REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

HARMONIC ANALYSIS OF DIMMABLE POWER LEDS FOR STREET LIGHTING

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MSc. THESIS
DEPARTMENT OF ELECTRICAL ENGINEERING
PROGRAM OF POWER PLANTS

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A thesis submitted by Hazem JOUDA in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 21.10.2015 in Department of Industrial Engineering, Systems Engineering Program.

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Hazem Fayek JOUDA

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LIST OF SYMBOLS

Q	Radiant energy
φ	Radiant flux
I	Radiant Intensity or Current or Luminous intensity
L	Radiance or Luminance
E	Irradiance or Illuminance
M	Radiant exitance or emittance or luminous emittance
J	Radiosity
Q_V	Luminous energy
L_V	Spectral radiance

LIST OF ABBREVIATIONS

AMI	Advanced Metering Infrastructure
AMR	Automated Meter Reading
ASC	Adaptive Street lighting Control
CCF	Current Crest Factor
CCT	Correlated Color Temperature
CFL	Compact Fluorescent Light
CRI	Color Rendering Index
DALI	Digital Addressable Lighting Interface
GDL	Gas Discharge Lamp
HID	High Intensity Discharge
HPS	High Pressure Sodium
ICT	Information and communications technology
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
IES	Illuminating Engineering Society of North America
ISL	Intelligent Street Lighting
LED	Light Emitting Diode
PCC	Point of Common Coupling
PLS	Public Lighting System
PQ	Power Quality
ROI	Return of Investment
SPBP	Simple Pay Back Period
SSL	Solid State Lighting
THD	Total Harmonic Distortion

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ABSTRACT

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MSc. Thesis

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Power LEDs have several advantages over the widely HPS lamps used in street lighting. Greater energy efficiency, optical characteristics, white light night vision, long life and light control are better, but the possibly higher harmonic emission from these lamps due to the need of switched mode electronic drives has been mentioned as a drawback. These drives cause high disturbances in harmonics. The study presented here is completely based on measurements. The aim of this master thesis is to investigate the emission of harmonics and power quality of LED street light technology and conduct a comparison between LED lamps. For this aim, a power LED lamp has been tested in laboratory then our results has been compaired with a nother investigated LED lamp results. Dimmable electronic ballast has been used to drive a power LED lamp. LED lamp has been tested with different power levels using dimming on a constant voltage power supply and with different supply voltages on full power level as well. Results are somehow similar to other studies showed broadband spectrum of harmonics in the case of power LED lamps and decreasing in harmonic distortions values with increasing harmonic orders.The purpose of this dissertation is to investigate harmonic generation from two different power LED lamp used in public lighting system (PLS). Measurements of LED lamps are carried out during their start-up and normal operation and results are analyzed. A comparative analysis of active and reactive power and current harmonics (in accordance with the IEC 6000-7-4) is performed for high power Light emitting diode lamps. Harmonic distortion has been studied in depth. The first conclusion to be drawn from outcomes is that 3^{rd}, 5^{th} harmonics are dominant. The remained odd harmonics have the same level. Results also indicate a decrease in the harmonic value with increasing harmonic order, and increase in the harmonic value at half load (60%) compared with full load (100%). Power remains nearly constant when decreasing input voltage so it is perceived that harmonic emissions are decreasing due to increase in total current value.

Key words: Dimmable function, discharge lamp, electric variables measurement, energy efficiency, harmonic analysis, harmonic distortion, light emitting diodes (LEDs), power quality, street lighting.

YILDIZ TECHNICAL UNIVERSITY

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ÖZET

YOL AYDINLATMASINDA AYARLANABILIR GÜÇ LEDLERİNİN HARMONİK ANALİZİ

Hazem JOUDA

Elektrik Mühendisliği Anabilim Dalı

Yüksek Lisans Tezi

Tez Danışmanı: Yrd. Doç. Dr. Mustafa BAYSAL

Yüksek güçlü LED lerin yol aydınlatmasında yaygın olarak kullanılan yüksek basınçlı sodyum buharlı armatürlere göre çeşitli üstünlükler vardır. Yüksek verim, optik karakteristik, gece görüşü için beyaz ışık, uzun ömür ve ışık kontrolunun daha iyi olması bu üstünlüklerden birkaçıdır. Fakat anahtarlamalı elektronik sürücülerin kullanılmasından dolayı yüksek harmonik içermesi eksik yönlerinden birisidir. Bu çalışma tamamıyla ölçümlere dayanmaktadır. Tezin amacı LED li yol aydınlatma teknolojisinin harmonik salınımını incelemek ve LED armatürler arasında kıyaslama yapmaktır. Bu amaçla laboratuvarda bir güç LED armatür test edilmiş ve bir başka LED armatür sonuçları ile karşılaştırılmıştır. LED armatür sürmek için ayarlanabılır (dimlenebilir) elektronik balast kullanılmıştır. LED armatür sabit kaynak geriliminde dimleme yapılarak farklı güç seviyelerinde ve tam güçte farklı gerilim seviyelerinde test edilmiştir. Ölçümler LED in çalışmaya başldığı an ve sürekli hal için alınarak analiz edilmiştir. Aktif – reaktif güç ve harmoniklerin kıyaslamalı bir analizi geçekleştirilmiştir (IEC–6000–7–4 std göre). Harmonik bozulma incelendiğinde 3. ve 5. harmoniklerin baskın olduğu ve diğer tek harmoniklerin aynı seviyelerde olduğu sonucuna varılmıştır. Ayrıca harmonik derecesi artarken harmonik bozulmanın azaldığı ve tüm yüke (%100) kıyasla yarı yükte (%60) harmonik değerlerin arttığı görülmüştür. Gerilim azaldığında güç değerinin aynı kaldığı ve böylece artan toplam akım değerine bağlı olarak harmonik salınımın azaldığı anlaşılmıştır.

Anahtar Kelimeler: Aydınlatma, deşarj lambası, elektrik değişkenlerinin ölçümü, enerji verimliliği, güç kalitesi, harmonik distorsiyon, ışık yayan diyotlar (LED'ler), yol aydınlatması.

CHAPTER 1

INTRODUCTION

1.1 Literature Review

Nowadays saving energy is a crucial issue, due to severe energy crisis. Efficient lighting design of outdoor applications is the main factor to confront energy crisis but it is important for the lighting design scheme to be effective from energy point of view and power quality of distribution system. Consequently, in the public lighting systems it is highly needed to combine between energy consumption of lighting installation and the quality of lighting system. Customers are mainly concerned of the energy saving featured lighting technologies with reasonable prices. Selecting the convenient type of lamps with suitable choice of ballast as well is important to attain an accepted power quality in street lighting. The primary focus of this study is LED lamps for street lighting. Due to the fact that LED lamps make a direct conversion of electrical energy into light it is selected as an energy efficient alternative to the prevailed high intensity discharge lighting lamps. Lighting control is considered an acceptable solution in reducing energy consumption in case it can reduce the lighting levels without compromising user's satisfaction and productivity. It is found that between 30% and 50% of electricity consumed by lighting installations could be saved by investing in energy-efficient lighting systems. Such investments results mostly not only in achieving profits but also in enhancing lighting quality accompanied with reductions in CO_2 emissions [1]. Results [2] show the necessity of encouraging installation of Smart dimmable electronic ballasts receiving switching and dimming commands from street light segment controller. Some measures are proposed for decreasing electrical energy consumed by the public lighting as following [3]: dimming lamps during hours with reduced traffic density, applying the international standards and establishing the light technical parameters based on street classification, adopting a special price for the electric energy consumed by the public lighting during night hours, Enhancing the maintenance method by installing a smart control system based on communication system which in turn minimizes the expenses by better managing the replacement of failed lamps. High pressure sodium lamps are currently the main lamps used in public lighting. However, as a result of their successful development LED based street lighting is getting more and more popular. High efficiency (169 lm/W in 2015) [4], robustness, long life and light control are the main advantages of LED lamps. On the one hand, new lighting technologies are very vital for their overall efficiency in reducing the consumed energy and the operating and maintenance costs. On the other hand, they can provoke power quality problems such as harmonic distortions, losses on the grid and power factor. To sum up, Sustainable lighting technology should meet at least three criteria: (i) high efficiency or energy saving, (ii) long product lifetime and (iii) recyclability [5].

The main factors to keep the energy consumption of a lamp to a low level and the power quality to an acceptable limit are the types of lamps and control gears selected for the lighting installation. After the introduction of high power light emitting diode lamp in market it has become a promising alternative to high pressure sodium lamp. In modern outdoor lighting design LED lamps are hugely used as replacement of HPS lamps. The reason for such revolution is well known and accepted to lighting designers. But apart from their advantages over HPS lamps they have certain disadvantages which have a great impact on power quality of the system.

Researchers who focus on LED lamps are aware of a strong link between the power source and lamp characteristics; such as color temperature, operating power or luminous flux. However, there are hardly any analytic works linking the lamps characteristics with their electrical properties. Little power quality researches have been carried out on high power solid state street lights; more over it is particularly focused on low power LEDs [6-19] and not on high-power LED Street lights. Gil-de-Castro et al [20] carried out a completely measurement Lab work studying power quality of high-power lighting networks based on LED and high-pressure sodium lamps. Both electromagnetic and dimmable electronic ballasts, which can dim the lamp output smoothly and uniformly, have been used connected only to high pressure sodium lamps. High-pressure sodium lamps connected to electronic equipment have been tested with different arc power levels using dimming on a 230V power supply. The study included harmonic currents in the frequency range up to 150 kHz for high-power LED lamps and HPS lamps. Results showed a broadband spectrum in LED lamps with a decrease in the harmonic value with increasing harmonic order, and a decrease in the harmonic value at half load (60%) compared with full load (100%) for HPS lamps while LED lamps have not been dimmed in the study. Even though total harmonic distortion of the current is lower with high-pressure sodium lamps connected to electronic ballast rather than electromagnetic ballasts, the lowest total harmonic distortion was achieved by the LED lamps.

Using different methods on locations (streets) and in laboratory ***Kovas and Varadine*** [21] investigated transient electric behavior of LED lamps and their harmonic emissions. As a result of the investigations a high current distortion and high transient of current are observed.

Trying to introduce a feasible solution for the power consumption of the present wide used HID (HPS and MH) lamps with magnetic ballast ***Rakotomalala et al*** [22] contributed with a simple dimming method for public lighting by controlling the amplitude of rated voltage. The proposed method resulted in about 55% energy saving per lamp dimming for HPS lamp and 52.72% for MH lamp. The restriction of this method to areas where a central autotransformer can be used and THD and CCF fluctuations when the central dimming is applied are drawbacks of the method.

Based on IEEE trial standards for measurement of electric power ***Brenna et al*** [23] conducted a comparison experimental analysis of power quality for different public lighting technologies (GDL and LED) used in a railway station. Investigations involved both onsite and laboratory measurements in different working conditions. The outcome stemmed from this study is in favor of LED systems in terms of energy consumption, operating, and maintenance cost. Also, the study deduced that ballasts are the main reason stands behind the harmonic current content and not the typology of the lamps itself.

Harmonics produced by aggregation of street lamps were analyzed and estimated by ***Gil-de-Castro et al*** [24] referring to harmonic summation methods defined in IEC 61000-3-6. They examined the method basing their work on measured data from HPS lamps connected to electronic ballasts and different LED street lamps connected to the same PCC. The study concluded that the investigated method gives results often different from measurements.

With several experimental tests done in the campus and in the street ***Gil-de-Castro et al*** [25] analyzed both current and voltage harmonics in electromagnetic and electronic ballasts connected to HPS lamps. In the campus only electromagnetic ballasts were used and harmonics from one, two finally three lamps were observed. In the street dimming featured electronic ballast was used with the same three scenarios as well. Then a comparison of both previous experiments was conducted by using the electromagnetic along with electronic ballast, the last one with power set to three levels for one, two and three lamps. Results revealed decrease in the harmonic value as increase the harmonic order, and also the decrease in the value at half load. Also it was found that the harmonic current distortion in a single lamp type is highly dependent on the loading level; at half load it was higher.

1.2 Objective of the Thesis

The vital objective of our study is to provide disturbances investigation of smart street lighting, as well as producing a contribution in creating guidelines to minimize the PQ deterioration.

1. Improve the power quality of the electrical system.
2. Alleviate global warming by reducing CO_2 emissions.
3. Increase the electrical capacity as well as Smart Street lighting cost effectiveness.
4. Achieve technical - Environmental - Economical- Social aspects (TEES- test).

1.3 Hypothesis

The world has suffered from limited resources of energy. It is classified as the first top challenges for 21th century. Conservation of energy is indispensable scenario.

Poor power quality is a real challenge because it wastes energy, affects the electrical capacity and can harm equipment and electrical distribution system.

Harmonic frequencies in the power grid causes frequent power quality problems. And also, Harmonics in power systems result in increased heating in the equipment and conductors. Ultimately, harmonic mitigation is considered the best guarantee for operation of equipment.

Our work is proposed to reduce these problems by studying the effect of voltage value or light dimming level on harmonics components and Total Harmonic Distortion (THD).

Brief description of Chapters is given below:

Chapter 2 covers fundamentals and basic concepts of lighting science.

Chapter 3 explores the nature of street lighting today and presents the background information on the topic. Within this chapter different forms of streets lights and LED technology are presented, including the technical information necessary to understand the differences between different types of street lighting.

Chapter 4 deals with general discussions on harmonics in electrical circuits. It consists of discussions on different types of electrical loads-linear and nonlinear and voltage, current waveforms generated by them are presented in detail. This Chapter also deals with parameters related to power quality of electrical systems. International Standards of harmonic in electrical systems have been tabulated in this chapter. Mathematical method to find out harmonic components and THD from signal waveform has also been described.

Chapter 5 deals with experimental measurements of harmonics generated by commercial electronic ballast manufactured for up to 60W LED lamps. Ballast has been driven at rated supply voltage and at rated current with LED lamp. This chapter also contains experimental results and discussion.

CHAPTER 2

THEORITICAL BACKGROUND

This chapter covers fundamentals of lighting concepts in term of lighting components design as following:

2.1 Science of Lighting

The main two components of lighting design are: (I) Quantity: or the amount of light, specified in terms of luminance and intensity; and (II) Quality: referred to color-rendering properties of a lighting system, the absence or presence of veiling reflections, the effectiveness of a luminaire lighting its intended target, and the amount of glare caused by a lighting system within its sphere of influence. Efficient lighting design requires paying attention to both quantity and quality [26].

2.2 Photometric vs. Radiometric quantities

There are two parallel systems of quantities known as photometric and radiometric quantities. Every quantity in one system has an analogous quantity in the other system. Some examples of parallel quantities include:

- Luminance (photometric) has an analogous radiometric quantity which is radiance.
- Luminous flux (photometric) has a radiometric quantity which is radiant flux.
- Luminous intensity (photometric) has an analogous radiometric quantity which is radiant intensity.

Photometry is the science of light measurement, in terms of its *perceived* brightness to the human eye. In photometry, the radiant power at each wavelength is weighted by a luminosity function that models human brightness sensitivity. While radiometric quantities use un-weighted absolute power. For example, the eye responds much more strongly to green light than to red, so a green source will have greater luminous flux than a red source with the same radiant flux would. Radiant energy outside the visible spectrum does not contribute to photometric quantities at all, so for example a 1000 watt space heater may put out a great deal of radiant flux (1000 watts, in fact), but as a light source it puts out very few lumens. Table 2.2.1 and table 2.2.2 show units of both radiometry and photometry quantities.

Table 2.2.1 S.I. radiometry units

No.	Quantity	Symbol	Unit
1	Radiant energy	Q	Joule (J)
2	Radiant flux	φ	Watt(W)
3	Radiant Intensity	I	Watt per Sterdian (WSr^{-1})
4	Radiance	L	($WSr^{-1}m^{-1}$)
5	Irradiance	E, I	Watt per sq. meter (Wm^{-2})
6	Radiant exitance or emittance	M	Watt per sq. meter (Wm^{-2})
7	Radiosity	J	Watt per sq. meter (Wm^{-2})
8	Spectral radiance	L_v	($WSr^{-1}m^{-3}$) Or ($WSr^{-1}m^{-2}Hz^{-1}$)

Table 2.2.2 S.I. photometric units

No.	Quantity	Symbol	Unit
1	Luminous energy	Q_v	Lumen-second
2	Luminous flux	φ	Lumen (lm)
3	Luminous intensity	I	Candela(cd)

Table 2.2.3 (cont'd)

4	Luminance	L	Candela per sq. meter (cdm^{-2})
5	Illuminance	E	Lux (lm/m^2)
6	Luminous emittance	M	Lux
7	Luminous efficacy		Lumen/watt

2.3 Radiant Energy

The energy transported by electromagnetic radiation when hits an object in its path, it may be absorbed partly or completely and is transformed into some other form. Standard unit of radiant energy is ***Joule***. Radiant flux is always measured by flow of energy per unit time. Standard unit of radiant flux is ***Watt*** (joule/sec).Our case of interest is of course the energy transported by electromagnetic radiation within the spectral band visible to human eye. While radiation is discussed in our environment, it is conventional to express it in terms of electromagnetic waves having different wavelengths (λ) and corresponding frequencies (f). Electromagnetic radiation can be of any wavelength (or frequency). Based on this property, it is classified in different names of different ranges of wavelengths as shown in figure 2.1 below.

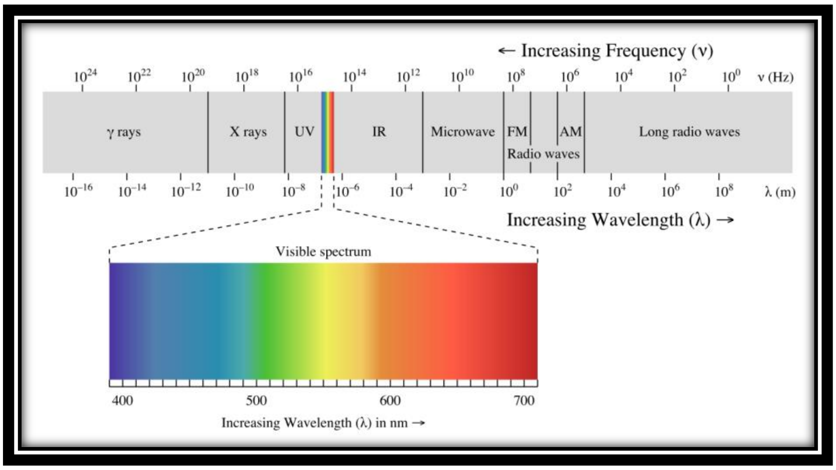


Figure 2.1 Electromagnetic spectrum [37]

2.4 Electromagnetic Spectrum and Visible Light

The visible spectrum is the visual portion of the electromagnetic spectrum and includes the wavelengths between 380 – 760 nm (nanometers). Different wavelengths of energy are perceived as different colors, as summarized in Table 2.4.1.

