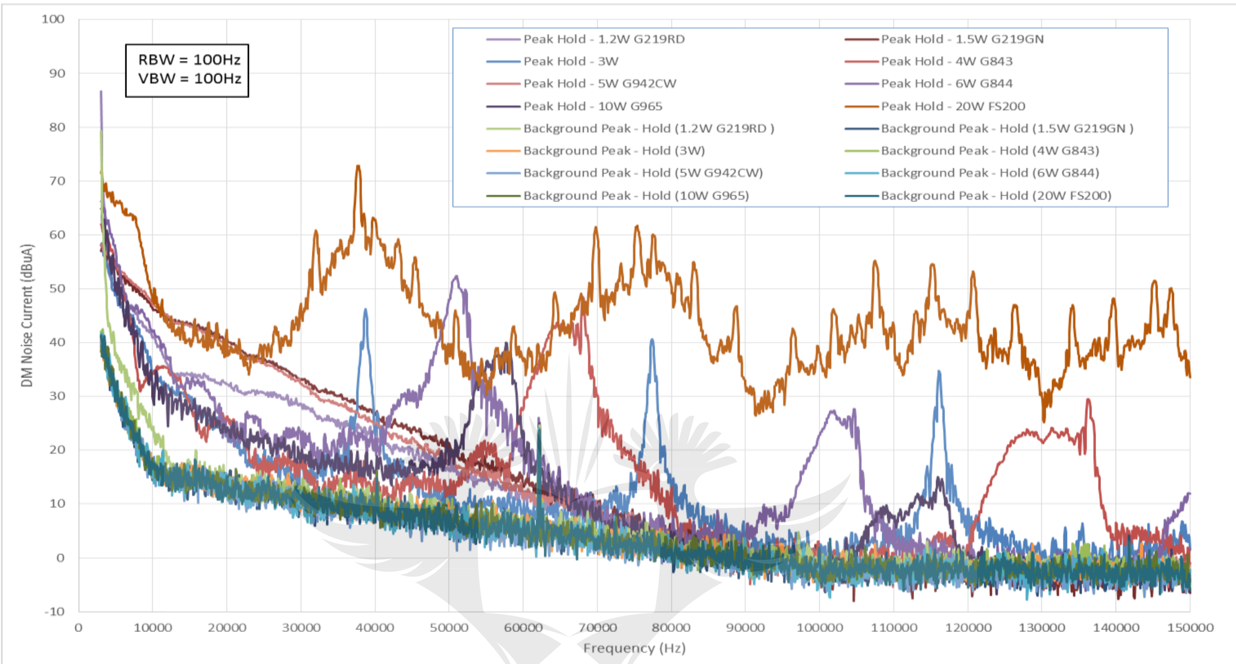

Figure 7.4: LED frequency domain waveforms and harmonics for the 3kHz – 150kHz range.

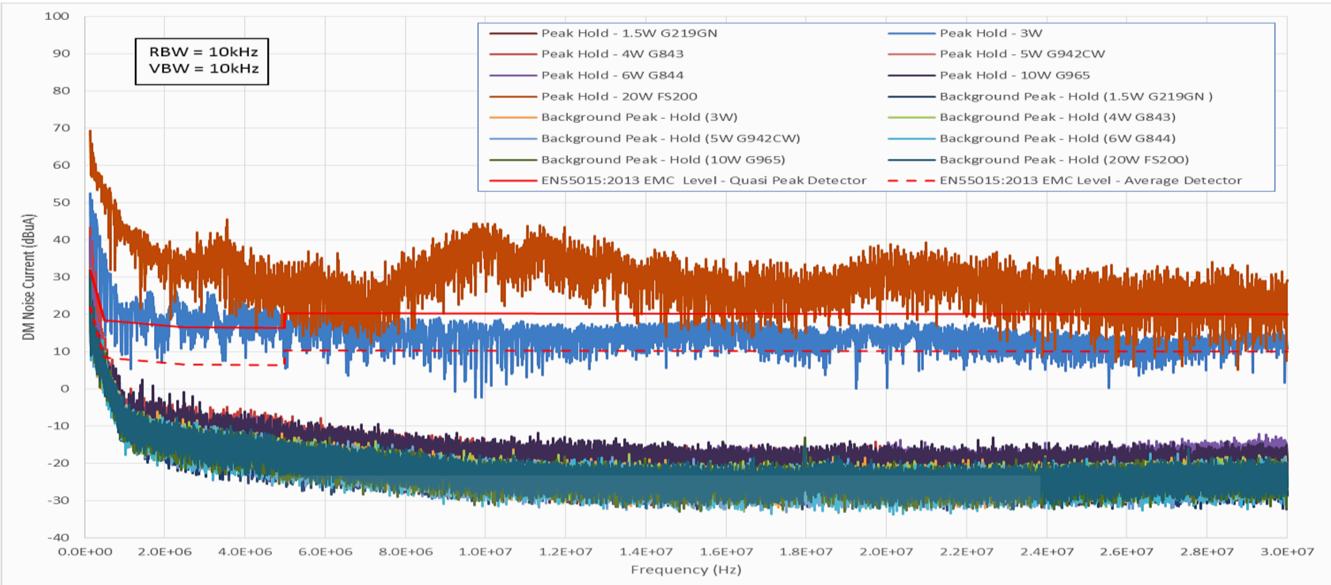

Figure 7.5: LED frequency domain waveforms and harmonics for the 3kHz – 30MHz range.

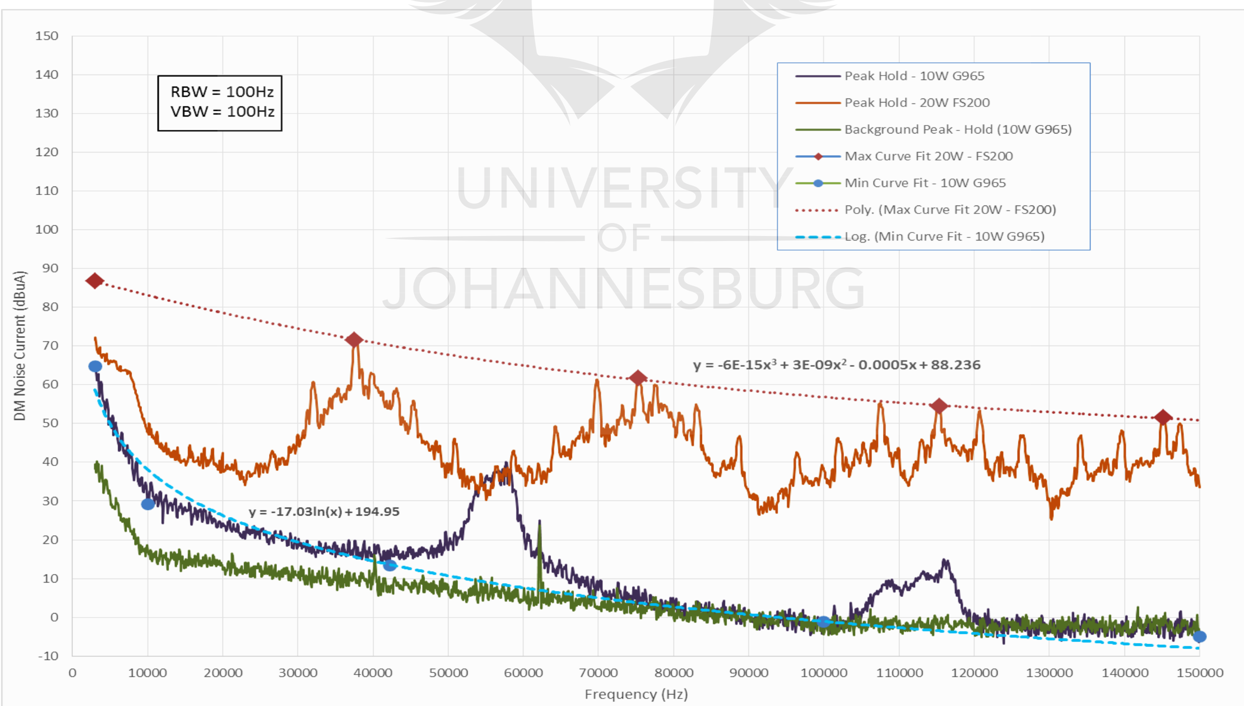

Figure 7.6: Curve fitting for LED lamps NB-PLC 3kHz – 150kHz DM.

