A Systematic Approach to Address the Reliability of Solid State Lighting Drivers

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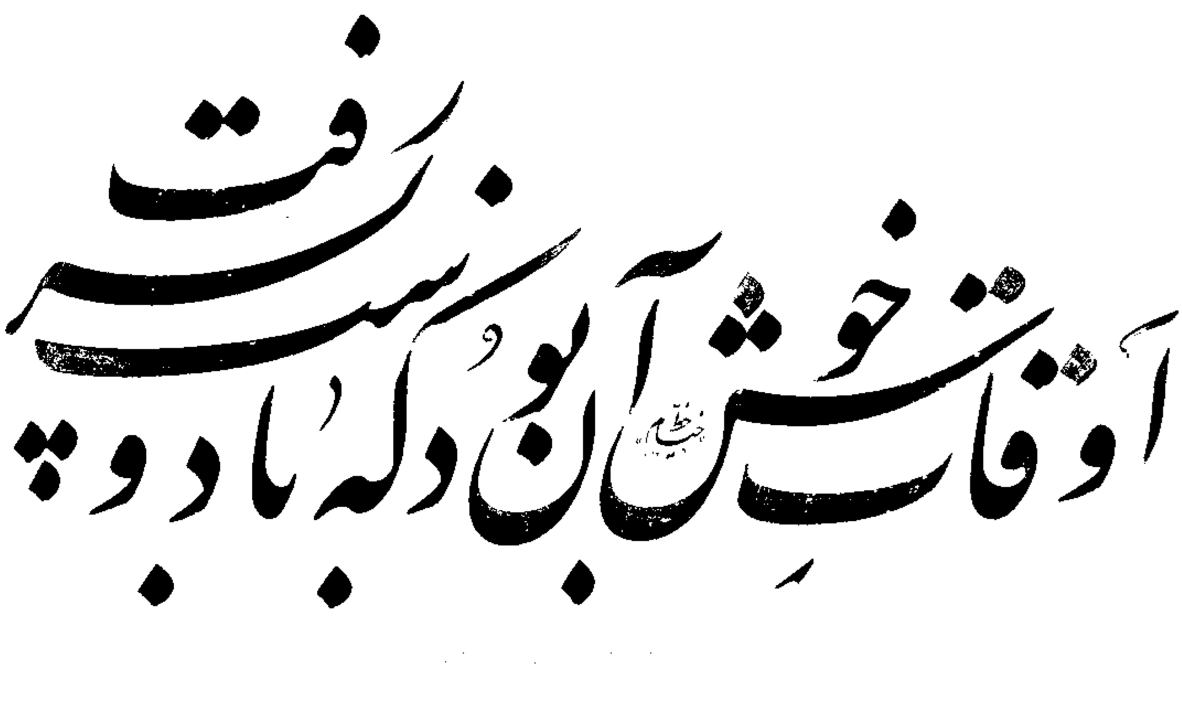
تقدیم به بابا، مامان، سعید، و سارا که اندازه دنیا عزیزین برای من.

To Ulf for the great and lovely life we have together.



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Chapter 1

Introduction

Solid State Lighting, commonly called SSL, is the new lighting technology based on light emitting diodes. It is applied in a variety of applications such as indoor, street lighting, automotive, and agriculture. This new lighting technology has great advantages over conventional lighting technologies such as high efficiency, long lifetime and design flexibility. Like any other newly introduced and fast growing technology, reliability is an issue which should get enough attention. In this thesis the focus is on SSL electronic drivers which are the interface between the input power, user controls, and the optical part of an SSL device. After some historical background information about SSL technology, this chapter presents system architecture of SSL devices and different application fields which they can be applied in. Subsequently, the primary challenges in SSL reliability examinations are addressed. This builds up the platform for formulating the problem statement dealt with throughout this thesis. The chapter is concluded with the outline of this thesis.

1.1 Words Before Starting Reading

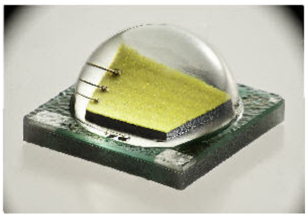
The work of this thesis is a multidisciplinary and touches many topics related to the reliability study of SSL drivers. This chapter introduces each of the topics with a brief explanation. The background information and literature study regarding each of the topics are located in the relevant chapter. This way of spreading the literature study through the thesis makes it easier to follow.

1.2 Solid State Lighting: A New Era in Lighting

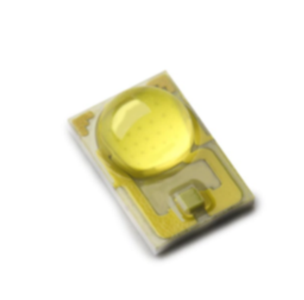
Solid State Lighting, commonly called SSL, is the new lighting technology based on light emitting diodes (LED). Although LEDs has been used for a very long time for different applications (mostly as indicators), the idea of using LEDs for lighting applications has only been introduced in the recent decade. The architecture of the first few lighting systems based on LEDs was using a large number (over 10 or 20) of 20mA 3-5Volt conventional LEDs to compensate for the required light output [1]. Recently due to technological improvements of the LED designs, the high brightness LEDs (HB LEDs) with higher output lumen flux are used instead. Fig. 1.1 shows five examples of HB LEDs.