Table 2.4.1 Color versus Energy Wavelength

Color	**Wavelength (**nanometer**)**
Red	**760 – 630**
Orange	**630 - 590**
Yellow	**590 - 560**
Green	**560 - 490**
Blue	**490 - 440**
Indigo	**440 - 420**
Violet	**420 - 380**

2.5 Spectral Sensitivity of Eye

Spectral sensitivity is the relative efficiency of detection, of light or other signal, as a function of the frequency or wavelength of the signal. In visual neuroscience, spectral sensitivity is used to describe the different characteristics of the photo pigments in the rod cells and cone cells in the retina of the eye. It is known that the rod cells are more suited to scotopic vision and cone cells to photopic vision, and that they differ in their sensitivity to different wavelengths of light. Emitted radiation by light sources is differently perceived by the eye depending on the wavelength of light wave. When wavelength is 555 nm it appears brightest and the sensitivity changes for the eye from 380 nm to 780 nm. The variation of sensitivity is shown in curves of Fig 2.5.1.

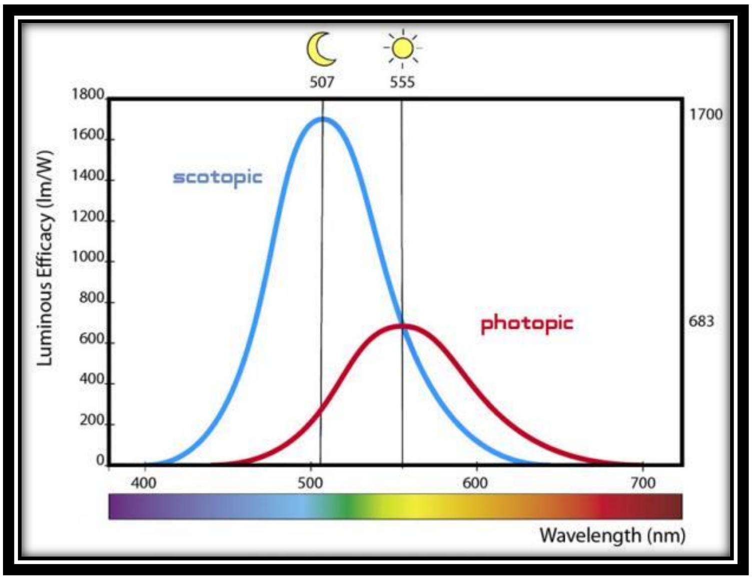


Figure 2.5.1 Relative spectral distribution curves [38]

2.6 Radiant Flux:

Total radiation emitted or received by a body or transmitted through an enclosed area in space which is measured in Watt.

2.7 Spectral Radiant Flux:

It is important to measure flux per unit wavelength to represent such distribution of flux over wavelengths. The value of flux obtained against corresponding wavelength is called *spectral radiant flux* and is denoted by φ unit of which is Watt per nm (W nm-1). The spectral radiant flux is plotted against wavelength, and then the area under curve (Fig. 2.7.1) is the total radiant energy with a specific waveband.

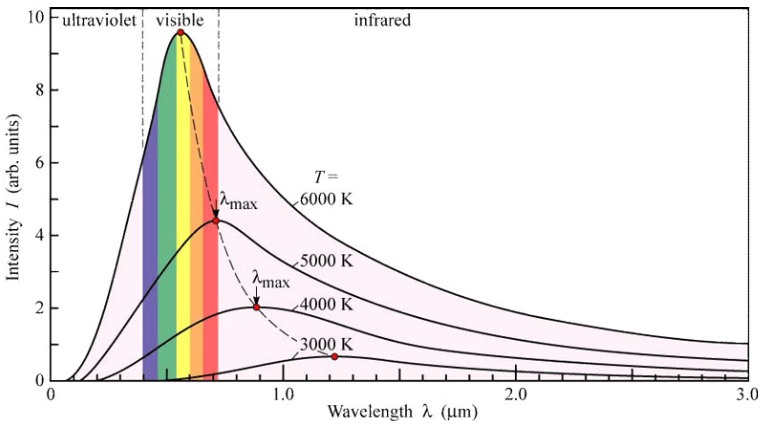


Figure 2.7.1Spectral Radiant Curve [39]

2.8 Measurement Units of Light (Photometric parameters)

Lumen is the unit measure of flux (φ) which is the amount of total light output from a luminaire. Because the actual light sources are not omnidirectional its radial pattern is specified by the Intensity (I) which is the amount of lumens being emitted at a given angle in a specified direction and measured in lumens per sterdian. The relationship between flux and intensity is determined in the following equation:

$$\boldsymbol{I} = \frac{\boldsymbol{\varphi}}{\boldsymbol{4\pi}} \tag{2.1}$$

2.9 Illuminance:

The amount of light that strikes a surface or an area is called *Illuminance* (E).Standard unit of illuminance is **Lux** which is foot-candles (Lm/Sq. foot) or **lumen per square meter** (Lm/m²).Table 2.4 shows some typical illuminance values. If φ lumen flux is incident on an area of 'A' m^2, then illuminance E is given by:

$$E = \frac{\varphi}{A} \tag{2.2}$$

Illuminance has a relationship with the intensity as follows:

$$E = \frac{I\cos\theta}{r^2} \tag{2.3}$$

Where r: is the distance between the light source and the point where the illuminance is being specified. **θ**: Denoting the angle between the normal of the surface and the line connecting the source and the point where the illuminance being specified as shown in figure 2.9.1. Table 2.9.1 also shows some standard illuminance values of different lights.

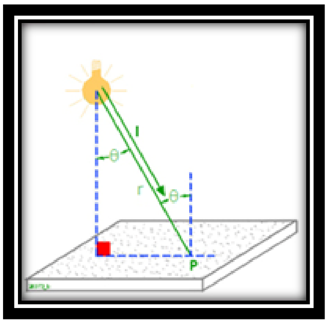


Figure 2.9.1 Illuminance of a light [40]

Table 2.9.1 Some standard illuminance values

No.	Quantity	Illuminance
1	Full moon	1 lux
2	Street lighting	10 lux
3	Workspace lighting	100-1000 lux
4	Surgery lighting	10,000 lux
5	Plain sunshine	100,000 lux

Luminance is a photometric measure of the luminous intensity per unit area of light travelling in a given direction. The light leaving the surface can be due to reflection, transmission or emission. The luminance indicates how much luminous power will be detected by an eye looking at the surface from a particular angle of view as shown in figure 2.9.2.

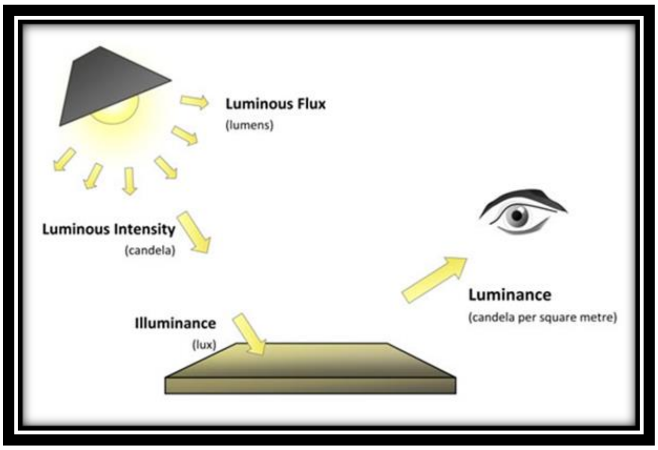


Figure 2.9.2 Luminance, Illuminance, Luminous intensity and Luminous flux [41]

The luminance equation is defined as:

$$L = E\frac{\rho}{\pi} \quad (2.4)$$

Whereρ: the reflectance of the surface. Standard unit of Luminance is **candela per square meter** (cd/m^2).

2.10 Luminous Exitance:

It is the total amount of visible light leaving a point on a surface into all directions above the surface. Therefore luminous exitance is equivalent to *radiant exitance* weighted with the response curve of the human eye. Unit of luminous exitance is lumen per square meter (lm/m^2).

2.11 Solid Angle:

The angle that is seen from the center of a sphere includes a given area on the surface of that sphere. The value of the solid angle is numerically equal to the size of the area divided by the square of the radius of the sphere. It is a measure of how large that object appears to an observer looking from that point. A small object nearby may subtend the same solid angle as a larger object farther away. An object's solid angle is equal to the area of the segment of unit sphere (centered at the vertex of the angle) restricted by the object. A solid angle equals the area of a segment of unit sphere in the same way a planar angle equals the length of an arc of unit circle. Standard unit of solid angle is *Sterdian* (S_r). Solid angle is depicted in figure 2.11.1.

$$\Omega = \frac{A}{r^2} \tag{2.5}$$

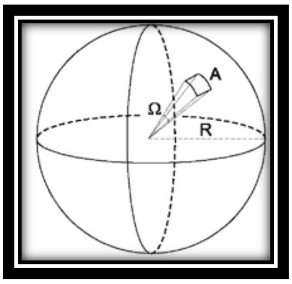


Figure 2.11.1 Solid Angle [42]

2.12 Luminous Intensity:

The *luminous intensity* is the luminous flux emitted from a point per unit solid angle into a particular direction. Standard unit of luminous intensity is *Candela (cd)* and it is also expressed as Lumen per sterdian (lm/Sr). Luminous intensity is described in details in figure 2.12.1.

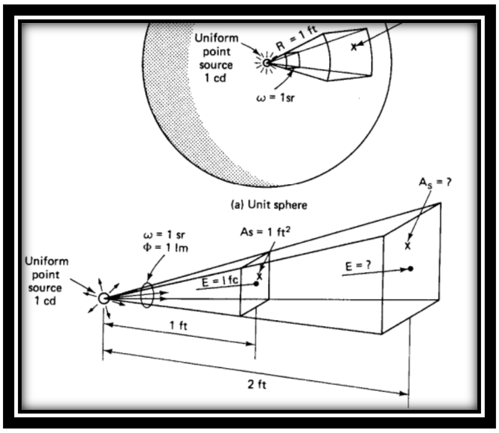


Figure 2.12.1 Luminous Intensity [43]

2.13 Beam Angle:

The ***Beam Angle*** is the angle between the two directions opposed to each other over the beam axis for which the *luminous intensity* is half that of maximum luminous intensity as shown in figure 2.3.1.

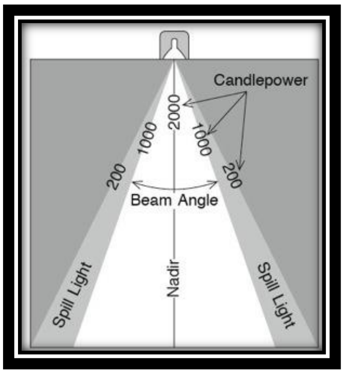


Figure 2.13.1 Beam Angle [44]

2.14 Color Rendering Index:

The color rendering index (CRI): describes a different characteristic of the light source – not how the source itself appears, but rather how well object colors appear under that light source compared to its color appearance under a reference light source. It is expressed on a scale of 1 to 100 where 100 represent the color rendering of daylight as shown in table 2.14.1.

Table 2.14.1 Color Rendering Index

Parameter	Color Rendering Index
Color matching	91 - 100
Good color rendering	81- 90
Moderate color rendering	51 - 80
Poor color rendering	21 - 50

2.15 Correlated Color Temperature:

Correlated color temperature (CCT): Color temperature of a light source is the temperature of an ideal black-body radiator that radiates light of comparable hue to that light source. Standard unit of Color Temperature is Kelvin and it identifies the 'warmness' or 'coolness' of the light color. Cool light is preferred for visual tasks because it produces higher contrast than warm light. Warm light is preferred for living spaces because it is more flattering to skin tones and clothing. Typical color temperature values of different sources are shown in table 2.15.1.

Table 2.15.1 Typical color temperature values of different sources

Type of Light	Color Temperature in K
Candle Flame	1,500
Incandescent	3,000
Sunrise, Sunset	3,500
Midday sun, Flash	5,500
Bright sun, Clear sky	6,000
Cloudy sky, shade	7,000
Blue sky	9,000

2.16 Glare

Glare is an interference with visual perception caused by an uncomfortably bright light source or reflection or any form of visual noise.

Finally, an important concern when comparing quality of two types of lamps is *Efficacy*. Efficacy is the ratio between the total emitted luminous flux by a source and the total power input to the source.

2.17 Light Pollution

The scene of lights seem to illuminate the sky that can be seen many miles away from a large metropolitan area is the effect called *light pollution*, is the cumulative result of hundreds, thousands, even tens of thousands of poorly designed and improperly placed streetlights, billboard and roadside lights, commercial and industrial building lights, and residential lights. Figure 2.17.1 offers dramatic testimony to the wastefulness of outdoor lighting. It is difficult to prove from this photo that outdoor nighttime lighting is primarily designed to shine downward!

Figure 2.17.1 Light pollution in city [45]

Since the energy crisis of the 1970s, exterior lighting has gained increasing importance as a key component of environmental design. In the past, poor lighting design could be compensated for by increased lighting levels, but the present day awareness of energy conservation has created a need to use nighttime light wisely and efficiently. While it was once acceptable to use approximately 35 watts per square meter to illuminate a building exterior, current guidelines nowadays are considering mandatory limits of 10 watts per square meter. The efficient and effective use of outdoor lighting can offer major energy and cost savings. New, much improved light fixtures, or *luminaires*, are now available which provide considerably more light per unit of energy consumed. Most new fixtures offer better light control, aiming the light downward toward the ground where it is needed rather than wasting it by letting it scatter upward and skyward. Replacement of older fixtures with new luminaires can greatly improve efficiency.

CHAPTER 3

STREET LIGHTING

Through thischapterwepresentseveralsubjectsthatrelatedwithstreetlighting. It is reviewed as difference between conventional and Smart Street Lighting, structure of conventional street lighting structure of Smart Street lighting system comparison difference street lighting technologies.

3.1 Conventional Lighting System

Generally, a Street light is a raised source of light on the edge of a road or walkway, which is turned ON at a certain time every night. Street light is placed on the road to make visible everything on the road at night to prevent accidents and to increase safety of people. Artificial lights are required to light streets during night time after the absence of the main natural source of light which is the sun. There are several kinds of light bulbs available. These light sources can broadly be classified as follows:

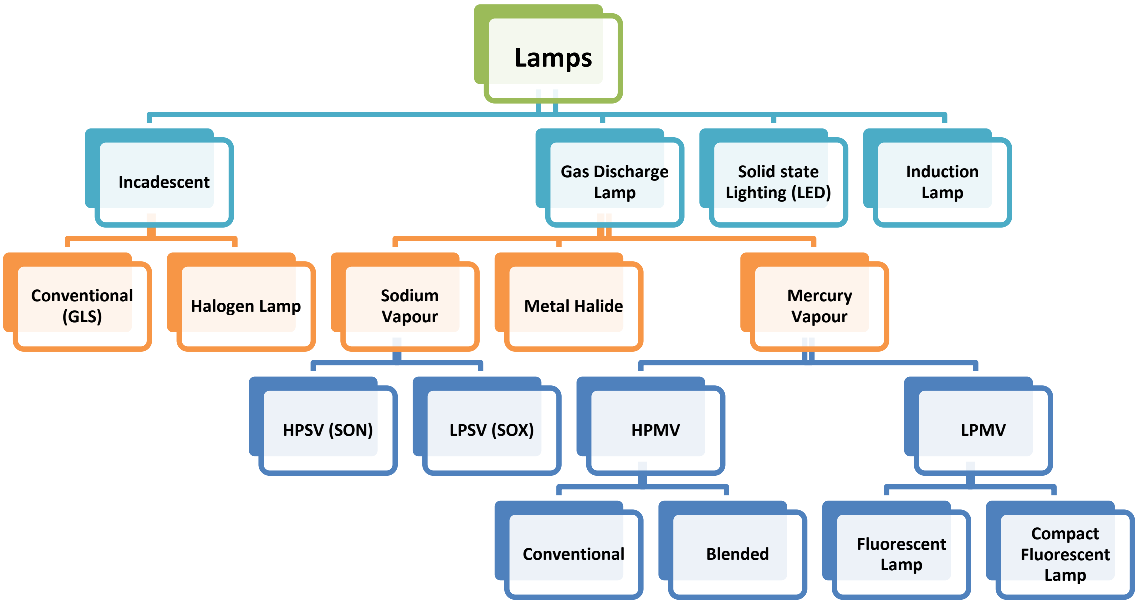


Figure 3.1.1 Classification of light sources [46]

- **Incandescent:** the most common light bulb in the house until about 2003.
- **Gas discharge lamp**: Principle of operation depends on generating light by sending an electrical discharge through an ionized gas. Fluorescent lights and compact fluorescent lights (CFLs) have now replaced incandescent light bulbs in the house, due to the fact that they convert electrical power into useful light more efficiently than an incandescent lamp. Fluorescent lamp is more costly because it requires a ballast to regulate the flow of current through the lamp. Typically, such lamps use a noble gas (argon, neon, krypton and xenon) or a mixture of these gases. Most lamps are filled with additional materials, like mercury, sodium, and metal halides. In operation the gas is ionized, and free electrons, accelerated by the electrical field in the tube, collide with gas and metal atoms. Some electrons circling around the gas and metal atoms are excited by these collisions, bringing them to a higher energy state. When the electron falls back to its original state, it emits a photon, resulting in visible light or ultraviolet radiation. Ultraviolet radiation is converted to visible light by a fluorescent coating on the inside of the lamp's glass surface. Gas-discharge lamps offer long life and high light efficiency.
- **Low Pressure Sodium:** It is the most efficient light source which is used in street lighting. LPS lamp is producing a monochromatic orange-yellow light and is also a good way to reduce sky glow. The drawback of this lamp is only CRI. Everything

around it looks yellow-orange when the lamp is in ON position and it uses more wattage as the age of lamp increases.