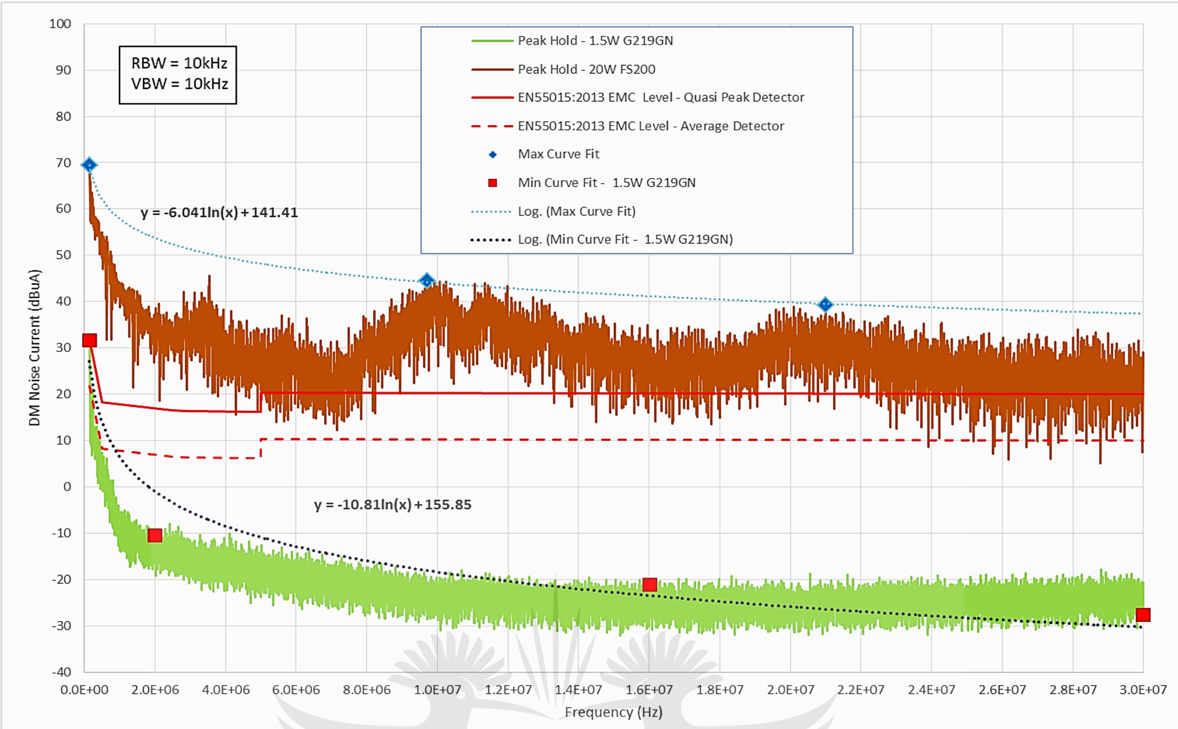

Figure 7.7: Curve fitting for LED lamps BB-PLC 150kHz – 30MHz DM

7.5 CURVE FITTING

This experimental study involves the relationship between different interacting variables and series of values on the narrowband frequency and broadband spectrum. To form a general model for the LED lamp structure, one should highlight the minimum and maximum values of current harmonics that LED lamps generally produce.

The relationship between the obtained peak values of the current harmonics on the CENELEC band is expressed in a curve-fitting shape in Fig. 7.6. This curve fitting graph represents the best scenario, as well as the worst scenario when an LED lamp is in operation and that the probability sets of data on the PLC network are being transmitted and/or received.

In Fig. 7.7, the curve fitting is presented on the broadband spectrum of the power lines. It also represents the best and worst scenarios, and shows the average of minimum and maximum values of the LED current harmonics. Generally, design of LED lamps will then need to fall below the maximum values shown in Figs. 7.6 and 7.7, as this will dictate a better manufacturing quality of LEDs, which allows better communications on the power line channel.

7.6 A SIMPLIFIED MODEL OF LED WITH BRIDGE RECTIFIER

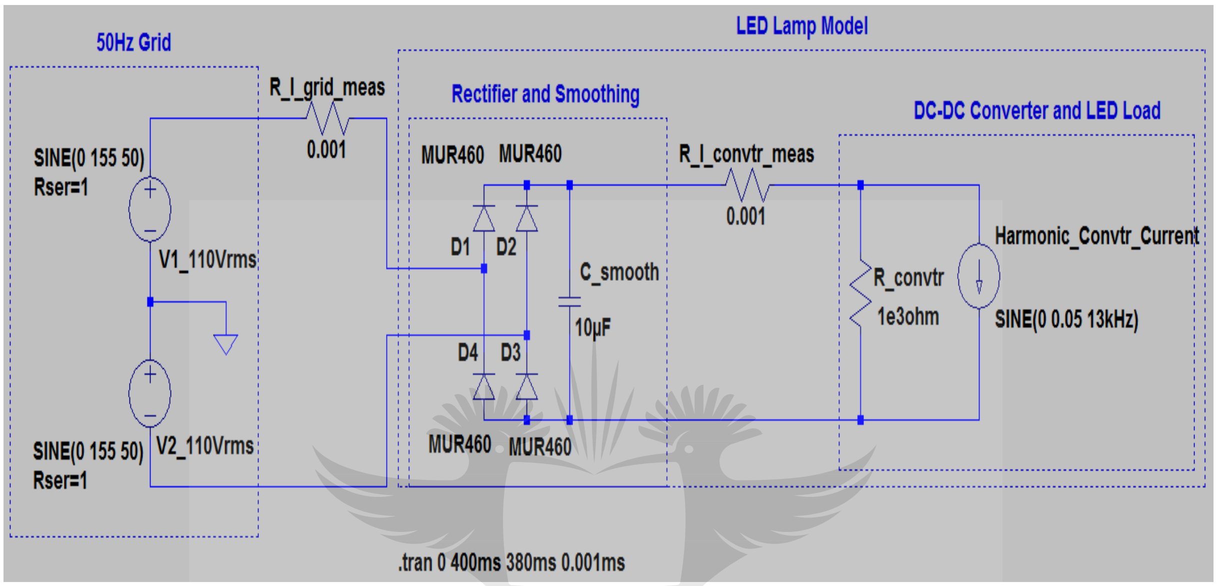

Figure 7.8: LED electronic circuit with bridge rectifier.

Fig. 7.8 shows the Spice design and simulation of the LED bridge rectifier and high frequency conversion process. A simulation study was performed and analysis of the current harmonics is shown and a conclusion can be given about the harmonics where the current increases as the value of the capacitor increases where Fig. 7.10 represents the time domain waveforms of the Fourier transforms used in this section. The LED frequency domain waveforms and harmonics for the 3kHz – 150kHz range are shown in Fig. 7.11.

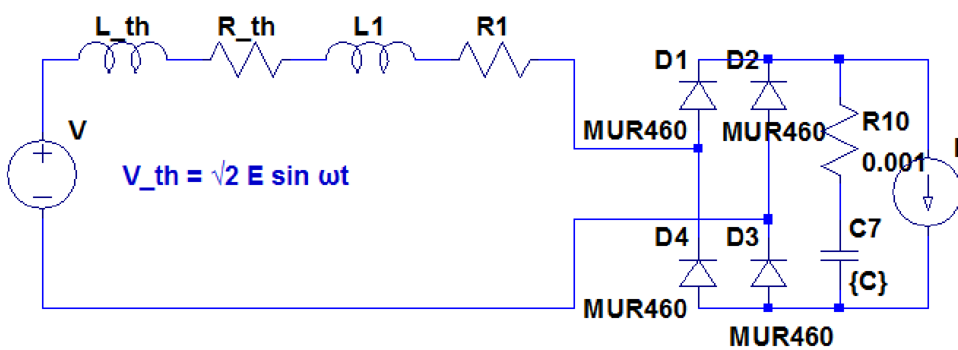

Figure 7.9: New proposed LED electronic circuit with bridge rectifier.

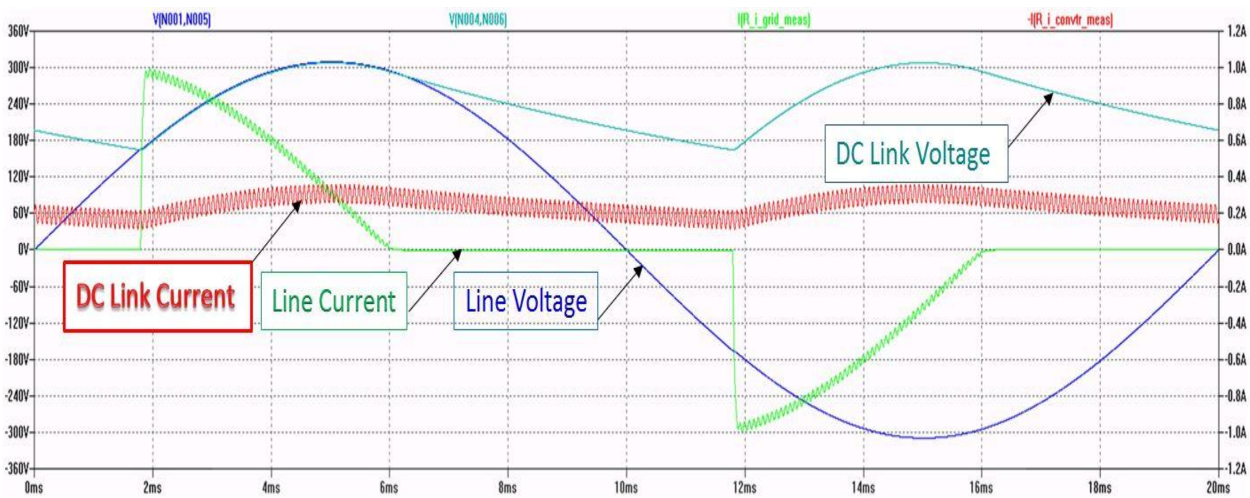

Figure 7.10: Time domain waveforms of different capacitors in the bridge rectifier circuit.

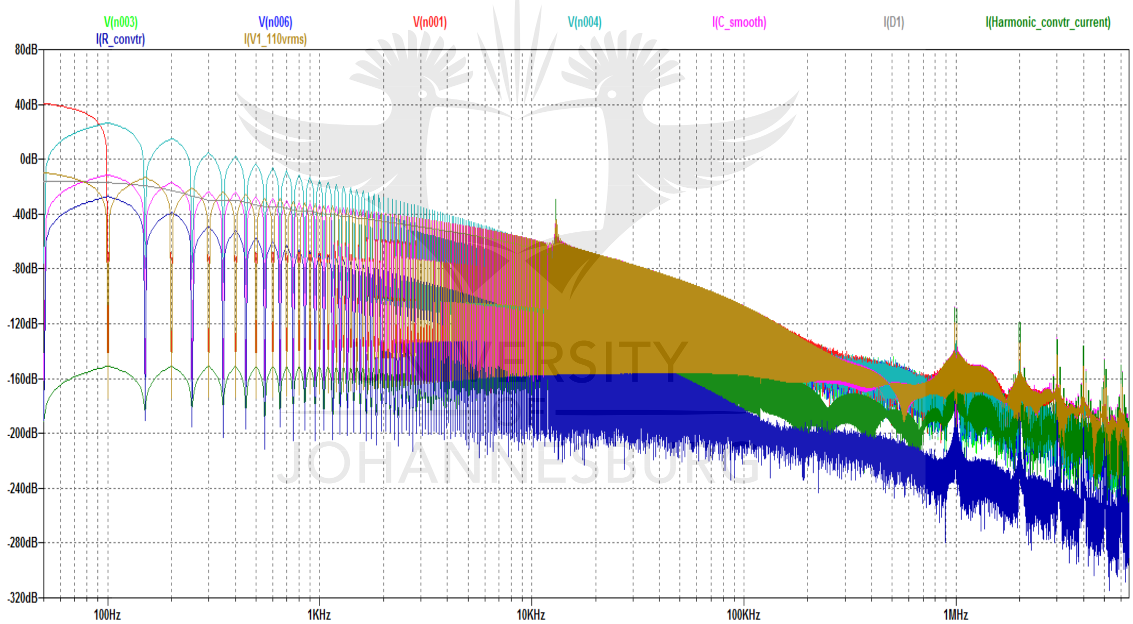

Figure 7.11: LED frequency domain waveforms and harmonics for the 3kHz – 150kHz range.

The proposed circuit in Fig. 7.9 is connected to the bridge rectifier (AC-DC converter), and R_{10} has the value R_2 and C_7 has the value C in the following. The detailed explanation of the other side of the AC-DC converter circuit can be found in [177] and [178].

In order to carefully design a simplified model of LED with bridge rectifier, we did the following analysis of the circuit in Fig. 7.9.

$$R_t = R_{th} + R_1 \ , \ \ L_t = L_{th} + L_1 \tag{7.14}$$

$$\text{KVL:} \ \ V_{th}(\theta) \ = R_t \, i_s + \omega L_t \frac{di_s}{d_\theta} + \ V_0(\theta) \tag{7.15}$$

$$\text{KCL:} \ \ i_s(\theta) \ = \omega c \frac{dV_c}{d_\theta} + \ i_1 \ = \ \omega c \left(\frac{\frac{1}{j\omega c}}{\frac{1}{j\omega c} + R_2} \right) \frac{dV_0(\theta)}{d\theta} \ + i_1 \tag{7.16}$$

$$\text{Define:} \ \ Y = \begin{bmatrix} i_s(\theta) \\ V_0(\theta) \end{bmatrix} \ , \ \ V = \begin{bmatrix} V_{th}(\theta) \\ i_1 \end{bmatrix} \ , \tag{7.17}$$

$$Y' = \ \alpha Y + \beta V \ , \tag{7.18}$$

$$\alpha = \begin{bmatrix} -\alpha_1 & -\alpha_2 \\ \alpha_3 + j\alpha_4 & 0 \end{bmatrix} \ , \quad \beta = \begin{bmatrix} \alpha_2 & 0 \\ 0 & -\alpha_3 - j\alpha_4 \end{bmatrix} \tag{7.19}$$

where

$$\alpha_1 = \frac{R_t}{wL_t} \ , \ \alpha_2 \ = \frac{1}{wL_t}, \ \alpha_3 \ = \frac{1}{wc}, \ \alpha_4 = R_2 \ . \tag{7.20}$$

By performing Laplace Transform:

$$Y(s) = (s\,I - \alpha)^{-1}\, Y(\theta_1) + (s\,I - \alpha)^{-1} \ \beta V(s) \tag{7.21}$$

with initial value:

$$Y(\theta_1) = \begin{bmatrix} 0 \\ \sqrt{2}\, E \sin\theta_1 \end{bmatrix} \tag{7.22}$$

Characteristic roots s_1 and s_2 are complex since:

$$s_{1,2} \ = \frac{-\alpha_1 \pm \sqrt{\alpha_1^2 - 4\alpha_2\,(\alpha_3 + j\alpha_4)}}{2} \quad \text{and } j\alpha_4 \ \text{ is complex.}$$

Therefore: $s_1 = \frac{\alpha_1}{2} + \frac{A}{2} + j\frac{B}{2}$ and $s_2 = \frac{\alpha_1}{2} - \frac{A}{2} - j\frac{B}{2}$

where

$$B = \frac{\sqrt{-\alpha_1^2 + 4\alpha_2\,\alpha_3 + \sqrt{\alpha_1^4 + 16\alpha_2^2\alpha_3^2 - 8\alpha_1^2\alpha_2\alpha_3 + 16\alpha_2^2\alpha_4^2}}}{2} \tag{7.23}$$

$$A = -2\alpha_2\,\alpha_4\,B^{-1} \tag{7.24}$$

Since different settings of ω, L_t and R_2 lead to different α's, the characteristic roots of (sI- α) can be complex. Hence, there are no uniform solutions for the inverse of the Laplace transform. However, a generalised two-step method is provided as follows: Step 1, input the settings of ω, L_t and R_2 to have exact values of α's. Based on α's, we can derive the characteristic roots of (sI- α), namely s_1 and s_2. Therefore, we can obtain:

$$Y(s) = \frac{c_1}{s - s_1} + \frac{c_2}{s - s_2} \tag{7.25}$$

where c_1, c_2, s_1 and s_2 are explicitly valued. The inverse Laplace transform is straight forward.

Step 2, provide the boundary conditions of i_s and V_0, we can further derive θ_1 and θ_2 as recommended in [177] and [178] by using the Gauss-Seidel approach.

7.7 DISCUSSION

This chapter introduced the reader to the circuit design of the bridge rectifier used in LED and CFL light sources, and showed their impact on the power lines. The curve fitting then illustrated the best and worst scenarios for communications on the power lines in the presence of LED lamps. This is typically done to show the average of minimum and maximum values of LED current harmonics, which is considered a partial contribution towards a general design for LEDs' circuit of the bridge rectifier. Another main contribution was the mathematical approach enriched by the simulation presented in this chapter.

As a result, we propose a basic design of a low pass filter (LPF) to eliminate or reduce the amount of current harmonics LED lamps produce. The design is based on the resonance frequency equation:

$$f_r = \frac{1}{2\pi\sqrt{LC}}. \tag{7.26}$$

For inductance: $2\pi\, f_r = \frac{1}{\sqrt{LC}}$, where $(2\pi\, f_r)^2 = \frac{1}{LC}$, then $L = \frac{(2\pi\, f_r)^2}{C}$.

The LPF is made of a capacitor and an inductor (Trafo type), using the equation:

$$\frac{V_P}{V_S} = \frac{N_P}{N_S} = \sqrt{\frac{L_P}{L_S}} \tag{7.27}$$

where V is voltage, P is primary coil, S is secondary coil, N is number of turns and L is inductance.

The LPF can then be mounted in parallel to the input side of the LED driver circuit as in Fig. 7.1.

Other EMI filters can be based on first order low pass RC filters as in the equation:

$$f_c = \frac{1}{2\pi\,\tau} = \frac{1}{2\pi\,RC}, \tag{7.28}$$

where $\omega_c = \frac{1}{\tau} = \frac{1}{RC}$, or a second order low pass filter as in the equation:

$$f_c = \frac{1}{2\pi\,R_2 C}, \tag{7.29}$$

where $\omega_c = \frac{1}{R_2 C}$.

Design of such filters can be taken into account as a future work theme.

Chapter 8 – Conclusion

The most important achievement in this thesis was the realistic and plausible results obtained through the duration of this research. Lighting technology is one of the main pillars of "modern" life; therefore, we have introduced the reader to the main used light sources and went through the characteristics and features of those lights, and showed the impact of the lights on the power lines when used as a communications medium.

8.1 SUMMARY AND CONTRIBUTIONS

In this thesis, we have introduced the reader to the importance of the modern lighting technology and showed its relationship to power line communications. Efficiency and accuracy were taken in consideration through the measurement campaign, and the study was made feasible by simplifying the steps followed during the measurement set-ups. We showed that the modern light sources have a serious and "risky" impact on the wiring infrastructure of the power lines when used as a communications medium.

Furthermore, we deeply studied the LED lighting technology and focused on the disadvantages caused by this technology as it is becoming one of the main light sources in many parts of the world.

The other objective of this thesis was to contribute towards the design of a general model for LED lamps that were introduced for scientific and commercial use, as well as contribute to the future manufacturing industry.

In Chapters 4 and 5, we have studied the structures and characteristics of the low energy light sources used for indoor purposes, and focused on the amount of interference produced by such lights, as well as the effects on the CENELEC band and broadband spectrum. We have also shown the impact of the colour LEDs and CFLs on the PLC network, as well as the data rate or throughput that gets affected when using LED tubes while communicating on the network.

Chapter 6 dealt with the high energy light sources that are often used as an outdoor lighting technology. Some of those lights were more harmful to the PLC grid than those from the low energy section.

According to the extensive measurements undertaken, we could clearly elicit that if many of those lights are switched on simultaneously (such as street lights), this will result in stopping any communications on the PLC network for at least a few seconds.

Analysis of a bridge rectifier and high frequency converters used in LED lighting were addressed in Chapter 7. The high frequency RFI interference and current harmonics that bridge rectifiers produce cause distortion to the voltage waveform which hinders communications on the PLC channel. A mathematical approach, aided by computer simulation, was presented in this chapter as to form a general model for LED lamp structure which is to be used in future research and industry operations.