- **High Intensity Discharge:** It requires an external ballast to operate. It takes 3 to 5 minutes to reach its full intensity. The lamp will be shut off if there is a dip in electricity. HPS must cool sufficiently to restrict, which usually takes about 1 minute to 10 minutes. HPS lamps are of following types:
  - **Mercury vapor:** It is a high intensity discharge lamp. It uses an arc through vaporized mercury in a high pressure lamp to create a weaker light that mainly creates UV light to excite the phosphors. Lamps have a good efficiency and Color rendering is better than that of high pressure sodium street lights.
  - **Metal halide:** It consists of an arc tube with an outer bulb. It may be made of either quartz or ceramic and contains an argon gas, mercury and metal halide salts. Traditional quartz MH arc tubes are similar in shape to mercury vapor arc tubes, but they operate at high temperatures and pressures. They are more energy efficient than mercury vapor and greater lumen output.
  - **High pressure sodium:** It is the most common lamp for street lighting and this is an improvement over the LPS lamp i.e. it has a more CRI with greater efficiency of a sodium lamp.

3.1.1 High-pressure sodium (HPS) lamps

They are smaller than low pressure sodium lamps and contain mercury, and produce a dark pink glow when first struck, and a yellowish orange light when warmed. Some bulbs also briefly produce a pure to bluish white light in between. This is probably from the mercury glowing before the sodium is completely warmed. The sodium D-line is the main source of light from the HPS lamp, and it is extremely pressure broadened by the high sodium pressures in the lamp; due to this broadening and the emissions from mercury, colors of objects under these lamps can be distinguished. HPS Lamps are favored by indoor gardeners for general growing because of the wide color-temperature spectrum produced and the relatively efficient cost of running the lights.

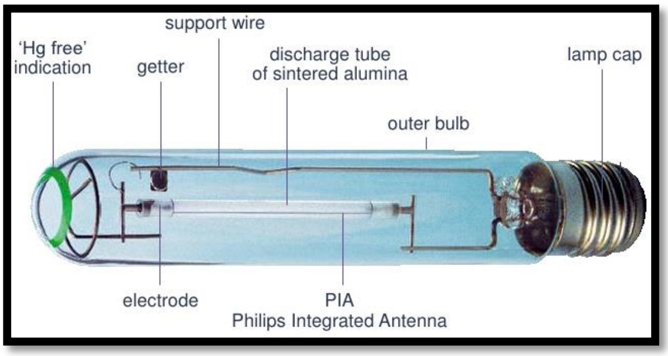


Figure 3.1.2 Construction of HPS Lamp [47]

3.1.1.1 The principal parts of SON lamps are:

- Discharge tube and supports
- Electrodes and feed through
- Filling
- Outer bulb

The material of sintered discharge tube of the high-pressure sodium lamp is polycrystalline alumina tubing, or PCA. Its imperviousness to sodium vapor (1500 K) with melting point of (2300 K), transparency and gas-tight, reasonable resistance to thermal shock, all of which have made it the ideal manufacturing material of SON lamps charge tubes. Electrodes consist of a rod of tungsten with a tungsten coil wound round it in two layers. They are coated with an emitter material, consisting of a mixture of yttrium, barium and calcium oxides. The discharge tube of a standard high-pressure sodium lamp contains some tens of milligrams of sodium-mercury amalgam, which is partially vaporized when the lamp attains operating temperature. The sodium content of the amalgam is of the order of 20%. The non-vaporized amalgam collects in the coolest part of the discharge tube, usually in the space behind one of the electrodes. The discharge tube is operated within an outer bulb to protect the electrical evacuated feed through at each end of the tube, as these react readily with oxygen or water vapor at high temperatures. The outer bulb may be filled with an inert gas, or simply evacuated. The latter is usually preferred as this conserves the thermal energy of the discharge tube much better than does a gas filling. The vacuum must, of course, be maintained throughout the life of the lamp, and to this end the inner surface of the outer bulb near the cap is provided with a getter mirror of barium metal. This serves to absorb the gases liberated by the various lamp components during the life of the lamp, especially hydrogen as this could otherwise diffuse through the niobium feed through into the discharge tube and so produces an increase in the lamp voltage.

3.1.1.2 Principle of operation of HPS lamp

An amalgam of metallic sodium and mercury lies at the coolest part of the lamp and provides the sodium and mercury vapor in which the arc is drawn. The temperature of the amalgam is determined to a great extent by lamp power. The higher the lamp power, the higher will be the amalgam temperature. The higher the temperature of the amalgam, the higher will be the mercury and sodium vapor pressures in the lamp. At a sodium pressure of approximately 0.5 Pa - the working pressure of a SOX lamp - nearly all visible radiation is emitted in the sodium D-lines (589 nm and 589,6 nm). It is at this low pressure that the highest luminous efficacy is obtained. With increasing pressure, a phenomenon that is called self-absorption will gradually develop. The radiation generated in the core of the discharge is absorbed by the surrounding cooler gas and re-emitted, partly in the form of heat and partly in the form of new (resonance) lines at both sides of the D-lines, which become weaker. At the same time, the luminous efficacy drops steeply, until a minimum is reached at 75 Pa. At the same time, the process of self-absorption has advanced so far that the sodium D-lines has now completely disappeared. In their place there is a narrow gap in the spectrum, of about 10 nm width. This effect is called 'self-reversal' of the sodium D-lines. At 10 kPa, the pressure in the standard SON lamp, the resonance bands cover a substantial part of the long-wave end of the visible spectrum. The result is a lamp with a golden-yellow light color, some degree of color rendering (Ra = 23) and the highest possible luminous efficacy for a high-pressure sodium lamp (120 lm/W for the 400 W lamp). A further increase in sodium vapor pressure will result in a widening of the self-reversal gap. The spectrum now consists of two maxima- produced by the resonance bands - separated by a dark region. As it is just in this region that the eye sensitivity is the highest, this will cause the luminous efficacy to drop again. On the other hand, color rendering will improve, as the radiation further spreads to the red and blue ends of the spectrum. At sodium pressure of about 40 kPa the width of the self-reversal gap has increased to approximately 25 nm. It is here that a favorable compromise between a moderately high luminous efficacy (90 lm/W) and fairly good color rendering (Ra = 60) is found.

Increasing the sodium vapor still further, to about 95 kPa, results in a widening of the for self-reversal gap to about 45 nm. The dark region now fills almost the whole yellow waveband, whereas, at the same time, the spectral distribution in the other wavebands becomes quasi-continuous. The characteristic yellow color appearance of the sodium discharge has completely disappeared and the color rendering index has increased to a maximum value of about 80. All this however, is at the consequence of a further drop in luminous efficacy. Any further increase of the sodium vapor pressure is no longer worthwhile, as the self-reversal gap will only become wider and cause the Ra to drop again, together with the luminous efficacy.

3.1.1.3 Quality parameter of HPS lamp

HPSV lamps do not have good color rendering index which restricts its usage areas. This is the main disadvantage of SON. But it offers high luminous efficacy in the range of 80-150 lm/watt. The CRI of the lamp is improved by using *xenon* as inert gas. Its pink reddish improves CRI of the lamp to 25. The other qualitative parameter of the lamp is its life. The main reason of shorter life of the lamp is the leakage of sodium amalgam from the arc tube. So a new technology is used to increase the life of the lamp by adding an amalgam reservoir to the top of the arc tube. It feeds the arc tube with amalgam and hence increases the life of the lamp. In another version, two separate arc tubes are used in the lamp. At a time only one arc tube operates but in case of power interruptions, the second arc tube operates with re-striking time less than 2 minutes. Some other features are:

- The new *Zirconium* in the lamp ensures a higher quality of vacuum in the other bulb than with other getter systems.
- The new Reliable Starting Technology, GRS, improves the starting characteristics by permanently bonding an electrically conductive ceramic to the arc tube surface.
- Higher ceramic transparency manufactured to improve the light output.
- The body and the end plug is now a single unit.
- ‘Extra Output’ lamps always retain the sodium amalgam at the monolithic end.
- This feature reduces the undesirable chemical reactions and end blackening.

3.1.1.4 Applications of HPS lamp

High pressure sodium vapor lamps are quite efficient, efficacy is about 150 Lm/w. These are widely used for outdoor lighting such as street lighting and security lighting. SON finds wide range of application in Horticulture, industrial shed lighting, area lighting for flood lighting.

3.1.2 METAL HALIDE LAMP

Metal halide lamps, a member of the High Intensity Discharge (HID) family of lamps, produce high light output for their size, making them a compact, powerful, and efficient light source. By adding rare earth metal salts to the mercury vapor lamp, improved luminous efficacy and light color is obtained. Like most HID lamps, metal halide lamps operate under high pressure and temperature, and require special fixtures to operate safely. Since the lamp is small compared to a fluorescent or incandescent lamp of the same light level, relatively small reflective luminaires can be used to direct the light for different applications.

3.1.2.1 CONSTRUCTION

At first sight, metal halide lamps look like high-pressure mercury lamps. However, there are clear differences. The main parts of the lamps are:

- Discharge tube.
- Electrodes.
- Outer bulb.
- Fillings.
- Lamp cap.

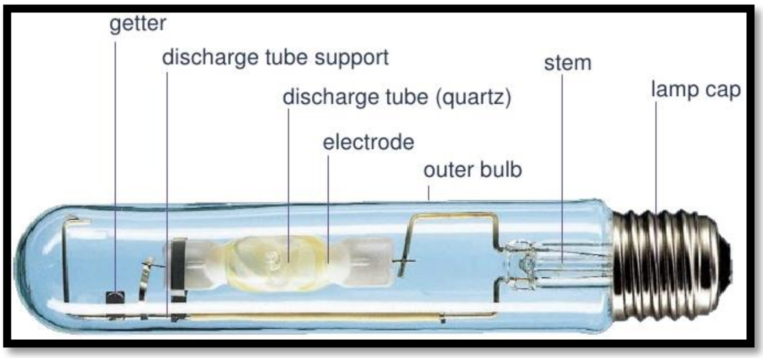


Figure 3.1.3 Construction of Metal Halide lamp [48]

The discharge tube is of pure quartz and must be so shaped that all the light emitted is of the right color and that the color is consistent. This implies, for instance, that the place where the iodides are deposited must be hot enough. Of course, this temperature depends on the cocktail used, but it is usually far in excess of 900 K. The maximum temperature allowed for quartz is approximately 1200 K, for above this temperature re-crystallization will occur. The zirconium oxide applied to the outside of the electrode chamber serves to increase the wall temperature at this point. In those places where this coating is not strictly necessary, it is dispensed with, since it has an adverse effect on the light output. Just like the electrodes of the high-pressure mercury lamps those of the metal halide lamps consist of three parts, namely:

1. The lead-out rod forming the connection outside the discharge tube;

2. The molybdenum foil, which provides a gas-tight seal in the quartz between the lead-out rod and the electrode.

3. The electrode itself. In HPI lamps, thorium oxide is used as emitter.

This is applied as a pellet in the electrodes. In scandium lamps, thorium iodide is added to the filling and rare-earth lamps have krypton85 added to the fill gas to facilitate ignition.

Just as in the higher wattage mercury lamps, the glass outer bulb of HPI lamps is made of hard glass, either tubular in shape (un-coated) or ovoid and coated. Double-ended MHN-TD and MHW-TD lamps have the outer bulb made of quartz. Again, just as in the mercury lamp, the inner surface of the ovoid bulb is coated with europiurn-activated yttrium vanadate phosphor to convert the ultraviolet radiation from the discharge into visible

radiation. However, the halides employed in the metal halide lamp produce only a small amount of ultraviolet radiation, in the long-wave ultraviolet region of the spectrum (viz. 300 - 350 nm) where conversion into visible radiation is poor. The fill-gas of the discharge tube consists of a mixture of two rare gases, namely neon and argon, or krypton and argon, with a cold tilling pressure of4000 to 5000 Pa. The disadvantage of using neon as a fill-gas is that diffuses through the quartz wall of the discharge tube. Measures have therefore to be taken to prevent the discharge tube from emptying. Therefore, neon is also introduced into the outer bulb. Besides the fill-gas, mercury and certain metal iodides are admitted to the discharge tube. The type of metal iodides used depends on the lamp type. The outer bulb of a metal halide lamp whose discharge tube is filled with neon-argon mixture, must also be filled with neon so that the neon pressure inside and outside the tube is the same. If the discharge lube is filled with krypton-argon mixture, nitrogen can be used in the outer bulb, or the outer bulb can be evacuated. Hydrogen, which can be formed by decomposition of the water vapor present in the lamp, has an adverse effect on the lamp properties (rise in arc voltage and decrease in light output). For this reason, a getter is used in the outer bulb to chemically bind any escaping hydrogen. This getter is made of zirconium-aluminum or zirconium-nickel. There are a great variety of caps for the metal halide lamp. The type of cap used depends on the type of lamp. In general, E40 caps are used except for the double-ended lamps. For these, R7s or Fc2 lamp contacts are used. The ceramic, insulated cap is generally used for those lamps, which employ an igniter. The ignition pulse may vary between ca. 600 V and ca. 5000 V. Using glass instead of ceramic insulation increases the risk of arcing. This is therefore only used for lamps with a built-in ignitor, for instance the Philips HPl-BUS lamps. The high wattage lamps (greater than 1 kW) have an E40cap with a second ceramic insulation ring. This cap is designatedE40/80x50. The ring is employed to avoid making the upper half electrically conducting, with the consequent risk of electric shock. The lamps that are suitable for immediate re-ignition have another connection on the other side of the lamp, to which a high voltage of 60 kV can be applied.

3.1.2.2 PRINCIPLE OF OPERATION

When a metal halide lamp first starts, the spectrum is initially that of the mercury vapor, since the halides remain un-vaporized on the relatively cool wall of the discharge tube. As the wall temperature increases, the halides melt and vaporize. The vapor is carried into the hot region of the arc by diffusion and convection, where the halide compound is dissociated into the halogen and metal atoms. Different halides dissociate at different temperatures. The metal atoms become excited in the hot core of the discharge and radiate their appropriate spectrum. They then move nearer the cooler wall of the tube, where they recombine with the halogen atoms to once again to form the halide compound. The whole cycle then repeats itself. The high-pressure mercury lamps can be simply ignited by means of an auxiliary electrode, partly because the electrodes carry an electron emissive coating and also because the vapor mixture in the cold lamp is such that an ignition voltage of less than 200 V is sufficient. However, in a metal halide lamp things are different. Because of the chemical activity of the lamp filling, normal emitter materials cannot be used, and the discharge tube of this lamp contains electro-negative iodine so that the electrons are removed from the discharge. The lamp will therefore at least be very difficult to ignite without special aids. In addition, the electrodes are often coated with iodides that reduce their power to emit electrons. Sometimes, when special measures are taken to avoid soiling of the electrodes with iodides, it is possible to ignite smaller lamps without an external igniter, but with an auxiliary electrode. This is the case for HPI-BUS lamps. After ignition of the lamp, the other metal compounds and the mercury in the discharge tube will evaporate and dissociate and generate light as a result of the current flow. This process lasts a few minutes. During this time the color changes until, at the end of the run-up period, the final color point is reached. If there is an interruption in the supply voltage and the lamp extinguishes, it will take approximately 10 to 20 minutes before the pressure within the lamp has fallen enough for it to be re-ignited by its own igniter. Immediate re-ignition is possible with rare-earth (dysprosium and thulium) lamps by applying a very high (typically 60 kV) voltage pulse. As normal single-ended lamp caps are insufficiently well insulated for such a high voltage, this is only possible with double-ended (e.g. MHN) lamps, or with lamps provided with a special top cap for re-ignition. These lamps can only be used in special luminaires. Three-color (HPI) lamps cannot be reignited in this way, as the excess of Nal present would provide a conductive path for the re-ignition pulse.

3.1.2.3 QUALITY PARAMETER

The orientation of metal halide lamp during operation can have a major influence on its performance. In most cases the preferred orientation places the long axis of the discharge tube horizontally, regardless of lamp design parameters. The horizontal orientation enables the lamp to exhibit almost symmetrical thermodynamic characteristics in which a uniform change in temperature occurs from the two hot spots near the electrodes down to the ends of the shafts. In a vertical position, the electrodes often acquire an uneven temperature balance which compromises lamp performance. The metal halide lamps have a high lumen depreciation; higher, for instance, than that of the high-pressure mercury lamps. This is mainly due to the high degree of blackening of the discharge tube. Since the electrodes, from a thermal point of view, are very heavily loaded, the evaporation of the tungsten, and consequently the blackening of the discharge tube, is very pronounced. For coated lamps, depreciation of the fluorescent powders also plays a role.

3.1.2.4 APPLICATION

Metal Halide lamps have huge range of applications due to good CRI, wattage flexibility and good efficacy. Metal halide lamps are used both for general lighting purposes, and for very specific applications which require specific UV or blue-frequency light. Due to their wide spectrum, they are used for indoor growing applications, in athletic facilities and are quite popular with reef aquarists, where high intensity light source for their corals is needed. It has wide application in sports lighting, area lighting or flood lighting. Miniature forms of lamps with lower wattage are commonly used in Retail lighting, Corridor lighting, Architectural lighting, Façade lighting etc.

3.2 Modern Lighting

Although light emitting diodes, or LEDs, were developed in the early 1960s as indicators, *Indication* means the type of light usage where the source of light is viewed as an object by itself (e.g.: signals, signs, and indicator lights on electronic equipment), the wider adoption of LED lights for different applications started only in the last decade of the 20th century after Nakamura introduced white light LED in the mid-1990s.Rapid technological advances in the early 21st century expanded the usage of LEDs to the illumination purposes in a variety of applications, including the LED based streetlights. Solid-state lighting (SSL) refers commonly to light emitted by solid-state electroluminescence (LEDs), as opposed to incandescent bulbs (which use thermal radiation) or fluorescent tubes, organic light-emitting diodes(OLED), or polymer light-emitting diodes (PLED) as sources of illumination rather than electrical filaments, or gas. Compared to incandescent lighting, SSL creates visible light with reduced heat generation or parasitic energy dissipation. Most common "white" LEDs convert blue light from a solid-state device to an (approximate) white light spectrum using photoluminescence, the same principle used in conventional fluorescent tubes. In recent years, efficacy and output have risen to the point where LEDs are now being used in niche lighting applications. Indicator LEDs are known for their extremely longer life, up to 100,000 hours, but lighting LEDs are operated much less conservatively (due to high LED cost per watt), and consequently have much shorter lives than indicator LEDs. Due to the relatively high cost per watt, LED lighting is most useful at very low powers; typically for lamp assemblies of fewer than 10 W.LEDs are currently most useful and cost-effective in low power applications, such as night lights and flashlights. Colored LEDs can also be used for accent lighting, such as for glass objects. They are also being increasingly used as holiday lighting. LED efficiencies vary over a very wide range. Some have lower efficiency than filament lamps, and some significantly higher. LED performance in this respect is prone to being misinterpreted, as the inherent directionality of LEDs gives them a much higher light intensity in one direction per given total light output.