8.2 FUTURE DIRECTIONS

Lighting technology is an important and interesting research environment. Influence of 3-D lighting techniques on PLC, radiations caused by light sources and the effects of other loads on the power line on the light sources are subjects of interest for future research directions. This can be considered as a "long-term" future work direction.

For “short-term” future work direction, considering a feasible and cost effective EMI filter design for lighting technology is one of the important issues that researchers and industrial bodies can look at.

High frequency impedance studies of the power network and its effect on lighting interference generation can also be a future study area.

References

[1] H. C. Ferreira, L. Lampe, J. Newbury and T. G. Swart, *Power Line Communications: Theory and Applications for Narrowband and Broadband Communications over Power Lines*, Chichester, England: John Wiley & Sons, 2010.

[2] L. B. Wang, P. L. So, K. Y. See, M. Oswal, and T. S. Pang, "Investigation of Radiated Emissions in Power Line Communication Networks," *Proceedings of the IEEE International Power Engineering Conference*, Singapore, Singapore, December 3-6, 2007, pp. 455 – 460.

[3] Y. Zhao, Y. Dong, X. Lu and N. Jiang, "Radiated EMI Estimation for Power Line Communication Based on Conducted Noise Separation Network," *Proceedings of the IEEE Asia-Pacific International Symposium on Electromagnetic Compatibility*, Beijing, China, April 12-16, 2010, pp. 1405 – 1408.

[4] P. Pagani, R. Razafferson, A. Zeddam, B. Praho, M. Tlich, J. –Y. Baudais, A. Maiga, O. Isson, G. Mijic, K. Kriznar and S. Drakul, "Electro Magnetic Compatibility for Power Line Communications," *Proceedings of the IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Istanbul, Turkey, September 26-30, 2010, pp. 2799 – 2804.

[5] J. Song, S. Liu, G. Zhou, B. Yu, W. Ding, F. Yang, H. Zhang, X. Zhang and A. Amara, "A Cost-Effective Approach for Ubiquitous Broadband Access Based on Hybrid PLC-VLC System," *Proceedings of the IEEE International Symposium on Circuits and Systems*, Montreal, QC, Canada, May 22-25, 2016, pp. 2815 – 2818.

[6] J. B. Anderson, *Digital Transmission Engineering*, IEEE Press, 1998.

[7] J. G. Proakis, *Digital Communications*, McGraw-Hill, 1995.

[8] M. Arzberger, K. Dostert, T. Waldeck and M. Zimmermann, "Fundamental Properties of the Low Voltage Power Distribution Grid," *Proceedings of the International Symposium on Powerline communications and its Applications*, Essen, Germany, April 2-4, 1997.

[9] A. G. Burr, D. M. W. Reed and P. A. Brown, "HF Broadcast Interference on LV Mains Distribution Networks," *Proceedings of the International Symposium on Powerline Communications and its Applications*, Tokyo, Japan, March 24-26, 1998, pp. 253 – 262.

[10] K. Dostert, "RF-Models of the Electrical Power Distribution Grid," *Proceedings of the International Symposium on Powerline Communications and its Applications*, Tokyo, Japan, March 24-26, 1998, pp. 105 – 114.

[11] I. Froroth, "More than Power Down the Line," Licentiate of Technology Thesis, Department of Teleinformatics, Royal Institute of Technology, Stockholm, Sweden, March, 1999.

[12] O. Hooijen, "A Channel Model for the Low-Voltage Power-Line Channel," *Proceedings of the International Symposium on Powerline Communications and its Applications*, Essen, Germany, April 2-4, 1997, pp. 51 – 56.

[13] G. Marubayashi, "Noise Measurements of the Residential Powerline," *Proceedings of the International Symposium on Powerline Communications and its Applications*, Essen, Germany, April 2-4, 1997, pp. 104 – 108.

[14] H. Philipps, "Performance Measurements of Powerline Channels at High Frequencies," *Proceedings of the International Symposium on Powerline Communications and its Applications*, Tokyo, Japan, March 24-26, 1998, pp. 229 – 237.

[15] J. A. Malack and J. R. Engstrom, "RF Impedance of United States and European Power Lines," *IEEE Transactions on Electromagnetic Compatibility*, vol. 18, no. 1, February 1976, pp. 36 – 38.

[16] J. R. Nicholson and J. A. Malack, "RF Impedance of Power Lines and Line Impedance Stabilisation Networks in Conducted Interference Measurements," *IEEE Transactions on Electromagnetic Compatibility*, vol. 15, May 1973, pp. 84 – 86.

[17] R. M. Vines, H. J. Trussel, K. C. Shuey and J. B. O'Neal, "Impedance of the Residential Power-Distribution Circuit," *IEEE Transactions on Electromagnetic Compatibility*, vol. 27, no. 1, January 1985, pp. 6 – 12.

[18] J. M. Alonso, D. Gacio, A. J. Calleja, J. Ribas and E. López Corominas, "A Study on LED Retrofit Solutions for Low-Voltage Halogen Cycle Lamps," *IEEE Transactions on Industry Applications*, vol. 48, no. 5, July 2012, pp. 1673 – 1682.

[19] A. S. de Beer, A. Emleh, H. C. Ferreira and A. J. Han Vinck, "Effects of LED Lamps on the Power-Line Communications Channel," *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications*, Johannesburg, South Africa, March 24-27, 2013, pp. 209 – 213.

[20] 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," *Proceedings of the Power Engineering Conference*, Sydney, Australia, December 14-17, 2008, pp. 1 – 5.

[21] J. Yong, L. Chen, A. B. Nassif and W. Xu, "A Frequency-Domain Harmonic for Compact Fluorescent Lamps," *IEEE Transactions on Power Delivery*, vol. 25, no. 2, April 2010, pp. 1182 – 1189.

[22] C. Jiang, D. Salles, W. Xu and W. Freitas, "Assessing the Collective Harmonic Impact of Modern Residential Loads—Part II: Applications," *IEEE Transactions on Power Delivery*, vol.27, no. 4, September 2012, pp. 1947 – 1955.

[23] M. Sugiura, "Review of metal-halide discharge-lamp development 1980-1992," *IET Proceedings: Science, Measurements & Technology*, vol. 140, no. 6, November 1993, pp. 443 – 449.

[24] Commercial Lighting, "Metal Halide Diagram", Metal Halide Diagram, 5137 Clifton Street, Tampa, Florida, USA, www.clcbulbs.com, Last Accessed: Oct. 16, 2017.

[25] J. W. ter Vrugt and J. K. P. Verwimp, "High Pressure Mercury Vapour Lamps," *IEEE Physical Science, Measurement and Instrumentation, Management and Education*, vol. 127, no. 3, April 1980, pp. 173 – 180.

[26] Commercial Lighting, "Mercury Vapor Diagram", Mercury Vapor Diagram, 5137 Clifton Street, Tampa, Florida, USA, www.clcbulbs.com, Last Accessed: October 16, 2017.

[27] G. Sincero and A. J. Perin, "High Pressure Sodium Lamp High Power Factor Electronic Ballasts Using AC–AC Converters," *IEEE Transactions on Power Electronics, Special Section on Lighting Applications*, vol. 22, no. 3, May 2007, pp. 804 – 814.

[28] R. Geens and E. Wyner, "Progress in High Pressure Sodium Lamp Technology," *IEE on Science, Measurement and Technology*, vol. 140, no. 6, November 1993, pp. 450 – 464.

[29] K. B. Suk and K. H. Jun, "High Power Factor Electronic Ballast for High Pressure Sodium Lamp," *Proceedings of the IEEE Region 10 Conference: TENCON*, Cheju Island, South Korea, South Korea, September 15-17, 1999, vol. 2, pp. 887 – 890.

[30] Commercial Lighting, "High Pressure Sodium Diagram," Sodium Vapor Arc, 5137 Clifton Street, Tampa, Florida, USA, www.clcbulbs.com, Last Accessed: Oct. 16, 2017.

[31] H. K. Podszeck, *Carrier Communication over Power Lines*, 4th Edition, New York: Springer-Verlag, 1972.

[32] K. Dostert, *Powerline Communications*, Englewood Cliffs, NJ: Prentice-Hall, 2001.

[33] J. Newel, "History and Theory of Ripple Communication Systems," *Proceedings of the National Telecommunications Conference*, Dallas, USA, November 29 – December 1, 1976, pp. 2 – 3.

[34] IEEE Guide for Power-Line Carrier Applications, IEEE Standard 643-1980.

[35] A. F. Collins, *The Radio Amateur's Hand Book*, LaVergne: Lightning Source Inc., 2004.

[36] G. Lokken, N. Jagoda and R. J. D'Autenil, "The proposed Winconsin Electrical Power Company Load Management System Using Power Line Carrier Over Distribution Lines," *Proceedings of the National Telecommunications Conference*, Dallas, USA, November 29 - December 1, 1976, pp. 221 – 223.

[37] G. Kaplan, "Two-Way Communication for Load Management," *IEEE Spectrum*, vol. 14, no. 8, August 1977, pp. 47 – 50.

[38] B. E. Eyre, "Results of a Comprehensive Field Trial of a United Kingdom Customer Telemetry System Using Mainsborne Signaling," *Proceedings of the 5th International Conference on Metering Apparatus and Tariffs for Electricity Supply*, London, UK, April 13-16, 1987, pp. 252 – 256.

[39] M. C. King, "Experimental systems for Tele-Reading over the Low-Voltage Network," *Proceedings of the International Conference on Metering Apparatus and Tariffs for Electricity Supply*, London, UK, April 3 – 5, 1990, pp. 154 – 157.

[40] C. Nunn, P. M. Moore, and P. N. Williams, "Remote meter reading and control using high-performance PLC communications over the low voltage and medium voltage distribution networks," *Proceedings of the International Conference on Metering Apparatus and Tariffs for Electricity Supply*, London, UK, November 17-19, 1992, pp. 304 –308.

[41] J.S. Barnes, "A Physical Multi-Path Model for Power Distribution Network Propagation," *Proceedings of the IEEE International Symposium on Power-line Communications and its Applications*," Tokyo, Japan, March 24-26, 1998.

[42] A. B. Dalby, "Signal Transmission on Power Lines; (Analysis of power line circuits)," *Proceedings of the International Symposium on Power-line Communications and its Applications*," Essen, Germany, April 2-4, 1997.

[43] J. Dickinson and P. Nicholson, "Calculating the High Frequency Transmission Line Parameters of Power Cables," *Proceedings of the International Symposium on Power-line Communications and its Applications*, Essen, Germany, April 2-4, 1997, pp. 127 – 133.

[44] H. Philipps, "Modelling of Powerline Communication Channels," *Proceedings of the IEEE International Symposium on Power-line Communications and its Applications*," Lancaster, UK, March 30 - April 1, 1999, pp.14 – 21.

[45] G. Duval, "Low Voltage Network Models to the Analysis of Unexpected Phenomena in PLC Communications," *Proceedings of the International Symposium on Power-line Communications and its Applications*, Tokyo, Japan, March 24-26, 1998.

[46] M. Zimmermann and K. Dostert, "A Multi-Path Signal Propagation Model for the Power Line Channel in the High Frequency Range," *Proceedings of the International Symposium on Power-line Communications and its Applications*, Lancaster, UK, March 30 - April 1, 1999, pp. 45 –51.

[47] O. Hooijen, *Aspects of Residential Power Line Communications*, Aachen: Shaker Verlag, 1998.

[48] O.G. Hooijen, "On the relation between network-topology and power line signal attenuation," *Proceedings of the International Symposium on Power-Line Communications and its Applications*, Tokyo, Japan, March 24-26, 1998, pp. 24 – 26.

[49] D. Chaffanjon, "A real knowledge of propagation: the way of efficiency and reliability making PLC generalization feasible*," Proceedings of the International Symposium on Power-Line Communications and its Applications*, Tokyo, Japan, 24-26 March 1998, pp. 57 – 66.

[50] M. Zimmermann and K. Dostert, "A Multipath Model for the Powerline Channel," *IEEE Transactions on Communications*, vol. 50, no. 4, April 2002, pp. 553 – 559.

[51] M. Luby, M. Watson, T. Gasiba and T. Stockhammer, "High-Quality Video Distribution using Power Line Communication and Aplication Layer Forward Error Correction," *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications*, Pisa, Italy, March 26-28, 2007, pp. 431 – 436.

[52] A. S. de Beer, H. C. Ferreira and A. J. Han Vinck, "Contactless Power-Line Communications," *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications*, Austin, TX, USA, March 30 - April 2, 2014, pp. 111 – 115.

[53] P. A. Janse van Rensburg, H. C. Ferreira, "Design of a Bidirectional Impedance-Adapting Transformer Coupling Circuit for Low-Voltage Power-Line Communications," *IEEE Transactions on Power Delivery*, vol. 20, no. 1, January 2005, pp. 64 – 70.

[54] P. A. Janse van Rensburg, H. C. Ferreira, "Step-by-Step Design of a Coupling Circuit with Bi-Directional Transmission Capabilities, "*Proceedings of the International*

Symposium on Power-Line Communications and its Applications," Zaragoza, Spain, March 31 - April 2, 2004, pp. 238 – 243.

[55] P. A. Janse van Rensburg, H. C. Ferreira, "Coupler winding ratio selection for effective narrow-band power-line communications," *IEEE Transactions on Power Delivery*, vol. 23, no. 1, January 2008, pp. 140 – 149.

[56] Hui-M. Oh, S. Choi, Jae-J. Lee, S. Shon, H. S. Kim, D. S. In and J. Bae, "Coupler with Transformer for Impedance Matching on MV Power Distribution Line for BPLC," *Proceedings of the International Symposium on Power Line Communications and Its Applications*, Jeju City, South Korea, April 2-4, 2008, pp. 409 – 412.

[57] B. Jensen, H. Slavensky and S. Kjærsgaard, "Benchmarking and QoS of In-House Powerline Equipment for AV- Streaming Applications," *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications*, Orlando, USA, March 26-29, 2006, pp. 160 – 165.

[58] B. Jensen and S. Kjærsgaard, "Benchmarking and QoS of In-House Powerline Equipment under Noisy Conditions," *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications*, Pisa, Italy, March 26-28, 2007, pp. 17 – 22.

[59] S. Bradner, "RFC 2544 - Benchmarking Methodology for Network Interconnect Devices," Harvard University, the Internet Society, March, 1999.

[60] EN 50065-1: Signaling on low-voltage electrical installations in the frequency range 3kHz to 148,5kHz - Part 1: General Requirements, Frequency Bands and Electromagnetic Disturbances. European Standard, CENELEC, Ref. No. EN 50065-1:2011 E, Brussels, April, 2011.

[61] M. Katayama, T. Yamazato and H. Okada, "A Mathematical Model of Noise in Narrowband Power Line communication systems," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 7, July 2006, pp. 1267 – 1276.

[62] M. Gotz, M. Rapp and K. Dostert, "Power line channel characteristics and their effect on communication system design," *IEEE Communications Magazine*, vol. 42, no. 4, April 2004, pp. 78 – 86.

[63] E. Yavuz, F. Kural, N. Çoban, B. Ercan, and M. Şafak, "Modelling of Power-Lines for Digital Communications," *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications*, Limerick, Ireland, April 5-7, 2000, pp. 161 – 168.

[64] H. Philipps, "Development of a Statistical Model for Power-Line Communication Channels," *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications*, Limerick, Ireland, April 5-7, 2000, pp. 153 – 159.

[65] M. Zimmermann and K. Dostert, "An Analysis of the Broadband Noise Scenario in Power-Line Networks," *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications*, Limerick, Ireland, April 5-7, 2000.

[66] T. V. Prasad, S. Srikanth, C. N. Krishnan and P. V. Ramakrishna, "Wideband Characterization of Low Voltage Outdoor Power Line Communication Channels in India," *Proceedings of the IEEE International Symposium on Power Line*

Communications and Its Applications, Malmö, Sweden, April 4-6, 2001, pp. 359 – 364.

[67] P. Corlay, F. X. Coudoux, M. Gazalet, F. Ruolt and F. Haine, "An efficient modelling of the impulse response of the indoor power line communication channels in high frequencies range," *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications*, Malmö, Sweden, April 4-6, 2001, pp. 149 – 154.

[68] V. Dégardin, M. Liénard, P. Degauque, A. Zeddam and F. Gauthier, "OFDM Transmission Corrupted by Colored and Narrow Band Noise," *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications*, Malmö, Sweden, April 4-6, 2001, pp. 41 – 46.

[69] M. Tlich, H. Chaouche, A. Zeddam and F. Gauthier, "Impulsive noise characterization at source," *1st IFIP Wireless Days*, November 24, 2008, pp. 1 – 6.

[70] M. Tlich, A. Zeddam, F. Moulin, F. Gauthier and G. Avril, "A broadband Powerline Channel Generator," *Proceedings of the IEEE International Conference on Power Line Communications and Its Applications*, Pisa, Italy, March 26-28, 2007, pp. 505 – 510.

[71] M. Tlich, A. Zeddam, F. Moulinand and F. Gauthier, "Indoor Powerline Communications Channel Characterization up to 100MHz – Part II: One-parameter deterministic model," *IEEE Transactions on Power Delivery*, vol. 23, no. 3, July 2008, pp. 1402 – 1409.

[72] M. Katayama, T. Yamazato, and H. Okada, "A Mathematical Model of Narrowband Power-Line Noise Based on Measurements," *Proceedings of the International Symposium on Power Line Communications and Its Applications*, April 6-8, 2005, pp. 152 – 156.

[73] M. Zimmermann and K. Dostert, "Analysis and Modeling of Impulsive Noise in Broad-band Powerline Communications," *IEEE Transactions on Electromagnetic Compatibility*, vol. 44, no. 1, February 2002, pp. 249 – 258.

[74] M. Katayama, S. Itou, T. Yamazatot and A. Ogawa, "Modeling of Cyclostationary and Frequency Dependent Power-Line Channels for Communications," *Proceedings of the International Symposium on Power-line Communications and its Applications*, Limerick, Ireland, April 5-7, 2000, pp. 123 – 130.

[75] H. Niwa, M. Katayama, T. Yamazato, A. Ogawa and N. Isaka, "A Spread-Spectrum System with Dual Processing Gains Designed for Cyclic Noise in Power Line Communications," *IEICE transactions on Fundamentals of Electronics, Communications and Computer Sciences*, vol. 80, no. 112, December 1997, pp. 2526 – 2533.

[76] O. Ohno, M. Katayama, T. Yamazato and A. Ogawa, "A Simple Model of Cyclostationary Power-Line Noise for Communication Systems," *Proceedings of the International Symposium on Power-line Communication and its Applications*, Tokyo, Japan, March 24-26, 1998, pp. 115 – 122.

[77] M. A. Sonmez and M. Bagriyanik, "Statistical model study for Narrowband Power Line Communication Noises, *Proceedings of the IEEE International Conference on*

Electrical and Electronics Engineering, Bursa, Turkey, Nov. 28-30, 2013, pp. 539 – 543

[78] N. Mohan, T. Undeland, and W. P. Robbins, *Power Electronics*. New York: Wiley, 1995.

[79] Tim William, *The circuit Designer's companion*, Second Edition.