3.2.1 Light Emitting Diode Lamps:

LED technology is useful for lighting designers because of its low power consumption, low heat generation and instantaneous on/off control. LEDs have become the driving force in the evolution of street lighting. The combination of improved night time visibility and safety, reduced maintenance/operational costs, no toxic chemicals and a decrease in carbon emissions have made LED lighting systems, a top consideration for municipalities and utility companies everywhere. Roadway lighting covers a broad range of locations, from low-traffic residential neighborhoods and rural roads. All have their own requirements for acceptable light levels and distribution patterns and this is where LED street light systems with “smart control” can be the most effective. The light can be easily controlled with intelligent systems. The light can be turned on and off instantly and can be dimmed for added energy savings at dawn, dusk, and also during hours of low traffic. LED lights contain no toxic materials and are 100% recyclable. Because of their long life, they can significantly reduce landfills and bulb disposal costs compared to conventional street lights.

3.2.1.1 Construction:

Like a normal diode, the LED consists of a chip of semiconducting material doped with impurities to create a *p-n junction*. Current flows easily from the p-side, or anode, to the n-side, or cathode, but not in there verse direction. Charge carriers electrons and holes flow into the junction from electrodes with different voltages. When an electron meets a hole, it falls into a lower energy level, and releases energy in the form of a photon. Similar to street lighting systems based on other technologies, LED lighting systems have a lighting source, a ballast (which is usually called a “driver” for LEDs), and the surrounding materials for optical and thermal control of the system. However, unlike traditional (for example, HPS or MV) systems with one or few sources of light, LED systems are built with a combination of many individual lighting sources arranged in arrays.

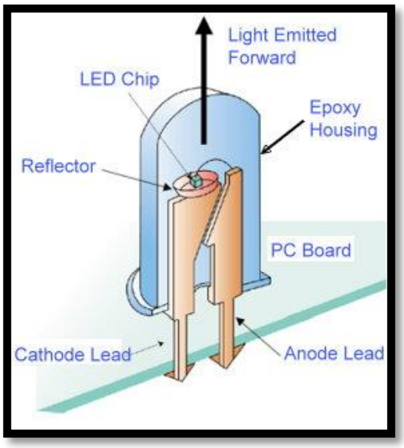


Figure 3.2.1Construction of LED [49]

3.2.1.2 Principle of Operation

When the diode is forward biased (switched on), electrons are able to recombine with holes within the device, releasing energy in the form of photons. This effect is called electroluminescence and the color of the light (corresponding to the energy of the photon) is determined by the energy gap of the semiconductor.

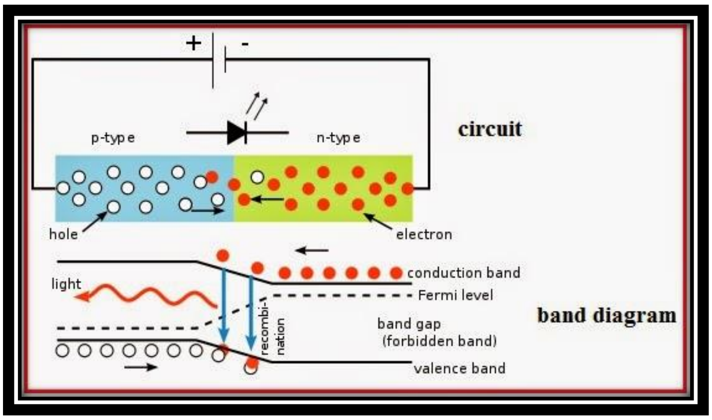


Figure 3.2.2 Inner working of LED [50]

3.2.1.3 APPLICATION

Applications of LEDs fall into four major categories:

- Visual signal application where the light goes more or less directly from the LED to the human eye, to convey a message or meaning.
- Illumination where LED light is reflected from object to give visual response of these objects.
- Generate light for measuring and interacting with processes that do not involve the human visual system.
- Narrow band light sensors where the LED is operated in a reverse bias mode and is responsive to incident light instead of emitting light.

3.2.1.4 Application Procedure

You are expected to attach the following documents to the online application module.

- Application form
- Learning agreement
- Dormitory request form
- Signed documents
- ID Card

The differences between the two technologies are detailed in table 3.2.2.

Table 3.2.1 Main characteristics of lamp technologies [20]

LED Lamp	HPS lamp and electronic ballast	HPS and electromagnetic ballast
Long operating life (50,000 hours life)	Long lifetime (from 40,000 to 60,000)[1]	Long lifetime (430 years at 105 8C)
High efficiency very low power consumption	High efficiency (up to 15% savings)	Not energy saving
Low installation and maintenance costs	Relatively expensive	Very low maintenance costs
Dimming possibilities	Dimmable	Not dimmable
	No flickering effect	Flickering effect
Low temperature and function well in cold temperatures		Suitable for extreme weather conditions (humidity, temperature variation, lightning)
Contain no hazardous materials	Not environmentally friendly	Recyclable materials (magnetic chokes are recyclable)
Quick start and re-start (do not need to firstly cool the system as with HID)		Self-recovery feature (when the ac mains voltage recovers after a disturbance)
Harmonized illumination Low glare and strobe-free		No constant light output
Good vibration resistant characteristics	Non audible noise	
Free from ultraviolet or IR	Low weight	
Possible use with renewable energies		

[1] Increased lamp life (up to 30% longer lamp life with electronic ballast)

3.3 Difference between Conventional and Smart Street Light:

In conventional street lights, the bulbs which are used consume more power and at that time there is no controlling technique available. So, energy wastage is more. The street lights remain switched ON even when there is no traffic. In smart street light technologies street lights are controlled by various techniques such as wireless sensor network, Zigbee based street light control system, and microcontroller based control scheme and much more. For instance, in the Zigbee control system, street light control is composed of three parts, centralized control center, remote concentrator and street light control terminals. Centralized control center resides in a local government office usually. At the centralized control center, operators monitor and control street lights by using the operator's terminal. Centralized control center computers communicate with remote concentrator which control lights installed alongside every road. Remote concentrators control lights and gather status information. Third, components of a street light control system is street light control terminals. To control each light individually, this street light control terminal is needed. It is installed to every street light pole to detect status of light and to control lighting. It communicates with remote concentrator to give and receive commands and status information for the control center. Zigbee is rising communication protocol, which is used for data transfer within centralized control center, remote concentrator and street light control terminals. With the help of these above mention control techniques, the energy consumption of street lighting can be reduced by the following methods:

- By switching the street lights in an organized manner.
- Controlling the lamps light intensity.
- Switching off the lights at selected locations where there is no traffic after midnight.

3.4 Structure of Conventional Street Lighting

The conventional street light may be mounted on wooden pole or steel pole that is excited by an underground cable line that connects to the nearest power source line. At the beginning of the development of street lights, all the street lights were turn ON daily at night time and turn OFF at morning time. So this system required a worker to do this daily. Sometimes, street lights were remaining ON in day time, which increased the bill cost. After few years, smart based controller in the form of timer was used to turn ON and OFF based on a pre-set time within the street light. With the invention of sensors, the street lighting system evolved to a higher level with the use of LDR, photodiode etc. These sensors are used to detect the surrounding ambient lighting and turn ON and OFF according to how much light intensity sensed. These are mounted on the top of the street light.

Conventional street lighting system structure consists of following components:
1. Lamp.

2. Ballast

3. Capacitor

4. Ignitor

5. Photo resistor

The lamp emits luminous light and normally consists of Sodium vapor. When the sensor detects dark in surroundings, then it sends signal to invoke the igniter. The function of igniter is as a time delay switch whereby it heats up the coated tungsten electrodes on both ends. The ionization by the mixture of gases and the electrodes heated up, results in formation of charges. The capacitor holds the charged to be released and that will start the arc and start up the lamp. The function of ballast is to maintain the current of the light which has been turned ON by limiting the current to an appropriate amount suitable for the lamp.

3.5 Structure of Smart Street Lighting System:

Another alternative strategy for the reduction of street lighting cost is usage of a *smart lighting system*. In order to save energy and cost electronic ballasts have been used in smart lighting. A compatibility problem has arisen as a result of using these ballasts with lamps without considering compatibility rules. Such incompatibility causes early failure of both lamp and ballast accompanied by malfunctions of energy management systems, centralized clock systems, and infrared based remote controls as well [26]. The concept of smart-lighting came with the advances in technology and is based on the ability to regulate light burn hours and to dim the individual lights from a central control station, rather than relying on individual sensors that turn streetlights on and off depending on the natural light changes during the day. In addition to providing central controls, smart-lighting systems monitor the status and conditions of individual lights and automatically raise alerts when a light requires maintenance due to failure of any of its components.

A suggested proposal for smart street lighting system consists of three types of circuitries, ZigBee module, microcontroller, sensor circuit and LED. It is based on wireless sensor network application that utilizes ZigBee communication by providing communication capabilities. This system is mostly powered by battery. So, there is no need of the underground cable system. The brain of the overall system called microcontroller that is controlling the inside and out going data. When these smart controllers detect surrounding as dark or bright then it immediately send a high or low signal to turn ON and OFF the street light. With the help of ZigBee transceiver, the microcontroller reports every activity and status of the street light to the control station wirelessly. The host of the control station is able to monitor and control the street light 24 hrs. In smart street lighting system, we can also check the status of the lamp like healthy, unhealthy and faulty. In healthy condition street light operates in a normal working condition by turning ON and OFF automatically for night and day light, but in unhealthy condition the street light does not turn ON or OFF and it sends a feedback message to control room to notify the host. The host is able to turn ON or OFF the street light manually and wirelessly with the help of graphical user interface. In a fault condition, the street light sends an error message to the control room to alert the host or operator regarding the fault. The operator is notified and takes further action to carry out repair works. The basic architecture of a smart lighting system includes intelligent ballast controllers; modems and routers for communicating with the central control station; segment controllers for scheduling, control, data logging, and access; and software middleware that ties the devices back to the service center. Figure 3.5.1 provides an example of smart-lighting system architecture.

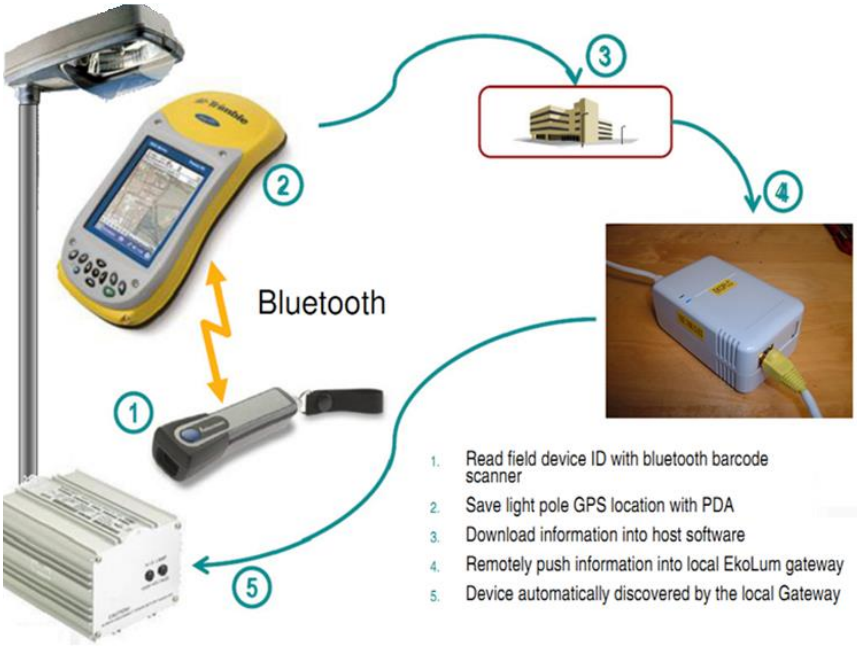


Figure 3.5.1 Smart-lighting system architecture [51]

3.5.1 Smart Street Lighting Functions:

As compared to the conventional street lighting system, the smart street system offers high reliability, low maintenance with the deployment of feedback system. The feedback system allows the street light to respond with the control room reporting its daily status and condition. Main Functions of Smart Street Functions are mentioned below:

a) Remote On-Off and dimming.

b) Control individual light.

c) Daily consumption report.

d) Accurate defects detection.

e) Energy saving and Co_2 reduction.

f) Data analysis.

Instead of the above scheme, many other controlling techniques that are used for smart street lighting system are follows:-

1. Street Light Control System Design by using ZigBee Communication Protocol.

2. GSM Based Autonomous Street Illumination System for Efficient Power Management.

3. PLC based Smart Street Lighting Control using LDR.

4. Remote-Control System of High Efficiency and Intelligent Street Lighting Using a ZigBee Network of Devices and Sensors.

5. Wireless Dimming System for LED Street Lamp Based on ZigBee and GPRS.

3.6 Comparison between Different Street Lighting Technologies

A detailed criteria comparison between the used technologies in street lighting is tabulated below:

Table 3.6.1 comparison between different street lighting technologies

Light Technology	Life Time (Hrs.)	Lumens per watt	Color temperature	CRI	Ignition time	Considerations
Incandescent light	1000 - 5000	11 – 15	2800 K	40	Instant	very inefficient, short life time
Mercury vapor light	12000 – 24000	13 – 48	4000K	15 – 55	up to 15 min	contains mercury
Metal halide light	10000–15000	60 – 100	3000-4300K	80	up to 15 min	contains mercury and lead
High pressure sodium light	12000–24000	45 – 130	2000K	25	up to 15 min	Low CRI, contains mercury and lead
Low pressure sodium light	10000–18000	80 – 180	1800K	0	up to 15 min	Low CRI, contains mercury and lead
Fluorescent light	10000–20000	60 – 100	2700-6200K	70 – 90	up to 15 min	UV radiation, contains mercury

Table 3.6.2 (cont'd)

Compact fluorescent light	12000–20000	50 – 72	2700-6200K	85	up to 15 min	Low life / burnout, dimmer in cold weather
Induction light	60000-100000	70 – 90	2700-6500K	80	Instant	Higher initial cost, negatively affected by heat
Light emitting diode	50000–100000	70 – 150	3200-6400K	85 – 90	Instant	Relatively higher initial cost

CHAPTER 4

POWER QUALITY AND HARMONICS

In this chapter focuses on types of electrical loads, mechanism of harmonic generation, calculating and analysis of harmonics by Fourier Series, power system quantities under non-sinusoidal conditions, in addition, going through the effects of poor power quality, and existing standards of harmonic and power quality.

4.1 Power Quality and Harmonics – Basic Concepts

Lighting systems have effects on the power quality of the electrical distribution system. Power Quality of electrical power is represented by the shape of voltage and current signal. Deviation of voltage and current waveforms from ideal single frequency sinusoidal shape indicates the degradation of power quality of the electrical power. Power Quality is defined by the interaction of electrical power with electrical equipment. If the electrical power drives the equipment reliably and properly that electrical power is said to have good PQ, whereas PQ is not good or bad when the equipment does not function properly or malfunctions under the same electrical power. A convenient set of definitions can be found in [27]. Power quality is defined as any power problem manifested in voltage, current, or frequency deviations those results in failure or disoperation of customer equipment. Hence, good power quality can be achieved by means of keeping the voltage at rated R.M.S. value with negligible amount of harmonics and frequency within its statutory limits and least amount of interruptions [24]. Poor power quality is a real challenge because it wastes energy, affects the electrical capacity and can harm equipments and electrical distribution system as well. With the common term power quality is; actually the quality of the voltage that is addressed at most of the time. In engineering terms, power is the rate of energy delivery and is proportional to the product of the voltage and current. It would be difficult to define the quality of this quantity in any meaningful manner. Steady state and transient disturbances are the main reason for power quality deteriorations. Steady state disturbances are harmonic distortion, unbalance, and flicker while transients are like voltage sags, voltage swells, impulses, etc. The power supply system can only control the quality of the voltage; it has no control over the currents that particular loads might draw. Therefore, the standards in the power quality area are devoted to maintaining the supply voltage within certain limits.AC power systems are designed to operate at a sinusoidal voltage of a given frequency [typically 50 or 60Hz)] and magnitude. Any significant deviation in the waveform magnitude, frequency, or purity is a potential power quality problem.

Harmonic frequencies in the power grid are a frequent cause of power quality problems. A harmonic of a wave is an integer multiple component of its fundamental frequency. Any non-sinusoidal periodic function can be represented by the summation of D.C. components, fundamental sine component and higher order sinusoidal components having integer multiple frequencies of fundamental frequency. Frequency of harmonics can be expressed as follow:

$$f_h = h * f \tag{4.1}$$

Where f: is the fundamental frequency and h: is the order of harmonics. For example if we have a current waveform having frequency 50 Hz and amplitude of 100A then, other components are third, fifth and seventh order harmonics, which have frequency 3 times, 5 times, 7 times of fundamental frequency of current waveform and amplitude of 1/3rd , 1/5th, 1/7th of the amplitude of fundamental component. The presence of such higher order harmonics in the current waveform results in a distorted current waveform shown in figure 4.1.1.

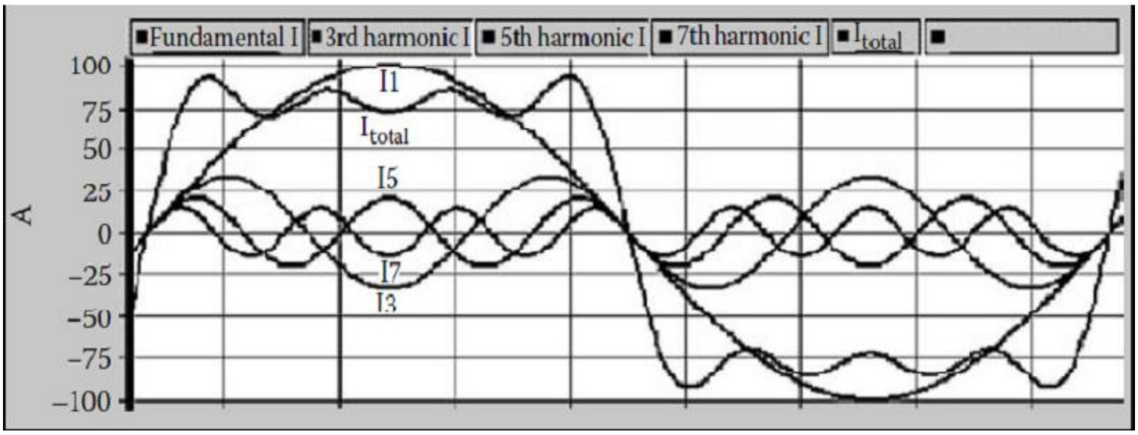


Figure 4.1.1 sinusoidal waveform containing harmonics [52]

And due to presence of harmonics the original sinusoidal gets distorted and the resultant waveform becomes a square wave.