[80] P. M. Nicolae, I. D. Nicolae and M. S. Nicolae, "Electromagnetic compatibility and power quality problems at low frequency for loads from an urban transportation system and in a power substation*," Proceedings of the IEEE International Symposium on Electromagnetic Compatibility*, Denver, USA, Aug 5-9, 2013, pp. 242 – 247.

[81] A.Y. B. Lau, D. R. Jackson and D. R. Wilton, "Investigation of feed line effects on near fields from broadband over power line communications," *Proceedings of the International Conference Wireless and Microwave Circuits and Systems*, Texas, USA, April 23, 2014, pp. 1 – 4.

[82] M. Chaaban, G. Bousaleh, R. H. Chehade, A. I.smail, K. E. K. Drissi and C. Pasquier, "Reduction of power field radiation for PLC applications," *Proceedings of the International Conference on Advances in Computational Tools for Engineering Applications*, Zouk Mosbeh, Lebanon, July 15-17, 2009, pp. 422 – 426.

[83] R. P. Rickard, "Power Line Communication," Patent WO9806188, February 1998.

[84] R. P. Rickard, "Coupling Communication signals to Power Line," Patent US6037678, March 2000.

[85] H. M. Schlicke and H. Weidmann, "Compatible EMI Filters," *Proceedings of the IEEE Transactions on Electromagnetic Compatibility*, vol. 4, no. 10, October 1967, pp. 59 – 68.

[86] A. Majid, J. Saleem and K. Bertilsson, "EMI Filter Design for High Frequency Power Converters," *Proceedings of the International Conference on Environment and Electrical Engineering*, Venice, Italy, May 18-25, 2012, pp. 586 – 589.

[87] Comité Européen de Normalisation Electrotechnique: Online- Available on http://www.cenelec.eu. Last Accessed: October 25, 2017.

[88] Federal Communications Commission, Title 47 of the Code of Federal Regulations, Government Printing Office, Washington, D.C., USA, Oct. 2011.

[89] S. Chen, "Ultra Wideband Gigabit Powerline Communication," PhD Thesis, Queen Mary University of London, UK, September 2009.

[90] B. S. I. Staff, "Signalling on Low-voltage Electrical Installations in the Frequency Range 3KHz to 148.5KHz. Immunity Requirements for Mains Communications Equipment and Systems Operating in the Range of Frequencies 3KHz to 95KHz and Intended for Use by Electricity Suppliers and Distributors". B. S. I. Standards, 2003.

[91] J. G. Mayordomo, A. Hernandez, R. Asensi, L. F. Beites and M. Izzeddine, "A Unified Theory of Uncontrolled Rectifiers, Discharge Lamps and Arc Furnaces. I. An Analytical Approach for Normalized Harmonic Emission Calculations," *Proceedings of the IEEE International Conference on Harmonics and Quality of Power*, Athens, Greece, Oct. 14 - 16, 1998, Vol. 2, pp. 740 – 748.

[92] J. G. Mayordomo, A. Hernandez, R. Asensi, M. Izzeddine and L. F. Beites, "A Unified Theory of Uncontrolled Rectifiers, Discharge Lamps and Arc Furnaces. II. An Analog

Model for Educational Purposes," *Proceedings of the International Conference on Harmonics and Quality of Power*, Athens, Greece, Oct. 14 - 16, 1998, vol. 2, pp. 1106 – 1112.

[93] I. K. Lee and B. H. Cho, "A new control method for a low frequency inverter of MHD lamp ballasts with a synchronous rectifier," *Proceedings of the IEEE Applied Power Electronics Conference and Exposition*, Austin, TX, USA, March 6-10, 2005, vol. 2, pp. 1060 – 1064.

[94] C. Ekkaravarodome, A. Nathakaranakule and I. Boonyaroonate, "Single-Stage Fluorescent Lamps Electronic Ballast Using Class-DE Low dv/dt Rectifier for Power-Factor Correction," *Proceedings of the International Conference on Power Electronics and Drive Systems*, Bangkok, Thailand, November 27-30 , 2007, pp. 1194 – 1198.

[95] S. Y. Chan, T. H. Yang and Y. N. Chang, "Design of Electronic Ballast for Short-Arc Xenon Lamp with Interleaved Half-Wave Rectifier," *IEEE Transactions on Power Electronics*, vol. 31, no. 7, July 2016, pp. 5102 – 511.

[96] T. Kim, M. Rylander, E. J. Powers, W. M. Grady and A. Arapostathis, "LED Lamp Flicker Caused by Interharmonics," *Proceedings of the IEEE Instrumentation and Measurement Technology Conference*, Victoria, BC, Canada, May 12-15, 2008, pp. 1920 – 1925.

[97] C. S. Daugherty, "Problems Encountered in Applying the Silicon-Controlled Rectifier to Control Tungsten Lamp Loads," *IEEE Transactions of the American Institute of Electrical Engineers, Part I: Communication and Electronics*, vol. 80, no. 4, September 1961, pp. 400 – 402.

[98] M. Amirabadi, "A new class of high-power-density universal power converters," *Proceedings of the IEEE Energy Conversion Congress and Exposition*, Montreal, QC, Canada, September 20-24, 2015, pp. 2596 – 2602.

[99] J. Grubor, S. Randel, K.D. Langer and Walewski, J.W. "Broadband information broadcasting using LED-based interior lighting," *Journal of Lightwave Technology*, vol. 26, no. 24, December 2008, pp. 3883– 3892.

[100] H. Elgala, R. Mesleh, and H. Haas," Indoor optical wireless communication: potential and state-of-the-art," *Proceedings of the IEEE Communication Magazine*, vol. 49, no. 9, September 2011, pp. 56 – 62.

[101] K. D. Dambul, D.C. O'Brien, and G. Faulkner, "Indoor optical wireless MIMO system with an imaging receiver," *Proceedings of the IEEE Photonics Technology Letters* , January 15, 2011, vol. 23, no. 2, pp. 97–99.

[102] J. Vucic, C. Kottke, S. Nerreter, K. Langer and J.W. Walewski, "513 Mbit/s Visible Light Communications Link Based on DMT-Modulation of a White LED," *Journal of Lightwave Technology*, vol. 28, no. 24, December 2010, pp. 3512– 3518.

[103] A. R. Ndjiongue, H. C. Ferreira and T. M. N. Ngatched, "Visible Light Communications (VLC) Technology," *Wiley Encyclopaedia of Electrical and Electronics Engineering*, June 2015, pp. 1 – 15.

[104] M. Kavehrad and P. Amirshahi, "Hybrid MV-LV Power Lines and White Light Emitting Diodes for Triple-Play Broadband Access Communications," Center for Information & Communications Technology Research, The Pennsylvania State

University, IEC Comprehensive Report on Achieving the Triple Play Technologies and Business Models for Success, January, 2006, ISBN: 978-1-931695-37-4.

[105] H. Haas, "Wireless Data from Every Light Bulb," Online: Available at: https://www.ted.com/talks/harald_haas_wireless_data_from_every_light_bulb, Last Accessed on October 25, 2017.

[106] M. Yoshino, S. Haruyamaa and M. Nakagawa, "High-accuracy positioning system using visible LED lights and image sensor," *Proceedings of the IEEE Radio and Wireless Symposium*, Orlando, FL, USA, January 22-24, 2008, pp. 439 – 442.

[107] K. Panta and J. Armstrong, "Indoor localisation using white LEDs," *Electronics Letters*, vol. 48, no. 4, February 2012, pp. 228 – 230.

[108] R. Roberts, P. Gopalakrishan and S. Rathi, "Visible light positioning: automotive use case," *Proceedings of the IEEE Vehicular Networking Conference*, Los Alamitos, CA, USA, December, 2010.

[109] S. Hann, J.H. Kim, S.Y. Jung and C.S. Park, "White LED Ceiling Lights Positioning Systems for Optical Wireless Indoor Applications," *Proceedings of the IEEE European Conference and Exhibition on Optical Communication*, Torino, Italy, September 19-23, 2010, pp. 1 – 3.

[110] W. Zhang and M. Kavehrad, "A 2-D indoor localization system based on visible light LED," *Proceedings of the IEEE Photonics Society Summer Topical Meeting Series*, Seattle, WA, USA, July 9-11, 2012, pp. 80 – 81.

[111] Y. U. Lee and M. Kavehrad, "Long-range indoor hybrid localization system design with visible light communications and wireless network," *Proceedings of the IEEE Photonics Society Summer Topical Meeting Series*, Seattle, WA, USA, July 9-11, 2012, pp. 82 – 83.

[112] A. R. Ndjiongue, T. Shongwe, H. C. Ferreira, T. Ngatched and A. J. Han Vinck, "PSK to CSK Mapping for Hybrid Systems Involving the Radio Frequency and the Visible Spectrum," *Telecommunication Systems*, Springer, US, vol. 64, no. 1, January 2017, pp. 173 – 192.

[113] D. Giustiniano, N. O. Tippenhauer and S. Mangold, "Low-Complexity Visible Light Networking with LED-to-LED communication," *IFIP Wireless Days*, Dublin, Ireland November 21-23, 2012, pp. 1 – 8.

[114] A. R. Ndjiongue, H. C. Ferreira, K. Ouahada and A. J. Han Vinck, "Low-complexity SOCPBFSK-OOK interface between PLC and VLC channels for low data rate transmission applications," *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications*, Glasgow, UK, March 30 - April 2, 2014, pp. 226 – 231.

[115] A. D. Familua, A. R. Ndjiongue, K. Ogunyanda, L. Cheng, H. C. Ferreira and T. G. Swart, "A Semi-Hidden Markov Modeling of a Low Complexity FSK-OOK In-House PLC and VLC Integration," *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications (ISPLC)*, Austin, USA, March 29, 2015, pp. 199 – 204

[116] A. R. Ndjiongue, H. C. Ferreira and T. Shongwe, "Inter-building PLC-VLC integration based on PSK and CSK techniques," *Proceedings of the IEEE International*

Symposium on Power Line Communications and Its Applications, Bottrop, Germany, March 20-23, 2016, pp. 31 – 36.

[117] A. R. Ndjiongue, T. Shongwe, H. C. Ferreira, T. M. N. Ngatched and A. J. Han Vinck, "Cascaded PLC-VLC Channel Using OFDM and CSK Techniques," *Proceedings of the IEEE Global Communications Conference (GLOBECOM)*, San Diego, CA, USA, Dec. 6-10, 2015, pp. 1 – 6.

[118] Z. Weiqiang and X. Dianguo and Chi-Hwan Lee, "Design and performance of digital ballast for HPS lamps," *Proceedings of the Applied Power Electronics Conference and Exposition*, Miami, FL, USA, February 9-13, 2003, vol. 2, pp. 1205 – 1208.

[119] X. Dianguo, M. Yingfeng, L. Xiaosheng and Z. Weiqiang, "Reliable distributed power line communication networks for new public lighting management system," *Proceedings of the IEEE International Conference on Industrial Informatics*, Banff, Alberta Canada, August 21-24, 2003, pp. 73 – 78.

[120] X. Dianguo, M. Yingfeng, L. Xiaosheng and Z. Weiqiang, "Performance of reliable intelligent power line communication network for digital HPS ballast remote monitor and control," *Proceedings of the IEEE Conference of the Industrial Electronics Society,* Banff, Alberta, Canada, August 21-24, 2003, vol. 2, pp. 1267 – 1271.

[121] C. Wang, D. I. Zhang, H. I. Qin, Y.Y. Yao, Y. Sun and Y. Shen, "HPS Street Lighting Lamp Networking over Power-lines," *Proceedings of the IEEE International Conference on Power System Technology*, Chongqing, China, Oct. 22-26, 2006, pp. 1 – 5.

[122] G. B. Maizonave, F. S. Dos Reis, J. C. M. Lima, A. J. Bombardieri, F. E. Chiapetta, G. B. Ceccon, R. R. N. Souza, R. Tonkoski and R. W. Dos Reis, "Integrated System for Intelligent Street Lighting," *Proceedings of the IEEE International Symposium on Industrial Electronics*, Montreal, Que, Canada, July 9-13, 2006, vol. 2, pp. 721 – 726.

[123] D. Brunelli, P. Tosato and R. Fiorelli, "Design and implementation of zero power wake-up for PLC modems in smart street lighting systems," *Proceedings of the IEEE Conference on Emerging Technologies & Factory Automation*, Luxembourg, September 8-11, 2015, pp. 1 – 7.

[124] A. Sittoni, D. Brunelli, D. Macii, P. Tosato and D. Petri, "Street lighting in smart cities: A simulation tool for the design of systems based on narrowband PLC," *Proceedings of the IEEE First International Smart Cities Conference*, Guadalajara, Mexico, October 25-28, 2015, pp. 1 – 6.

[125] E. Liu, Y. Gao, G. Samdani, O. Mukhtar and T. Korhonen, "Powerline communication over special systems," *Proceedings of the International Symposium on Power Line Communications and Its Applications,* Vancouver, BC, Canada, April 6-8, 2005, pp. 167 – 171.

[126] J. Granado, J. Chavez, A. Torralba and A. C. Oria, "Modeling Airfield Ground Lighting Systems for Narrowband Power-Line Communications," *Proceedings of the IEEE Transactions on Power Delivery*, vol. 25, no. 4, September 20, 2010, pp. 2399 – 2405.

[127] C. Li, J. Wu and X. He, "Realization of a general LED lighting system based on a novel Power Line Communication technology," *Proceedings of the IEEE Applied*

Power Electronics Conference and Exposition, Palm Springs, CA, USA, February 21-25, 2010, pp. 2300 – 2304.

[128] Y. S. Lee, Sand-Ui Choi and S. A. S. Mohamed, "An energy efficient extremely low voltage DC-LED lighting system," *Proceedings of the IEEE International Conference on Cybernetics and Intelligent Systems* and *Proceedings of the IEEE Conference on Robotics, Automation and Mechatronics*, Siem Reap, Cambodia, July 15-17, 2015, pp. 25 – 29.

[129] P. Kiedrowski, "Narrowband PLC transmission quality versus brightness dimmable lantern impedance," *Proceedings of the IEEE International Conference on Compatibility and Power Electronics*, Costa da Caparica, Portugal, June 24-26, 2015, pp. 572 – 576.

[130] M. Pikkarainen, S.Vehmasvaara, B. A. Siddiqui, P. Pakonen and P. Verho, "Interference of touch dimmer lamps due to PLC and other high frequency signals," *Proceedings of the IEEE Conference on Electric Power Quality and Supply Reliability*, Tartu, Estonia, June 11-13, 2012, pp. 1 – 6.

[131] H. Kaifeng, X. Weisheng and Y. Youling, "Design of a Fluorescent Lamp Control Platform, Based on Power-line Carrier," *Proceedings of the IEEE International Conference on Electronic Measurement and Instruments*, Xi'an, China, August 16-18, 2007, pp.1-618- 1-621.

[132] 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," *Proceedings of the IEEE Australasian Universities Power Engineering Conference*, Sydney, NSW, Australia, December 14-17, 2008, pp. 1 – 5.

[133] S. K Rönnberg, M. H. J. Bollen and M. Wahlberg, "Harmonic Emission Before and After Changing to LED and CFL — Part I: Laboratory Measurements for A Domestic Customer," *14th Proceedings of the IEEE International Conference on Harmonics and Quality of Power – ICHQP*, Bergamo, Italy, September 26-29, 2010, pp. 1 – 7.

[134] S. K. Rönnberg, M. Wahlberg and M. H. J. Bollen, "Harmonic Emission Before and After Changing to LED and CFL — Part II: Field Measurements for A Hotel," *Proceedings of the IEEE International Conference on Harmonics and Quality of Power – ICHQP*, Bergamo, Italy, September 26-29, 2010, pp. 1 – 6.

[135] S. K. Rönnberg, M. Wahlberg and M. H. J. Bollen, "Harmonic Emission Before and After Changing to LED Lamps — Field Measurements for an Urban Area," *Proceedings of the IEEE International Conference on Harmonics and Quality of Power – ICHQP*, Hong Kong, China, June 17-20, 2012, pp. 552 – 557.

[136] M. H. J. Bollen, S. K. Rönnberg, E. O. A. Larsson, M. Wahlberg and C. M. Lundmark, "Harmonic Emission from Installations with Energy-Efficient Lighting," *Proceedings of the 11th IEEE International Conference on Electrical Power Quality and Utilisation*, Lisbon, Portugal, October 17-19, 2011, pp. 1 – 6.

[137] T. Y. Lee, C. H. Huang, B. H. Wang, C. H. Kang, J. Y. Chen and I. H. Chou, "Energy-saving LED control module for agent-based Micro-Grid systems," *Proceedings of the IEEE International Conference on Consumer Electronics*, Taipei, Taiwan, May 26-28, 2014, pp. 127 – 128.

[138] O. Mukhtar, S. M. Golam, E. Liu and T. O. Korhonen, “Development of high-rate control system for LED based general lighting applications,” *Proceedings of the International Symposium on Power Line Communications and Its Applications*, Vancouver, BC, Canada, April 6-8, 2005, pp. 417 – 421.

[139] R. Han, C. Yang, X. Chen, X. Han, J. Zhang and C. Li, “Design of an Intelligent White-OLED Lighting System using power line communication,” *Proceedings of the International Conference on Consumer Electronics, Communications and Networks (CECNet)*, Yichang, China, April 21-23, 2012, pp. 3191 – 3194.

[140] A. Emleh, A. S. de Beer, L. Cheng, H. C. Ferreira and A. J. H. Vinck, “An Overview of Colour LED & CFL Lighting Interference on the Low Voltage PLC Network,” *Proceedings of the IEEE International Conference on Telecommunications and Signal Processing*, Barcelona, Spain, July 5-7, 2017, pp. 220 – 224.

[141] A. S. de Beer, A. Emleh, H. C. Ferreira and A. J. H. Vinck, “Influence of LED Tubes on the Throughput of an Indoor Broadband PLC Channel,” *Proceedings of the IEEE International Conference on Telecommunications and Signal Processing*, Barcelona, Spain, July 5-7, 2017, pp. 251 – 254.

[142] A. Emleh, A. S. de Beer, H. C. Ferreira and A. J. H. Vinck, “Noise Generated by Modern Lamps and the Influence on the Smart-Grid Communication Network,” *Proceedings of the IEEE International Conference on Smart Grid Communications*, Miami, FL, USA, November 2-5, 2015, pp. 7 – 12.

[143] A. Emleh, A. S. de Beer, H. C. Ferreira and A. J. H. Vinck, “On Mercury Vapor Lamps and Their Effect on the Smart-Grid PLC Channel,” *Proceedings of the IEEE International Conference on Applied Measurements for Power Systems*, Aachen, Germany, September 23-25, 2015, pp. 78 – 83.

[144] A. Emleh, A. S. de Beer, H. C. Ferreira and A. J. H. Vinck, “The Influence of High Pressure Sodium Lamps on the Power Line Communications Channel,” *Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications*, Austin, TX, USA, March 29 - April 1, 2015, pp. 172 – 177.