Nonlinear load is the main source of harmonics in electrical circuit. Mainly there are two types of electrical loads:

- ✓ Linear load
- ✓ Nonlinear load

4.2 Linear Load

Linear loads are those which follow ohm's law as in Eqn.1.2 which indicates that current through a resistive load is proportional to the voltage drop across a constant resistor. That is why the voltage and current waveforms of a resistive load are identical to each other.

$$i(t) = \frac{v(t)}{r} \tag{4.2}$$

When a pure resistor is supplied from an AC power supply the voltage and current waveforms remain in phase. But with the introduction of either an inductor or a capacitor only the phase relation changes between the voltage and current waveforms but the waveforms remain identical as in case of a resistive circuit. So, circuit elements like resistors, inductors and capacitors are linear loads.

4.3 Non-Linear Load

Non-linear loads are those which do not follow any linear relation between voltage and current. There are different kinds of non-linear loads such as power converters, arc furnaces and discharge lamps. The non-linear V-I characteristic causes the current waveform to get distorted and these loads generate harmonics in electrical systems. This distortion in current waveform leads to distortion of voltage waveform and under this type of condition voltage and current waveforms no longer stay identical.

4.4 Mechanism of Harmonic Generation

Electricity generation is normally produced at constant frequencies of 50 Hz or 60 Hz and the generators' e.m.f. can be considered practically sinusoidal. However, when a source of sinusoidal voltage is applied to a nonlinear device or load, the resulting current is not sinusoidal. In the presence of system impedance this current causes a non-sinusoidal voltage drop and, therefore, produces voltage distortion at the load terminals, and hence the latter contains harmonics.

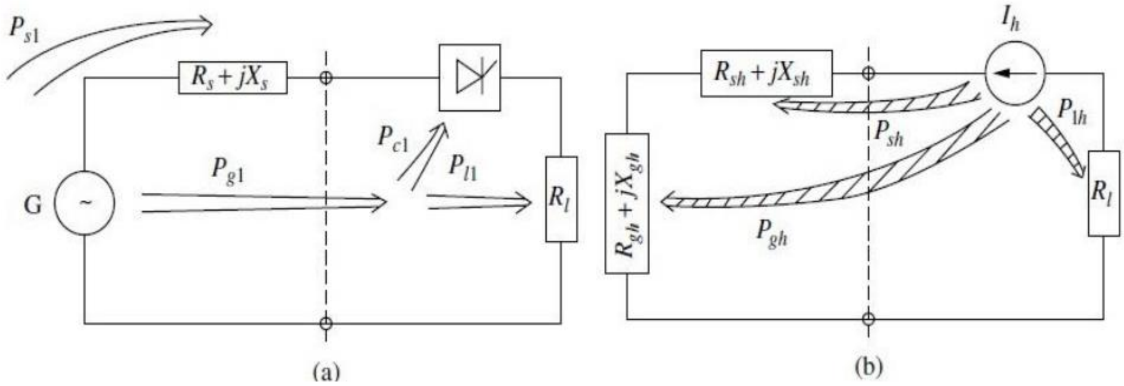


Figure 4.4.1 (a) Power flow at fundamental frequency, (b) Harmonic power flow. [26]

Let us consider the circuit of **Figure 4.4.1**, where generator *G* feeds a purely resistive load *Rl* through a line with impedance (*Rs* + *jXs)* and a static converter. The generator supplies power (*Pg*1) to the point of common coupling (PCC) of the load with other consumers. **Figure 4.4.1(a)** shows that most of this power (*Pl*1) is transferred to the load, while a relatively small part of it (*Pc*1) is converted to power at different frequencies in the static converter. Besides, there is some additional power loss (*Ps*1) at the fundamental frequency in the resistance of the transmission and generation system (*Rs*1). **Figure 4.4.1(b)** illustrates the harmonic power flow. As the internal voltage of the generator has been assumed perfectly sinusoidal, the generator only supplies power at the fundamental frequency and, therefore, the generator‘s e.m.f. is short-circuited in this diagram, i.e. the AC line and generator are represented by their harmonic impedances (*Rsh* + *jXsh*) and (*Rgh*+ *jXgh),* respectively. In this diagram the static converter appears as a source of harmonic currents. A small proportion of fundamental power (*Pc*1) is transformed into harmonic power: some of this power (*Psh* + *Pgh*) is consumed in the system *(Rsh)* and generator (*Rgh)* resistances and the rest (*Plh*) in the load. Thus, the total power loss consists of the fundamental frequency component (*Ps*1) and the harmonic power caused by the presence of the converter (*Psh*+ *Pgh* + *Plh)* [26].

4.5 Harmonic Indices

The two most commonly used indices for measuring the harmonic content of a waveform are the total harmonic distortion THD and the total demand distortion TDD.

Both are measures of the effective value of a waveform relative to the fundamental waveform and may be applied to either voltage or current[24].

$$T.H.D. = \frac{\sqrt{\sum_{n=2}^{N}=M_n^2}}{M_1} \tag{4.3}$$

Equation 4.3 shows the mathematical expression of Total Harmonic Distortion (T.H.D.).

Here, M_n is the R.M.S. value of harmonic component n of the quantity M; N is the maximum harmonic order to be considered and M1 is the fundamental line to neutral R.M.S. quantity. The THD is a very useful quantity for many applications. It can provide a good idea of how much extra heat will be realized when a distorted voltage is applied across a resistive load. Likewise, it can give an indication of the additional losses caused by the current flowing through a conductor.

When the fundamental current of an electrical system is very low in that case current distortion is characterized by TDD. When fundamental current is low THD becomes very high. TDD is expressed as percentage of rated or maximum current of the system. It is more realistic approach to determine the load current distortion as it is expressed as percentage of rated current.

$$T.D.D. = \frac{\sqrt{\sum_{n=2}^{N}=2I_n^2}}{I_{max}} \tag{4.4}$$

Equation 4.4 shows the mathematical expression for Total Demand Distortion (T.D.D.).

4.6 Harmonic Analysis by Fourier series

A non-linear load when connected to an AC power supply exhibits its non-linear V-I characteristics. Thus, load voltage and current waveforms becomes non-identical and gets distorted. This distorted voltage and current waveforms are continuous periodic signal having time period.

In 1822, J.B.J. Fourier proposed that any continuous function having time period T can be represented by the summation of dc component, fundamental component and harmonics having integer multiples of frequencies. For analyzing a distorted waveform and to find out the components present in that distorted waveform the most simplified tool is Fourier series. This analysis process is known as ‘Harmonic Analysis‘[26].

Any periodic signal $f(t)$ can be represented by trigonometric series having dc component and harmonics having integer multiple of fundamental frequency. The expression for the periodic function is given in **Equation 4.5**:

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty}(a_n \cos nwt + b_n \sin \mathrm{nwt}) \tag{4.5}$$

Where, a_0 is average value of the function and a_n and b_n are the coefficients of the series which can be expressed as:

$$a_0 = \frac{2}{T} + \int_0^T f(t)\ dt \tag{4.6}$$

$$a_n = \frac{2}{T}\int_0^T f(t) \cos nwt\, dt \tag{4.7}$$

$$b_n = \frac{2}{T}\int_0^T f(t) \sin nwt\, dt \tag{4.8}$$

The magnitude and phase angle of the n^{th} harmonic component can be expressed as:

$$M_n = \sqrt{a_n^2 + b_n^2} \qquad \text{4.9 (a)}$$

$$\varphi_n = \tan^{-1}\frac{a_n}{b_n} \qquad \text{4.9 (b)}$$

In practical situations where the function is often not given by a mathematical expression but given by a table or graph of corresponding discrete values; the above shown equations will fail to evaluate the values of coefficients. An alternative approach is needed in these types of cases.

A function $f(t)$ within limit (a, b) can be represented as:

$$f(t) = \frac{1}{(b-a)}\int_a^b f(t)dt \tag{4.10}$$

Hence, a0, a_n and b_n can be expressed as:

$$a_0 = \frac{2}{T}[Mean\ value\ of\ f(t)\ ]\ dt \tag{4.11}$$

$$a_n = \frac{2}{T}[Mean\ value\ of\ f(t) \cos nwt\ ] \tag{4.12}$$

$$b_n = \frac{2}{T}[Mean\ value\ of\ f(t) \sin nwt\ ] \tag{4.13}$$

When a signal is represented by a graph or a table of corresponding values then the values of a0, a_n and b_n can be found out following the above **Equations 4.11 to 4.13**. If for a continuous signal N number of samples are considered within a time period T. Then the expression of a0, a_n and b_n is given **Equation 4.14, 1.15 and 1.16**:

$$a_0 = \frac{2}{N}\sum f(t) \tag{4.14}$$

$$a_n = \frac{2}{N}\sum f(t)\cos(nwt) \tag{4.15}$$

$$b_n = \frac{2}{N}\sum f(t)\sin(nwt) \tag{4.16}$$

After evaluation of valuesa_0, a_n and b_n magnitudes & phases of different components of harmonics can easily be found out for any continuous periodic function using **Equation 4.9 (a) and 4.9 (b).**

4.7 Power System Quantities under Non-sinusoidal Conditions

Traditional power system quantities such as R.M.S., power (reactive, active, apparent), power factor, and phase sequences are defined for the fundamental frequency context in a pure sinusoidal condition. In the presence of harmonic distortion the power system no longer operates in a sinusoidal condition, and unfortunately many of the simplifications used for the fundamental frequency analysis do not apply [24].

4.7.1 Active, Reactive and Apparent Power

There are three standard quantities associated with power:

- Apparent power *S* [*volt-ampere* (VA)]: The product of the R.M.S. voltage and current.
- Active power *P* [*watt* (W)]: The average rate of delivery of energy.
- Reactive power *Q* [*volt-ampere-reactive* (VAR)]: The portion of the apparent power that is out of phase, or in quadrature, with the active power.

The apparent power *S* applies to both sinusoidal and non-sinusoidal conditions. The apparent power can be written as shown in **Equation 4.17**:

$$S = V_{rms} \times I_{rms} \tag{4.17}$$

Where, V_{rms} and I_{rms} are the R.M.S. values of the voltage and current. In a sinusoidal condition both the voltage and current waveforms contain only the fundamental frequency component; thus the R.M.S. values can be expressed as shown in **Equation 4.18(a)** and 4**.18(b).**

$$V_{rms} = \frac{1}{\sqrt{2}} V_1 \qquad 4.18(a)$$

$$I_{rms} = \frac{1}{\sqrt{2}} I_1 \qquad 4.18(b)$$

Where, V_1 and I_1 are the amplitude of voltage and current waveforms, respectively. The subscript '1' denotes quantities in the fundamental frequency. In a non-sinusoidal condition a harmonically distorted waveform is made up of sinusoids of harmonic frequencies with different amplitudes as shown in **Figure 4.4.1**. The R.M.S. values of the waveforms are computed as the square root of the sum of R.M.S. squares of all individual components as given by **Equation1.18 (a) & 1.18(b).**

$$V_{rms} = \sqrt{\sum_{h=1}^{h_{max}} \frac{V_h^2}{\sqrt{2}}} \qquad 4.19(a)$$

$$I_{rms} = \sqrt{\sum_{h=1}^{h_{max}} \frac{I_h^2}{\sqrt{2}}} \qquad 4.19(b)$$

Where, V_h and I_h are the amplitude of a waveform at the harmonic component h. In the sinusoidal condition, harmonic components of V_h and I_h are all zero, and only V_1 and I_1remain. The active power P is also commonly referred to as the average power, real power, or true power. It represents useful power expended by loads to perform real work, i.e., to convert electric energy to other forms of energy. Real work performed by an incandescent lamp is to convert electric energy into light and heat. In electric power, real work is performed for the portion of the current that is in phase with the voltage. No real work will result from the portion where the current is not in phase with the voltage. The active power is the rate at which energy is expended, dissipated, or consumed by the load and is measured in units of watts. P can be computed by averaging the product of the instantaneous voltage and current.

$$P = \frac{1}{T} \int_0^T v(t).i(t)dt \qquad 4.20$$

Equation 4.20 is valid for both sinusoidal and non-sinusoidal conditions. For the sinusoidal condition, P resolves to the familiar form, shown in **Equation 4.21.**

$$P = \frac{\mathrm{V_1 I_1}}{2} \cos\theta_1 = \mathrm{S} \cos\theta_1 \qquad 4.21$$

Where, θ_1: is the phase angle between voltage and current at the fundamental frequency. **Equation 4.21** indicates that the average active power is a function only of the fundamental frequency quantities. In the non-sinusoidal case, the computation of the active power must include contributions from all harmonic components; thus it is the sum of active power at each harmonic. Apparent power and reactive power are greatly influenced by the distortion. The apparent power *S* is a measure of the potential impact of the load on the thermal capability of the system. It is proportional to the r.m.s of the distorted current, and its computation is straightforward, although slightly more complicated than the sinusoidal case. Also, many current probes can now directly report the true r.m.s value of a distorted waveform. The reactive power is a type of power that does no real work and is generally associated with reactive elements (inductors and capacitors). For example, the inductance of a load such as a motor causes the load current to lag behind the voltage. Power that appearing across the inductance sloshes back and forth between the inductance itself and the power system source, producing no network. For this reason it is called imaginary or reactive power since no power is dissipated or expended. It is expressed in units of vars. In the sinusoidal case, the reactive power is expressed as shown in **Equation 4.22**.

$$Q = \frac{V_1 I_1}{2} \sin\theta_1 = S\,sin\,\theta_1 \tag{4.22}$$

There is some disagreement among harmonics analysts on how to define Q in the presence of harmonic distortion. If it were not for the fact that many utilities measure Q and compute demand billing from the power factor computed by Q, it might be a moot point. It is more important to determine P and S; P defines how much active power is being consumed, while *S* defines the capacity of the power system required to deliver P. Q is not actually very useful by itself. However, Q_1, the traditional reactive power component at fundamental frequency, may be used to size shunt capacitors. The reactive power when distortion is present has another interesting peculiarity. In fact, it may not be appropriate to call it reactive power. The concept of VAR flow in the power system is deeply ingrained in the minds of most power engineers. What many do not realize is that this concept is valid only in the sinusoidal steady state. When distortion is present, the component of *S* that remains after *P* is taken out is not conserved that is, it does not sum to zero at a node. Power quantities are presumed to flow around the system in a conservative manner. This does not imply that *P* is not conserved or that current is not conserved because the conservation of energy and Kirchhoff's current laws are still applicable for any waveform. The reactive components actually sum in quadrature (square root of the sum of the squares). This has prompted some analysts to propose that Q be used to denote the reactive components that are conserved and introduce a new quantity for the components that are not. Many call this quantity D, for distortion power or, simply, distortion volt-amperes. It has units of volt-amperes, but it may not be strictly appropriate to refer to this quantity as power, because it does not flow through the system as power is assumed to do. In this concept, Q consists of the sum of the traditional reactive power values at each frequency. *D* represents all cross products of voltage and current at different frequencies, which yield no average power. P, Q, D, and S are related as shown in **Equation 4.23** – **4.25**, using the definitions for *S* and *P p*reviously given in **Equation 4.17** &**4.21** as a starting point:

$$S = \sqrt{(P^2 + Q^2 + D^2)} \tag{4.23}$$

$$Q = \sum_k V_k I_k \sin\theta_k \tag{4.24}$$

$$D = \sqrt{(S^2 - P^2 - Q^2)} \tag{4.25}$$

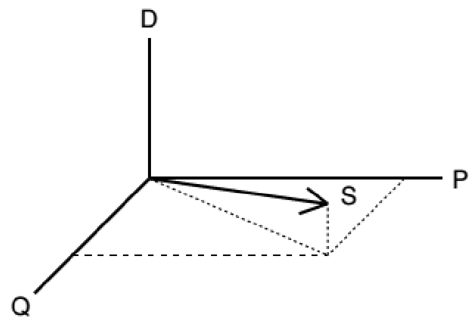


Figure 4.7.1 Relationships between components of the apparent power [26]

P and Q contribute the traditional sinusoidal components to *S*, while *D* represents the additional contribution to the apparent power by the harmonics as shown in figure 4.7.1.

4.7.2 Power Factor: Displacement and True

Power factor (PF) is a ratio of useful power to perform real work (active power) to the power supplied by a utility (apparent power). It is shown in the **Equation 4.26.**

$$P.F. = \frac{P}{S} \tag{4.26}$$

In other words, the power factor ratio measures the percentage of power expended for its intended use. Power factor ranges from zero to unity. A load with a power factor of 0.9lagging denotes that the load can effectively expend 90 percent of the apparent power supplied (volt-amperes) and convert it to perform useful work (watts). The term –lagging- denotes that the fundamental current lags behind the fundamental voltage by

25.84°.

In the sinusoidal case there is only one phase angle between the voltage and the current, since only the fundamental frequency is present; the power factor can be computed as the cosine of the phase angle and is commonly referred as the **displacement power factor** and it is shown in **Equation 4.27**:

$$P.F. = \frac{P}{S}\cos\theta \qquad (4.27)$$

In the non-sinusoidal case the power factor cannot be defined as the cosine of the phase angle as shown above. The power factor that takes into account the contribution from all active power, including both fundamental and harmonic frequencies, is known as the **true power factor**. The true power factor is simply the ratio of total active power for all frequencies to the apparent power delivered by the utility as shown in **Equation 4.26**.

4.8 Effects of Poor Power Quality

The ultimate reason for interested in power quality is economic value. There are economic impacts on utilities, their customers, and suppliers of load equipment. **Table 4.8.1** gives an overview of the poor power quality related problems [28].