[145] A. Emleh, A. S. de Beer, H. C. Ferreira and A. J. H. Vinck, “The Influence of Fluorescent Lamps with Electronic Ballast on the Low Voltage PLC Network,” *Proceedings of the IEEE International Power Engineering and Optimization Conference,* Langkawi, Malaysia, March 24-25, 2014, pp. 276 – 280.

[146] A. Emleh, A. S. de Beer, H. C. Ferreira and A. J. H. Vinck, “Effects of Plasma Lamps on the Power-line Communications Channel,” *Proceedings of the IEEE International Symposium on Electronics in Marine*, Zadar, Croatia, September 25-27, 2013, pp. 125 – 128.

[147] A. Emleh, A. S. de Beer, H. C. Ferreira and A. J. H. Vinck, “The Impact of the CFL Lamps on the Powerline Communications Channel,” *Proceedings of the IEEE International Symposium on Power Line Communications and its Applications*, Johannesburg, South Africa, March 24-27, 2013, pp. 225 – 229.

[148] L. Lampe, A. M. Tonello, T. G. Swart, *Power Line Communications: Principles, Standards and Applications from Multimedia to Smart Grid*, Chichester, England: John Wiley & Sons, 2016

[149] Y. Zhao, Y. Dong, X. Lu and N. Jiang, “Measurement and Analysis of Electromagnetic Emissions for Broadband Power Line (BPL) Communication,” *Proceedings of the IEEE International Symposium on Electromagnetic Compatibility (EMC-Beijing)*, Beijing, China, October 28-31, 2017, pp. 1 – 4.

[150] X. Chen, Y. Yi, K. Luan, Q. Sui, F. Zhang and C. Tian, “Impedance Characteristics of Outdoor Low-Voltage Distribution Power Line Communication,” *Proceedings of the IEEE Chinese Automation Congress*, Jinan, China, October 20-22, 2017, pp. 4750 – 4754.

[151] S. Gorshe, A. Raghavan, T. Starr and S. Galli, *Power Line Communications*, Wiley Telecom eBook Chapters, Edition 1, ISBN: 9781118878774, 2014.

[152] M. Tucci, M. Raugi, L. Bai, S. Barmada and T. Zheng, “Analysis of Noise in In-Home Channels for Narrowband Power Line Communications,” *Proceedings of the IEEE International Symposium on Environment and Electrical Engineering and IEEE Industrial and Commercial Power Systems Europe*, Milan, Italy, June 6-9, 2017, pp. 1 – 6.

[153] F. D'Innocenzo, G. Buccim, E. Fiorucci and F. Ciancetta, “Domestic Electrical Standard System for Power Line Communication Tests,” *Proceedings of the IEEE International Symposium on Instrumentation and Measurement Technology*, Turin, Italy, May 22-25, 2017, pp. 1 – 6.

[154] M. De Piante and A. M. Tonello, “Impedance Matching and Channel Capacity in Power Line Communication Systems,” *Proceedings of the IEEE International Symposium on Power Line Communications and its Applications*, Madrid, Spain, April 3-5, 2017, pp. 1 – 6.

[155] CISPR-16: Specification for radio disturbance and immunity measuring apparatus and methods, International Electrotechnical Commission (IEC).

[156] J. M. Alonso, D. Gacio, A. J. Calleja, J. Ribas, and E. L. Corominas, “A Study on LED Retrofit Solutions for Low-Voltage Halogen Cycle Lamps,” *IEEE Trans. on Industry Applications*, vol. 48, no. 5, July 2012, pp. 1673 – 1682.

[157] M. Ghafouri, A. R. Kazemi, P. Dehghanian and M. Vakilian, “Investigation of the Effects of Compact Fluorescent Lamps in Power Distribution Systems,” *Proceedings of the International Conference on Environment and Electrical Engineering*, Rome, Italy, May 8-11, 2011, pp. 1 – 4.

[158] R. C. Perkins and W. M. Honig, “A high-intensity pulsed light source in blue and UV from commercial fluorescent tubes,” *IEEE Photonics Technology Letters*, vol. 3, no. 1, January 1991, pp. 91 – 92.

[159] K. Takahashi, M. Jinno and M. Aono, “The study of electronic ballast for fluorescent lamp with an electronic device given two functions,” *Proceedings of the IEEE Industry Applications Conference. Thirty-Fifth IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy (Cat. No.00CH37129)*, Rome, Italy, October 8-12, 2000, vol. 5, pp. 3382 – 3387.

[160] S. B. Yaakov and M. Shvartsas, “An electronic ballast for fluorescent lamps with no series passive elements,” *Proceedings of the IEEE Applied Power Electronics*

Conference and Exposition, Anaheim, CA, USA, March 4-8, 2001, vol. 2, pp. 670 – 675.

[161] B. Parker, "Plasma Luminescent Art," *The MIT Museum, MIT Institute*, the MIT 150 Exhibition, Jan 2011.

[162] N. Tesla, "Incandescent Electric Light" *United States Patent Office, Patent No. 514170*, February 06, 1894.

[163] C. Jiang, D. Salles, W. Xu and W. Freitas, "Assessing the Collective Harmonic Impact of Modern Residential Loads—Part II: Applications," *IEEE Transactions on Power Delivery*, vol. 27, no. 4, pp. 1947 – 1955, September 2012.

[164] C.E. Shannon, "Communication in the presence of noise." *Proceedings of the IRE,* vol. 37, no. 1, 1949, pp. 10-21.

[165] L. Yonge, J. Abad, K. Afkhamie, L. Guerrieri, S. Katar, H. Lioe, P. Pagani, R. Riva, D. M. Schneider and A. Schwager, "An Overview of the HomePlug AV2 Technology," *Journal of Electrical and Computer Engineering,*Vol. 2013, Article ID 892628, 20 pages, 2013.

[166] J. Anatory, M.V. Ribeiro, A.M. Tonello, A. Zeddam, "Power-Line Communications: Smart Grid, Transmission, and Propagation," Journal of Electrical and Computer Engineering, vol. 2013, ID 948598, 2 pages, 2013.

[167] S. S. Dash, "Application of OFDM over Indoor Power Line Communication," *Proceedings of the IEEE International Symposium on Wireless Communications, Signal Processing and Networking*, Chennai, India, March 22-24, 2017, pp. 240 – 245.

[168] X. Liu, J. Liu, H. Sun, H. Liu and X. Gu, "A Timing Synchronization Method for OFDM Based Power Line Communication," *Proceedings of the IEEE International Symposium on Communication Software and Networks*, Guangzhou, China, May 6-8, 2017, pp. 543 – 547.

[169] C. S. Moo, S. Y. Tang, C. R. Lee, J. H. Chen and W. T. Tsai, "Investigation Into High-Frequency Operating Characteristics of Metal-Halide Lamps," *IEEE Transactions on Plasma Science*, vol. 37, no. 11, September 2009, pp. 2234 – 2240.

[170] T. J. Liang, W. H. Fu, Y. M. Chen and K. H. Su, "High frequency electrical characteristics of various metal-halide lamps," *Proceedings of the IEEE International Conference On Power Electronic Drives and Energy Systems for Industrial Growth*, Perth, WA, Australia, December 1-3, 1998, vol. 2, pp. 694 – 699.

[171] E. L .Corominas, M. R. Secades, J. A. F. Rubiera, J. M. Alonso, A. J. Calleja, J. Ribas and J. Cardesin, "A Novel Low Cost Two-Stage Electronic Ballast for 250W High Pressure Mercury Vapor Lamps Based on Current-Mode-Controlled Buck-Boost Inverter," *Proceedings of the IEEE Applied Power Electronics Conference and Exposition*, Anaheim, CA, USA, March 4-8, 2001, vol. 2, pp. 676 – 682.

[172] G. H. Wilson, E. L. Damant and J. M. Waldram, "The High-Pressure Mercury-Vapour Lamp In Public Lighting," *Journal of the Institution of Electrical Engineers*, September 1936, vol. 79, no. 477, pp. 241 – 264.

[173] W. Wang, W. Zhang, G. Gao and D. Xu, "A study of an electronic ballast for high pressure sodium lamp," *Proceedings of the International IEEE Power Electronics and Motion Control Conference*, Aug. 15-18, 2000, vol. 3, pp. 1056 – 1060.

[174] Y. Matsumoto, I. Wu. K. Gotoh and S. Ishigami, "Measurement and modeling of electromagnetic noise from LED light bulbs," *IEEE Electromagnetic Compatibility Magazine*, vol. 2, no. 4, 4th Quarter, 2013, pp. 58 – 66.

[175] C. Branas, F. J. Azcondo and J. M. Alonso, "Solid-State Lighting: A System Review," *IEEE Industrial Electronics Magazine*, vol. 7, no. 4, December 2013, pp. 6 – 14.

[176] S. Kanno, N. Hirasawa and Y. Akiyama, "A study on the correlation between common mode voltage measured by using CDNE and radiated electromagnetic field strength emitted from LED bulbs," *Proceedings of the IEICE Tech. Rep., EMCJ 2011-12*, December 2011, pp. 13 – 17.

[177] A. Mansoor, W. M. Grady, A. H. Chowdhury, M. J. Samotyj, "An Investigation of Harmonics Attenuation and Diversity Among Distributed Single-Phase Power Electronic Loads," *IEEE Transactions on Power Delivery,* vol. 10, no. 1, January 1995, pp. 467 – 473.

[178] A. Mansoor, W. M. Grady, R. S. Thallam, M. T. Doyle, S. D. Krein, M. J. Samotyj, "Effect of Supply Voltage Harmonics on the Input Current of Single-phase Diode Bridge Rectifier Loads," *IEEE Transactions on Power Delivery*, vol. 10, no. 3, July 1995, pp. 1416 - 1422.