Table 4.8.1 Effects of poor power quality on power system

Equipment	Effects
Power electronic equipment	Malfunction
Meters	Malfunction
Lamps	Reduced life
Digital equipment	Malfunction
Relays	Malfunction
Transformer	Reduced capacity, increased loss
Telephone/ Communication equipment	Interference
Conductors	Increased heating

Table 4.8.2 (cont'd)

Capacitors	Reduced life
Motors	Reduced motor life, reduced rating, increased loss

4.9 Existing Standards of Harmonics and Power Quality

Standards for harmonic control were first introduced in 1981 all over world; by IEEE in U.S and IEC in Europe. IEEE – 519 standard revised in 1992 was more realistic approach for limitation of harmonic injection in distribution system. Recommended Total Harmonic Distortion (THD) for current and voltage were established in 1992. Total Demand Distortion (TDD) was introduced in the revised version. Communication interference with low voltage DC converter was established in the revised version. All recommended limits established in 1992 were presented for different voltage levels – 69 KV and below, above 69 KV through 161 KV and above 161 KV. As per these standards a limitation was established on harmonic on harmonic current penetration into distribution system but limits were not specified for particular types of customers (industrial, commercial and residential). Similar to IEEE – 519, IEC also set limit for customer equipment and the last IEC standard IEC – 6100 focused on limiting equipment harmonic consumption. On the basis of harmonic consumption the equipments were classified into four different groups named as class A through D. Class D was considered as highly harmonic producing equipment. In IEC 6100-2-2 inter harmonic voltage compatibility limits are specified. IEEE – 519: 1992 does not specify limits of harmonics.

IEC 6100-3-2 classifies four different classes of equipments in establishing harmonic current distortion:

- Class A: Balanced three phase, household appliances, dimmers for incandescent lamps (but not other lighting equipments), audio equipments, anything not otherwise classified.
- Class B: Portable power tools.
- Class C: All lighting equipments except incandescent lamp dimmers.

- Class D: Single phase, under 600W, personal computer, personal computer monitor, TV receiver.

In **Table – 4.9.1**, IEC specification for harmonics current limitation of different equipment classes are shown.

Table 4.9.1 IEC specification for harmonics current limitation of different equipment classes

Odd Harmonic	Even Harmonic	Maximum Permissible Harmonic Current (A)		**Maximum Permissible Harmonic Current – Class: C**	Maximum Permissible Harmonic Current – Class: D	
		Class: A	Class: B		(mA/W) 75< P <600	(A) P>600
	2	1.08	1.62	**2**	-	-
3		2.3	3.45	**(30) × Pf**	3.4	2.3
	4	0.43	0.645	**-**	-	-
5		1.14	1.71	**10**	1.9	1.14
	6	0.3	0.45			
7		0.77	1.155	**7**	1	0.77
	8≤ n ≤40	1.84/n	2.76/n			
9		0.4	0.6	**5**	0.5	0.4
11		0.33	0.495		0.35	0.33
13		0.21	0.315	**3**	0.296	0.21
15≤ n ≤39		2.25/n	3.375/n		3.85/n	2.25/n

Chapter 5

Investigation of LED Street Lighting Disturbances – Experimental Study

5.1 Introduction

In this chapter, an experiment including laboratory LED street light investigation has been developed. The experiment has involved the individual monitoring of harmonic emissions of LED lamp and comparing it with a laboratory pre-investigated LED lamp carried out by different researchers. In the laboratory harmonic and transient behavior investigations can be carried out independently of outer electric network disturbances. Since a clean, low harmonic distortion and controllable power supply is available.

5.2 Harmonics Measurement of LED Lamp System

Reducing THDI of smart street lighting lamps is the main objective of all investigations. As such lamps are connected in groups; the aggregated emissions cannot be ignored. In laboratory, we investigated one type of LED lamp and compared our measurement results with previously 75 wattage investigated led lamp in [21]. The larger lamp (Lamp B) has about 75 W input power with *single-drive* system and a plane LED panel, using lens to focus light pattern. The lens is the bulb itself; to set the desired illumination characteristics and the whole construction is fairly flat. The construction is very similar to the construction used in HPS lamps. The smaller one [YAVUZ LED Lamp] (Lamp A) has about 45 W input power with 3*6 Edison Opto ET-3535 LED matrix every led has 2.5 W consumption and uses *single-drive* system too; the LEDs panel is plane as well. Luminaire is fortified with high cool capacity aluminum body and tempered glass. Figure 5.2.1 shows power LED lamp connection in laboratory.

Figure 5.2.1 Connection of power LED lamp in laboratory

The LED matrix is driven by MEAN WELL LCM-60 DA driver which is shown in figure 5.2.2. Investigated 45 wattage luminaire produces white light with efficacy 3888 lm which leads to efficiency of 86.4 lm per watt. We investigated the power quality parameters and active power value with respect to time domain by connecting the lamps to the power supply.

Figure 5.2.2 LCM-60 DA LED driver [53]

Additionally, we monitored the absorbed current by the lamps using (FLUKE 435 Three Phase Power Quality Analyzer) as shown in figure 5.2.3 in order to obtain one second values for all power quality parameters, beside 200 millisecond waveform duration of the voltage and current every 30 second interval and overall observation duration of 30 minutes as recommended in IEC 61000-4-7 [33]. Clean, sinusoidal one-phase AC voltage waveform was generated by pure power supply (THD less than 0.1%). In order to examine the short time transients, we set *sampling frequency* higher than it needed for standard measurement 12.8 kS/s. Odd harmonic spectrum of the current up to 2.5 KHz was measured. Finally, we calculated the harmonic distortion and power consumption of the under investigation LED lamp. The measurement was carried out in day time to avoid disturbances of night time traffic. Parameters of the lamps were registered during steady state time. Because of the total built in power of the investigated LED lamps is relatively low it was not expected to observe significant disturbances on the supply voltage so mainly the currents were analyzed. According to [20] ballasts can be dimmed in range from (60%-100%) of lamp input power. In our study we referred to the *logarithmic dimming curve* [36] in selecting three different dimming levels (60%, 76% and 100%) that equally located on curve.

Figure 5.2.3 FLUKE 435 Power Quality Analyzer [54]

5.3 Measurement Results of LED lamp

We aimed at studying different factors that affect the quality of the power system, so we changed the input voltage of investigated lamps ±10 % of their rated value. We also recorded the percentage values of harmonics components and computed the THD as well. Changes of input power have been also taken into measurements consideration. The total input power is approximately 50 W and the output power consumed by the LED load is 46 W. The driver loss is only 4 W. Thus, a high efficiency of 92 % has been achieved. Table 1 shows the differences in total harmonic distortion of lamps A and B. It is noticed that lamp B has definitely higher distortion in harmonics, as the output power is greater than power of Lamp A. The changes of input power are relatively low during the input voltage changes between ± 10 % of the nominal value (Table 5.3.1).

Table 5.3.1 Input power and harmonics measurement in laboratory

LED	[V]	Pmax [W]	Pmin [W]	Harmonics [%]				
				THDI	3.	5.	7.	9.
Lamp A	198	48.93	46.72	12	11.3	2.6	0.77	0.21
	230	49.63	46.92	13.3	12.5	2.05	0.13	0.75
	242	48.65	46.57	14.4	13.4	2.03	0.26	1.04
Lamp B	207	68	67	15.4	14	2.8	3.8	1.9
	230	68	67	17.9	16.4	2.8	4.3	2.2
	253	68	67	21.5	19.1	3	5.5	2.7

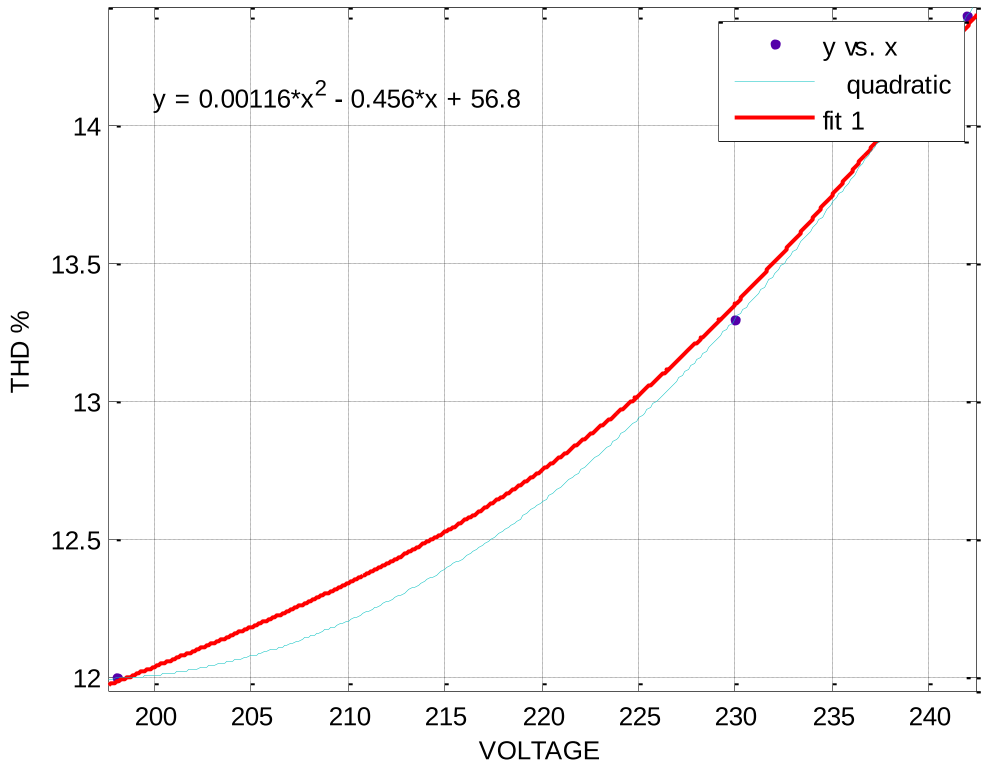


Figure 5.3.1 THD vs. Voltage curve

The relationship between THD and Voltage change is deduced from our measurements in figure 5.3.1. Applying input voltage more than the nominal one causes increase in THD and vice versa.

Table 5.3.2 shows the results of current total harmonic distortion of lamp A when controlling input power using push button. Measurements show higher total harmonic distortion when dimming power to 60% while the least THD where obtained when full load was applied.

Table 5.3.2 THD measurements of different dimming percentages of lamp A

LED	Dim[%]	Harmonics [%]				
		THDI	3.	5.	7.	9.
Lamp A	100	13.305	12.497	2.05	0.126	0.748
	76	16.748	15.38	2.764	1.649	2.168
	60	19.006	17.186	3.807	2.763	2.648

If dimming is (0-10V) then 60% and 76% dimming will be 6 and 7.6 volt respectively.

Dimming was attained by changing the driver six dips positions to “one” value in order to reach lamp’s full load then using push button to produce different levels of input power(100, 76 and 60%).Push button connection is depicted on driver case by schematic diagram as shown in figure 5.3.2 below.

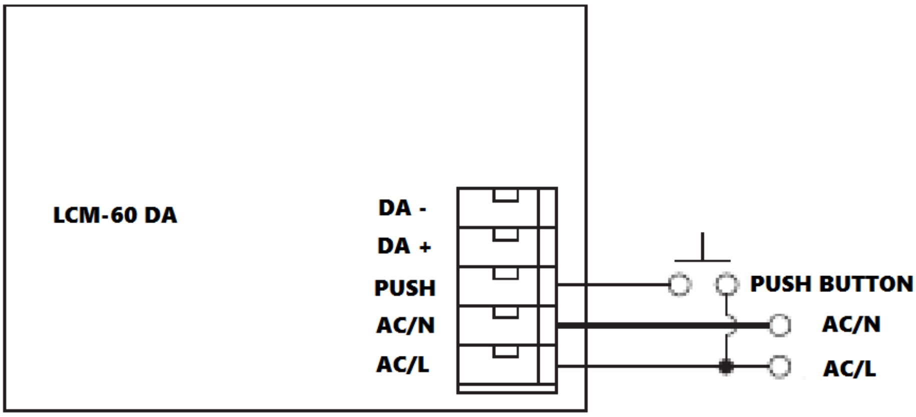


Figure 5.3.2 Push Button Schematic Diagram [55]

The highest power is consumed by the LED lamp with electronic driver set to 100% of the load; but this load does not have the highest harmonic distortion. In fact, this value is exceeded by LED lamp B with the electronic ballast (which has higher active power). Moreover, the first LED lamp A has lower input power (45W), and lower current harmonic distortion approximately (12.5%) compared with lamp B (18%).

Using dimming technology in smart street lighting has its own drawbacks whereas dimming LED lights conserve energy it produce more harmonics which affect the power quality of the electric network. Figure 5.3.3 describes the behavior of THD when dimming light intensity is set to specific levels regarding table 5.3.3.

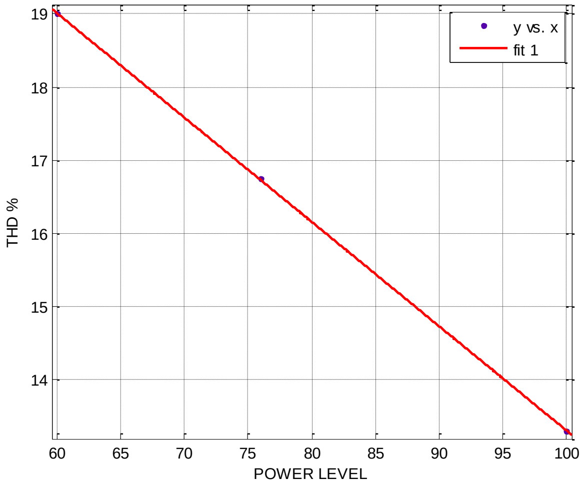


Figure 5.3.3 THD vs. Power Level curve on 230V

In order to evaluate what is happening with harmonic currents of investigated lamps, Table 5.3.3 specifically summarizes the fundamental of the current, total harmonic distortion of the current (THDI), apparent (S) active power (P), and the displacement power factor (DPF).

Table 5.3.3 Different measured power parameters of LED lamps

	FNDrms (A)	THDI (% FND)	S(VA)	P(W)	DPF*
Lamp A	0.216	13.305	50.37	48.7	0.98
Lamp B	0.326	17.9	72.8	70	0.976

***Displacement power factor (DPF)**

$$\text{DPF} = \frac{1}{\sqrt{1+(THDI/100)^2}} \quad (5.1)$$

This analysis has been compared with others made by different authors using LED lamps. The results obtained are partially similar, i.e. the decrease in the harmonic value as the harmonic order increases, in addition to the increase of the harmonic value at half load (60%) compared with full load (100%) is a consistency. Yet, the harmonic pattern is not the same because it changes with harmonic orders figure 5.3.4 displays both patterns.

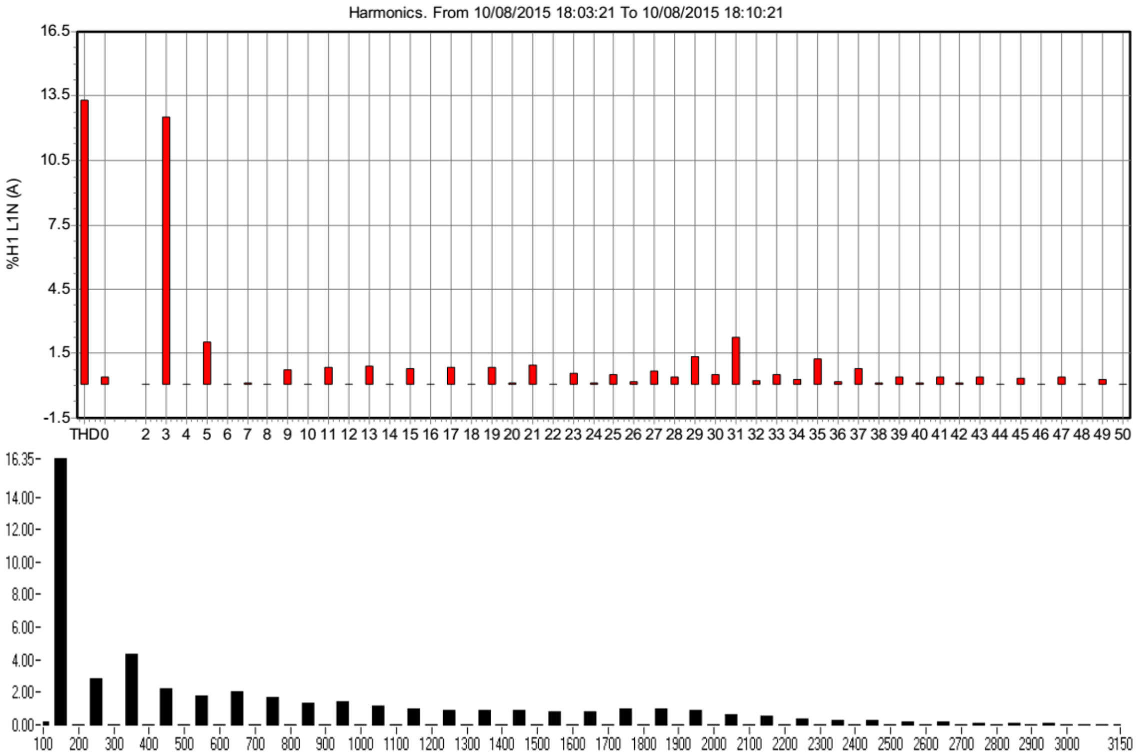


Figure 5.3.4 Harmonics of the current and THD [%] of Lamp A and B on 230V

In addition to this, a broadband spectrum has been observed in the LED lamps. Regarding spectrum, two peaks have been observed in these spectra as presented in figure 5.3.5 (31. and 35. harmonic orders). These peaks are probably due to the switching frequency of the active power factor correction circuit of LED driver.

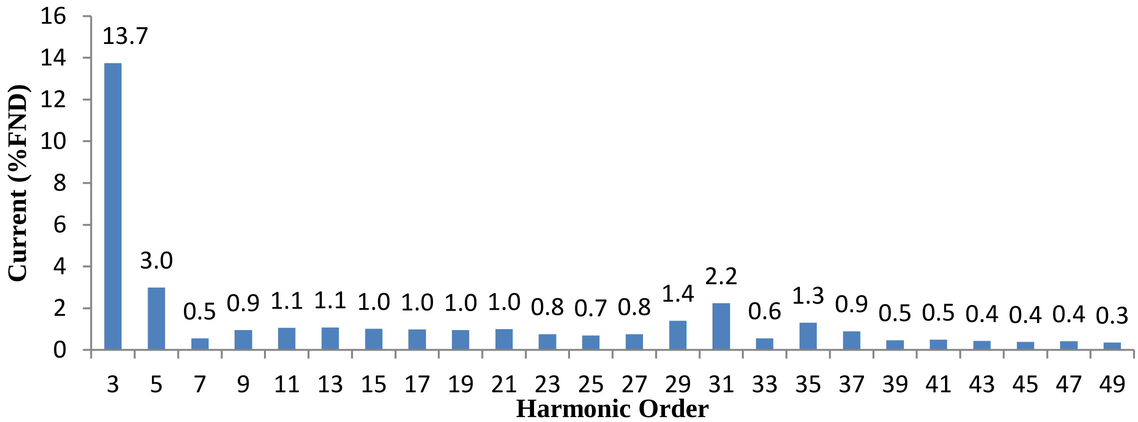


Figure 5.3.5 Full Load Average Current Spectrum (Odd harmonic spectrum)

As it can be seen the harmonic distortion is high and the 3rd, 5th, and even the next harmonics are significant but further harmonics can be observed in the higher frequency range, too. The 3rd harmonic is significant which may cause high current in 3 phase neutral line (depending on the network scheme).

The efficiency of the driver is high (about 92%) therefore most of the input power is used by the LEDs. Furthermore, the allowed range of changing in the input voltage could be higher as the output of switching power supply is less sensible for the input voltage changing. The LEDs are current controlled and the forward voltage of the LED depends only on the temperature [21]. Harmonics investigations with dimming LED lamps (power set to 60, 76, and 100%) are shown in figure 5.3.6 below.

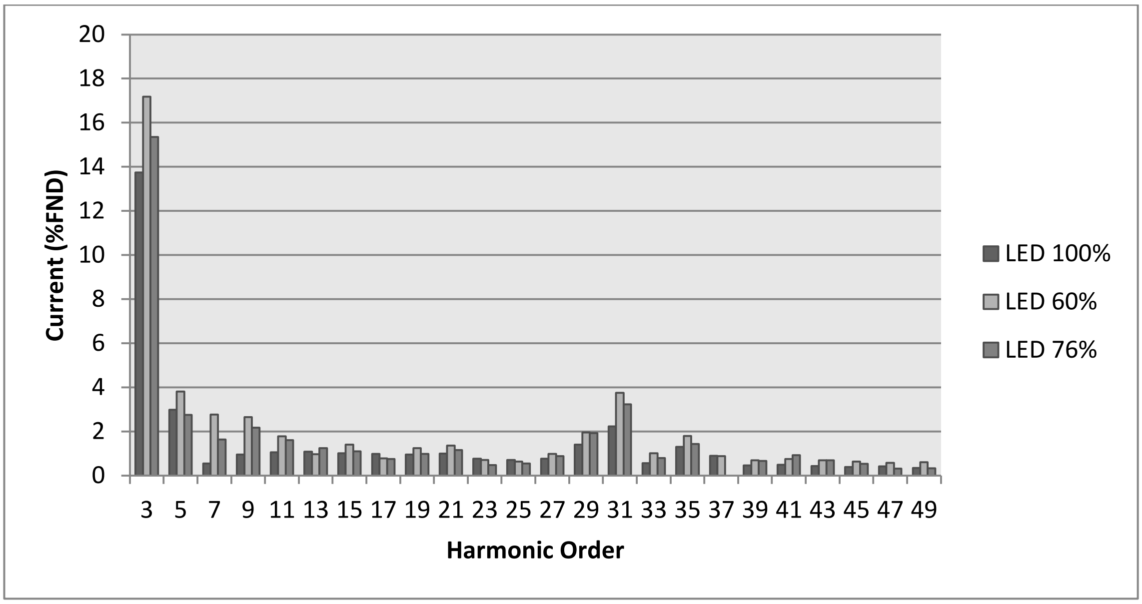
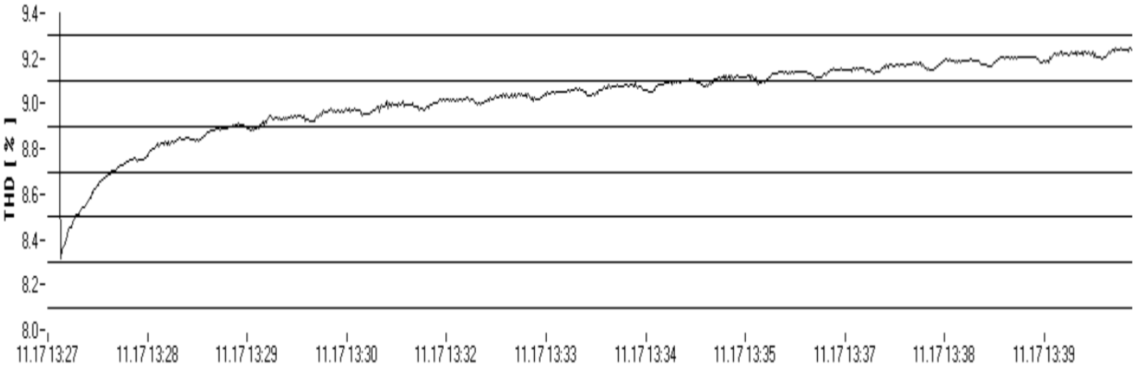


Figure 5.3.6 Harmonic current spectrum for a LED lamp A (%FND) current

During the power on time the power consumption, the input current and the THD are permanently changing (Fig.5.3.7). At the end of the switch on period the THD is regularly higher than at the beginning. The difference is approx. 10% for lamp B and 15% for lamp A.



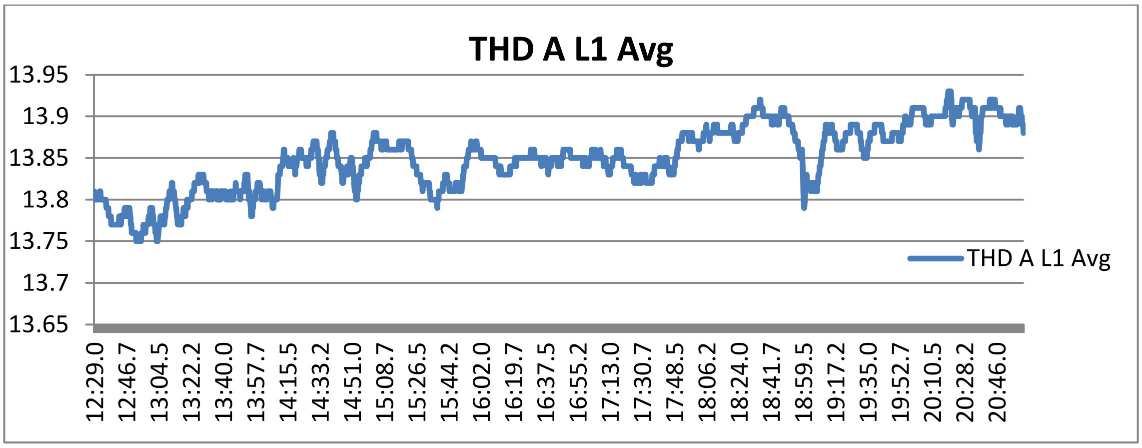


Figure 5.3.7 THD [%] vs. time at Lamp A on 230V (7 minute, THD= 13.305)

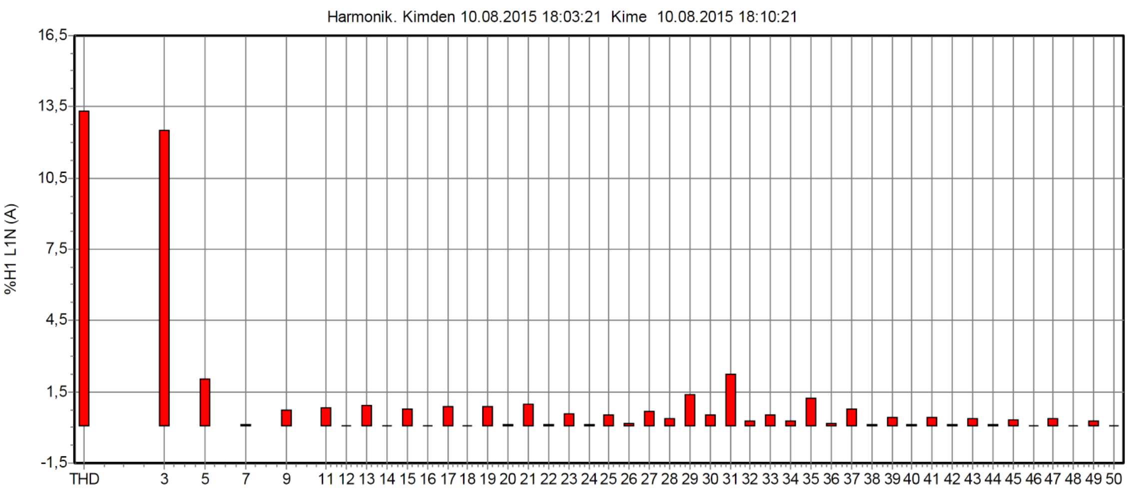


Figure 5.3.8 Harmonics of current and THD up to 2500 Hz [%] of LA on 230V (THDI= 13.305)

Figures 5.3.8 shows spectrum of Lamp A on 230 V supply level. It can be observed that the dominant harmonics are: 3rd, 5th, and 7th. The changing input voltage has a measurable effect on the spectrum. The THD is monotonic increasing when the power supply is changing from 198 to 242 V figures 5.3.9 and 5.3.10.

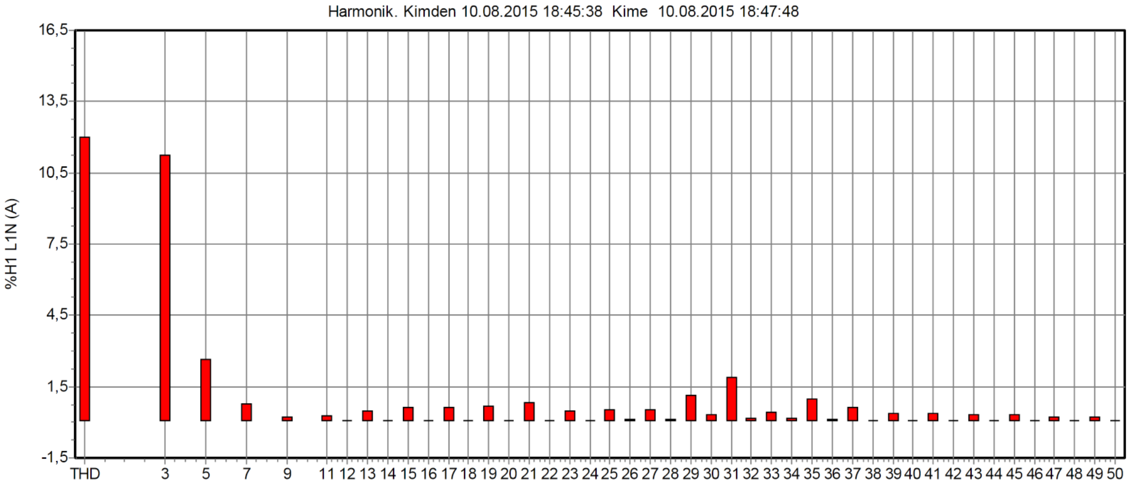


Figure 5.3.9 Harmonics of current [%] and THD of Lamp A on 198 V

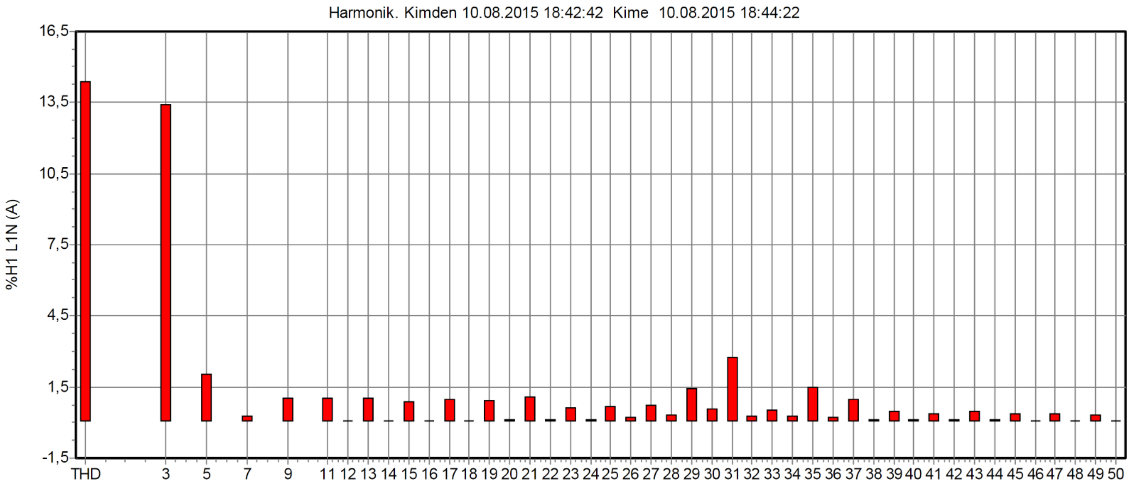
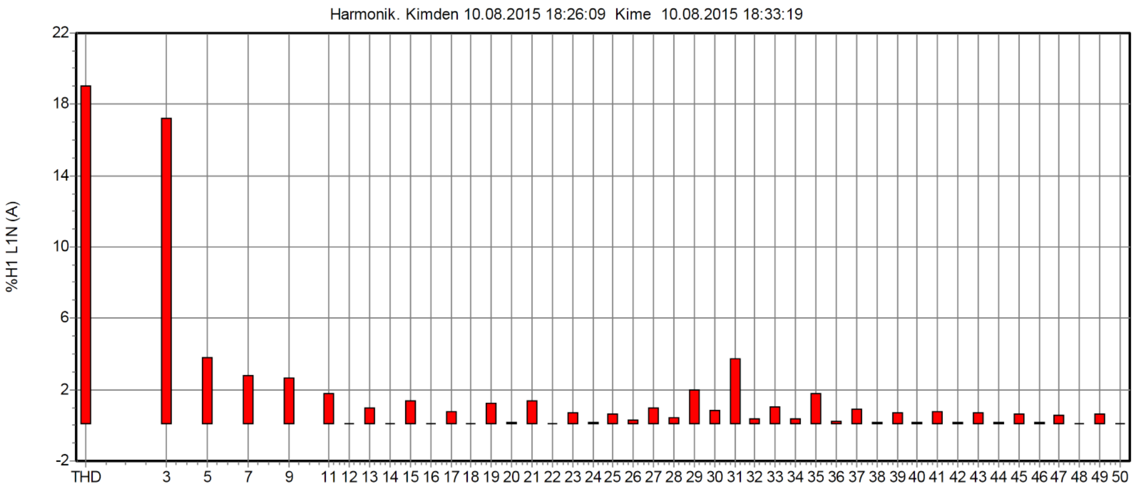


Figure 5.3.10 Harmonics of current [%] and THD of LA on 242 V (spectrum of No.6)

The harmonic distortion of the current depends on the lamp construction. Dimming lamp power increases harmonic emissions. Fig. 5.3.11 and Fig.5.3.12 show the input current of the Lamp A on different power supply levels. Lamp A shows far better behavior in the current harmonic distortion. The differences are in the converters used in drive system.



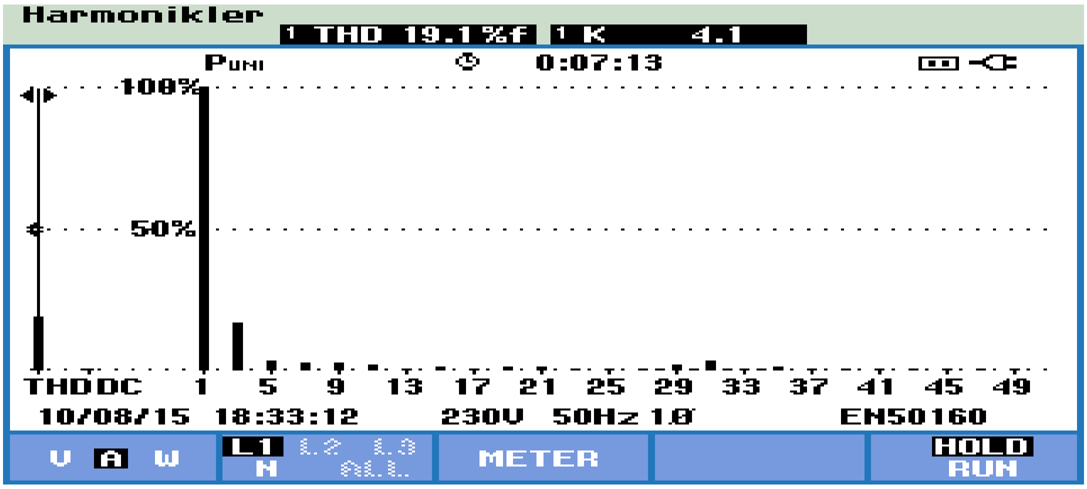


Figure 5.3.11 THDI [%] and Harmonics of current [%] up to 2500 Hz vs. time of lamp A on dimming level set to 60%. (7 minute, THD = 19.006)

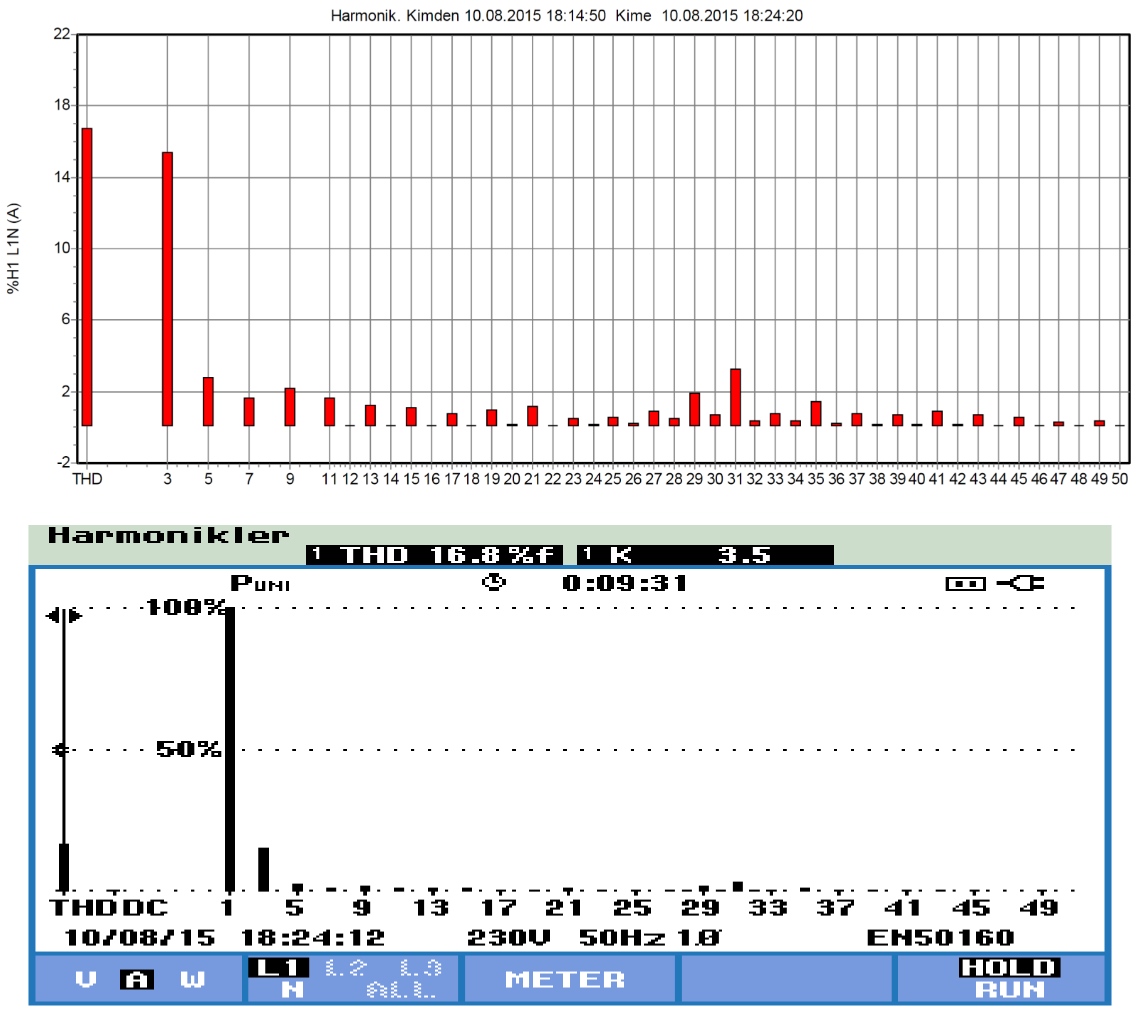


Figure 5.3.12 THDI [%] and Harmonics of current [%] up to 2500 Hz vs. time of lamp 1 on dimming level set to 76%. (7 minute, THD = 16.748)

5.4 EVALUATION OF MEASUREMENT RESULTS

Harmonic distortion has been studied in depth. The first conclusion to be drawn from outcomes is that 3rd, 5th harmonics are dominant. The remained odd harmonics have the same level. The 3rd harmonic of the current is the highest in magnitude, only 28 mA (11% of the fundamental). The other orders are around 1 mA (1% FND). Results also indicate a decrease in the harmonic value with increasing harmonic order, and increase in the harmonic value at half load (60%) compared with full load (100%). The fundamental harmonic of the current is 218 mA. Power stays nearly constant when decreasing input voltage so it is perceived that harmonic emissions are decreasing due to increase in total current value.

Fig. 5.4.1 shows a typical sinusoidal measured LED lamp current waveform of both lamp B and lamp A respectively by obtaining 200 ms waveform of the voltage and current every minute with a sampling frequency equals to 12.8 kS/s (sampling speed). There are some spikes noticed around the zero-crossing.

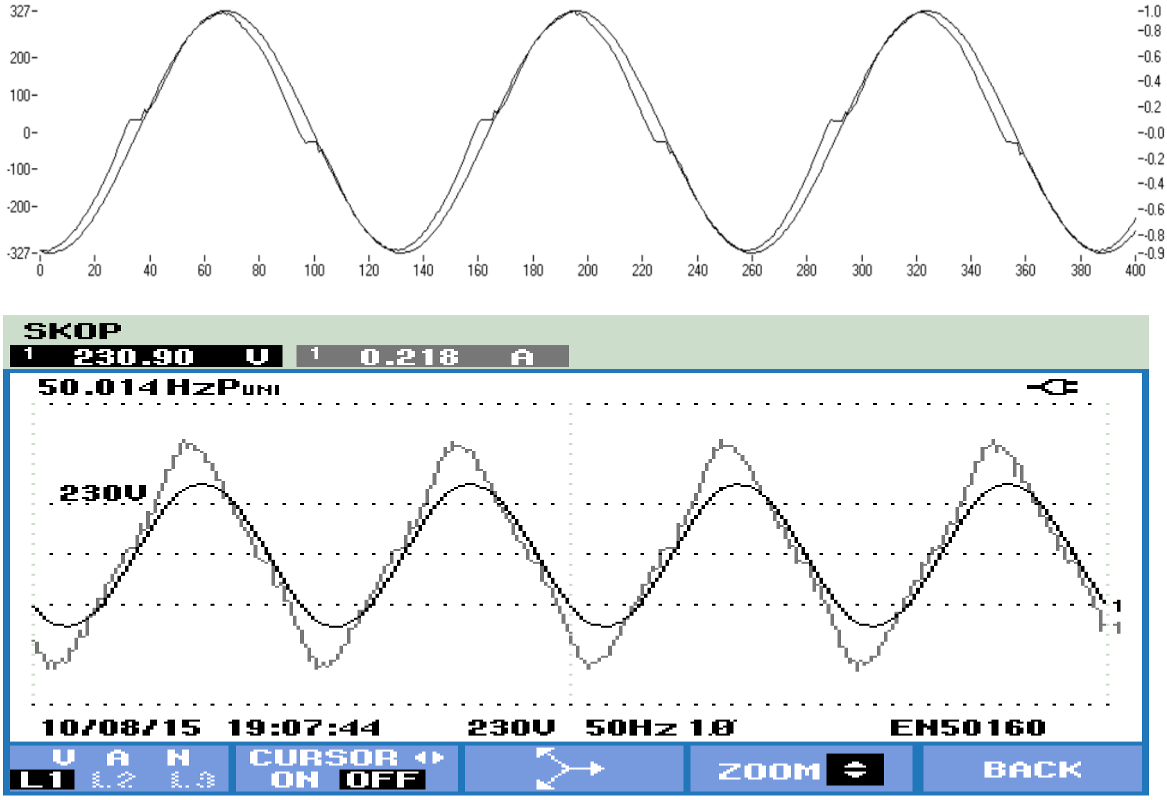


Figure 5.4.1 Steady state current [A] and voltage waveforms at (230V) of Lamp B and A

The LED street lamps have many advantages, like better and almost constant illumination and quasi optimal illumination characteristics, efficiency but they have also some disadvantages which may cause disturbances on the network and even the light spectra. Especially important are the harmonic distortion and the transients.

Some data measured from lamps are summed up in table 5.4.1, where total harmonic distortion of current and displacement power factor were measured with different dimming levels.

Table 5.4.1 THDI and DPF of multi-level dimmed LED lamp

Arc Power Level (%)	THDI (%)	DPF
100	**13.305**	0.98
76	**16.748**	0.9654
60	**19.006**	0.9523

5.5 Recommendations:

It is recommended to investigate harmonic emissions of LED lamps because emissions are different from type to another. The differences are in the converters used in drive system.

Effect of harmonic distortion can be even more significant when the voltage is increasing (Fig.5.3.10). Taking voltage value into consideration may mitigate harmonic emissions.

Power factor is an important question when electronic driver is used. Sometimes power factor corrector (PFC) is built in but in other case the power factor goes down to 0.7. The PFC has effect on the disturbances, too.

In fact, electronic drivers gain its efficiency from electronic circuitry advantages unlike conventional electromagnetic ballasts. To conclude, some advantages of dimmable electronic drivers are their energy saving, wider dimming range, better Control and Design flexibility and their robustness and reliability.

Further studies of modeling harmonics emissions when large number of LED lights is used can be an important contribution to the smart street lighting application. Also, measuring effects of harmonic distortions on visual characteristics of LED lamps is recommended as further investigations.

Including transient current measurements in deep studies is important. During the transient time significant over current occurs, three times higher than the nominal value of the current in steady-state operation. Using just one lamp this current has no effect on the network but if larger amount of lamps will be switched on in the same time, as it is usual in public lighting, the effect could not be ignored.

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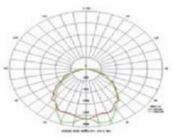
APPENDIX-A

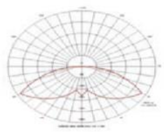
YAVUZ LED LUMINAIRE 45W MANUAL

YAVUZ LED Aydınlatma Sistemleri

LED YOL VE CADDE ARMATÜRLERİ
LED Highway and Street Luminaires

VL 548060

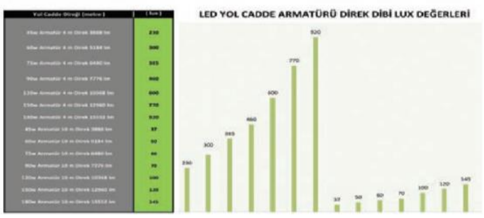




IP67 | 50.000 saat ömür | 2 yıl garantili | DIM | RoHS | Hg | min. UV | Pb

TEKNİK ÖZELLİKLER

GÜÇ (W) / Power (w)	45W - 60W - 75W
GÖVDE & CAM / Body & Glass	Yüksek Soğutma Kapasiteli Alüminyum Gövde & Temperli Cam / High Cool Capacity Aluminium Body & Tempered Glass
RENK / Color	RAL 9006 Gri, Elektrostatik Toz Boya / RAL 9006 Gray, Electrostatic Powder Coated Sheet
LED TİPİ & LED SAYISI / LED Type & LED Pieces	2,5 w Edison Opto ET-3535 Power LED & 18 - 24 - 30 Adet / 2,5 w Edison Opto ET-3535 Power LED & 18 - 24 - 30 Pieces
KORUMA SINIFI / IP	IP66
SÜRÜCÜ / Driver Type	Meanwell / Mearwell — CE RoHS
PCB KART / PCB Card	1,6 mm Alüminyum / 1,6 mm Aluminium — CE RoHS
IŞIK RENGİ / Light Color	Opsiyonel (Standart Renk Soğuk Beyaz) / Optional (Standart Color Cool White
ÇALIŞMA VOLTAJI / Operating Voltage	90-264 V AC
ÇALIŞMA FREKANSI / Operating Frecanse	47-63 Hz
LÜMEN (IŞIK AKISI)	(45W) 3888 lm (60W) 5184 lm (75W) 6480 lm
MERCEK AÇISI / Angle Lens	60°x135°
ÇALIŞMA SICAKLIĞI / Operating Heat	-30°/ +70°C
VERİMLİLİK / Power factor	> %85



Ürün Kodu / Product Code	Güç / Power	Ağırlık / Weight (kg)	Ölçüler / Dimensions (mm)	Koli Ad. / Pieces	Fiyat / Price ($)
VL548045	45W 45W	6,00	290x350x70	1	334,00 $
VL548060	60W 60W	6,00	290x350x70	1	356,00 $
VL548075	75W 75W	6,50	290x350x70	1	389,00 $

ISO 9001:2008 06 www.yavuzpano.com.tr Yavuz Pano A.Ş.'nin Tescilli Markasıdır.

APPENDIX-B

LCM 60 DA DRIVER INSTALLATION MANUAL

LCM-40(DA), LCM-60(DA) installation manual

Features

- 180~295VAC input only
- Built-in active PFC
- Output current level selectable by DIP switch
- Built-in DALI interface and push dimming function (DA version)
- Built-in 0~10Vdc and PWM signal dimming function (Non-DA version)
- Power supply synchronization function up to 10 units
- Temperature compensation function by external NTC
- Class II power unit, ungrounded
- Built-in 12V/50mA auxiliary output
- Full plastic case enclosed
- No load power consumption <1W (1.2W for DA version)
- Protections: Short circuit / Over voltage / Over temperature
- 3 year warranty
- Suitable for intelligent LED lighting

Wiring

- Housing with cable clamp for remote installation
- Use wires with an adequate cross-section (see 5)
- Use suitable mounting tools to do the wiring and mounting (see 5)
- Use a MCB (miniature circuit breaker) with an adequate current rating to protect the lighting system (see 6)

Environmental limitations

- Maximum ambient temperature must not exceed 60℃
- Always allow adequate ventilation clearances, 50mm, around the unit in use to prevent it from overheating
- Only install the unit in interior environments

Cautions

- This unit must be installed by a qualified electrician
- This unit is not suitable for applications that DC/DC converters are connected before LED lamps

Settings and connections

1. Output Current Level Settings

The LCM can provide various output currents by setting the DIP switch. The settings of the DIP switch are shown in the tables below.

LCM-40(DA)

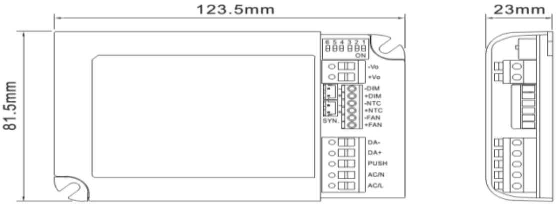
Voltage range	Selectable Current	1	2	3	4	5	6
2-100V	350mA	---	---	---	---	---	---
2-80V	500mA	ON	---	---	---	---	---
2-67V	600mA	ON	ON	---	---	---	---
2-57V	700mA*	ON	ON	ON	---	---	ON
2-45V	900mA	ON	ON	ON	ON	---	ON
2-40V	1050mA	ON	ON	ON	ON	ON	ON

LCM-60(DA)

Voltage range	Selectable Current	1	2	3	4	5	6
2-90V	500mA	---	---	---	---	---	---
2-90V	600mA	ON	---	---	---	---	---
2-86V	700mA*	ON	ON	---	---	---	---
2-67V	900mA	ON	ON	ON	---	---	ON
2-57V	1050mA	ON	ON	ON	ON	---	ON
2-42V	1400mA	ON	ON	ON	ON	ON	ON

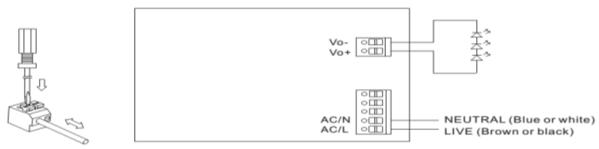
Note : 1.Factory default setting is 700mA.
2.Output voltage and output wattage must not exceed the rated values.

Terminal blocks assignment for LCM



2. Connection of LED Lamps

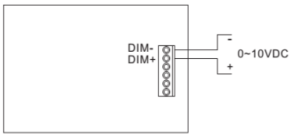
Press down the "push button" by a slotted screw driver to insert or remove the cable.



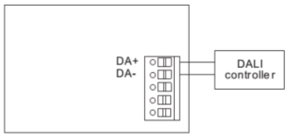
http://www.meanwell.com

3. **Connection of Dimming Functions**

a. 0-10Vdc or 10V PWM (non-DA version only)

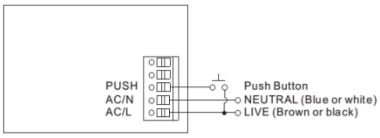


b. DALI (DA version only)



Note : Maximum DALI cable length is 300m
(based on a 1.5mm² or 14AWG cable)

c. Push dim (DA version only)



Note: ONLY use open push button without indicator light.

⚠ **Warning:** Risk of short circuit. The push button can only be linked between the PUSH and the AC/L (brown or black).
DO NOT connect the push button to the AC/N (blue or white).

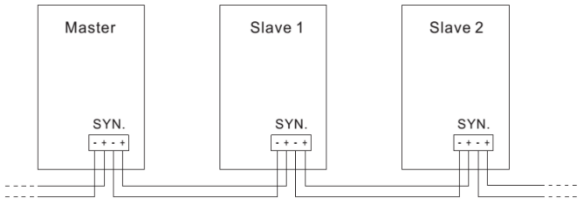
Dimming control mechanism

Function	Pushing time
Turn ON/OFF	0.1 ~ 1 sec
Dim UP/DOWN	1.5 ~ 10 sec
Reset	> 11 sec
None	< 0.05 sec

- It will always dim up when light intensity is lower than 10%, whereas it will always dim down when light intensity is higher than 90%
- Factory dimming setting: 100%

d. Synchronization operation

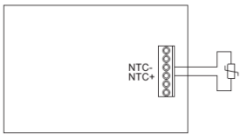
The lights driven by LCM units (slaves) can be dimmed synchronously through a LCM unit (the master) directly controlled via 0-10Vdc, 10V PWM, DALI or push dim dimming function. The wiring is shown as below.



- Mating housing for SYN. connectors : JST B2B-XH or equivalent
- Maximum number of the LCM units : 10 (1 master + 9 slaves)
- Maximum cable length between each units : 20m (based on a cable with cross-section of 0.15mm²~0.3mm² or AWG No. of 22 ~ 26)

Note: DO NOT connect dimming circuitry to slaves.

4. **NTC Connection**



5. **Recommended Screwdriver, Wire and Torque Setting**

Type	The cover (the blue one)	Screw terminal (FAN±, NTC±, DIM±)	Push terminal (ACL/N, PUSH, DA±, Vo±)
Solid wire	-----	φ0.404 - φ0.643mm	φ1.024 - φ1.628mm
Stranded wire	-----	0.129 - 0.326mm²	0.823 - 2.08mm²
American wire gauge	-----	22 - 26AWG	14 - 18AWG
Wire stripping length	-----	7mm (0.27")	10mm (0.39")
Screwdriver	6mm Philips	3mm Philips	3mm Philips
Recommended tightening torque	4.6 kgf-cm (4 lb-in)	2.88 kgf-cm (2.5 lb-in)	-----
Suggested push-down strength	-----	-----	3 - 4 kp (1.36-1.81 lbF)

6. **Suggested Maximum Number of the LCM Units that can be Connected to a MCB (miniature circuit breaker) at 230Vac**

Model	B10	B16	C10	C16
LCM-40(DA)	10	16	17	28
LCM-60(DA)	9	15	16	26

Note: These calculated values are based on MCB S201 series manufactured by ABB.

CURRICULUM VITAE

PERSONAL INFORMATION

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EDUCATION

Degree	Department	University	Date of Graduation
Undergraduate	Electrical Engineering	GAZA Islamic University	2011
High School	Science Branch	Beach Camp Martyr High School	2004