The first of the many reasons that made the idea of using LEDs as the light source very attractive was its low power consumption with respect to the conventional lighting sources. The electrical energy consumption for lighting in big cities is about 20% to 25% of the total consumed electrical energy. Therefore any energy saving lighting technology is very appealing to our societies. Furthermore as it is shown in Fig. 1.2, the efficacy[1] in all light sources except LED did not have any significant improvements in the recent years. This makes lighting based on LED a great new solution for lighting applications. A lot of research has focused on producing high power LEDs with high efficacy and better light quality, especially in the area of white LEDs for general purpose applications. Latest high

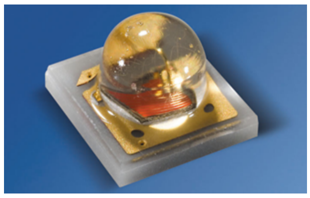
[1]In lighting design, "efficacy" refers to the amount of light (luminous flux) produced by a lamp (a lamp or other light source), usually measured in lumens, as the ratio of amount of power consumed to produce it, usually measured in watts. This is not to be confused with efficiency which is always a dimensionless ratio of output divided by input which for lighting relates to the watts of visible power as a fraction of the power consumed in watts.



(a) Cree XLamp XM-L

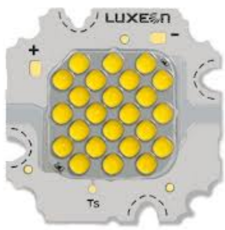


(b) LumiLed Luxeon Rebel ES



(c) OSRAM Oslon SSL 80

(d) LumiLed Luxeon Altilon



(e) LumiLed Luxeon K

Figure 1.1: *Five examples of the LEDs which are used in SSL devices.(a) XLamp XM-L white LED from Cree with typical forward current and voltage of 1500mA and 3.1V, and light output of 500lumen. (b) Luxeon Rebel ES white LED from LumiLed with typical forward current and voltage of 700mA and 3V, and light output of 200lumen .(c) Oslon SSL 80 white LED from OSRAM with typical forward current and voltage of 350mA and 2.20V, and light output of 80lumen. (d) Luxeon Altilon white LED from LumiLed for automotive applications with typical forward current and voltage of 1000mA and 6.4V, and light output of 700lumen. (e) Luxeon K white LED from LumiLed with typical forward current and voltage of 700mA and 63V, and light output of 2475lumen.*

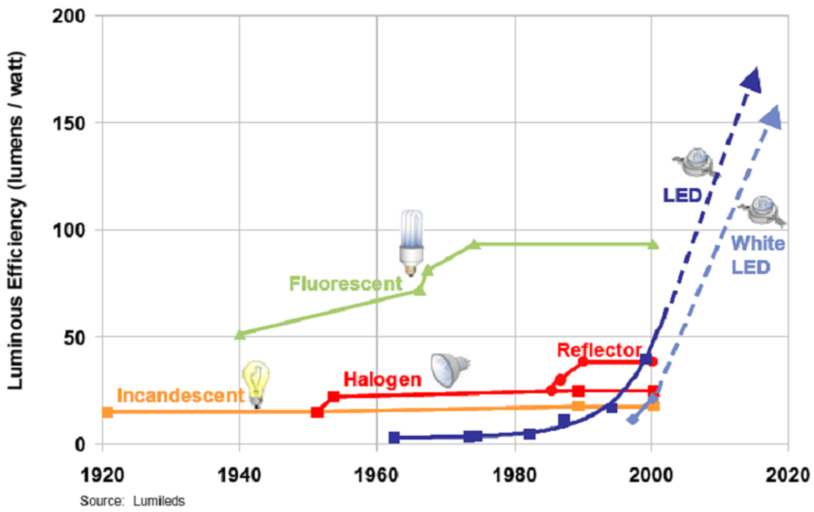


Figure 1.2: *Historical and predicted efficacy of different light sources. It can be seen that the efficacy in all light sources except LED did not have any significant improvements in the recent years [2].*

power LEDs, which are also known as high brightness LEDs (HB LEDs), has a power rating of 1W and even higher. Recent SSL devices have remarkably high efficacy of up to 150lumenm/W, as comparison to 15lumenm/W for conventional 60W to 100W incandescent light bulbs, and 60lumenm/W for compact florescent lights [3].

The second advantage of SSL over conventional lighting systems is its long lifetime. A common incandescent lamp has an average lifetime of around 1000hours whereas the fluorescent lighting technology has an average lifetime of about 10 times longer than incandescent light, which is around 10,000hours [1, 4]. It should be mentioned that fluorescent lighting technology is a mature technology now which almost has reached its limit of gaining longer lifetime. And it does not look promising that fluorescent lamps reach lifetime much longer than 10,000hours. The present LED lighting devices have an average lifetime of around 20,000hours (this value varies from manufacturer to manufacturer) with the potential of reaching up to 50,000hours lifetime and even more up to 100,000hours [5].

Regarding the price, even though an SSL single light bulb price is still much more expensive compared to for example a fluorescent light bulb, the total lifetime

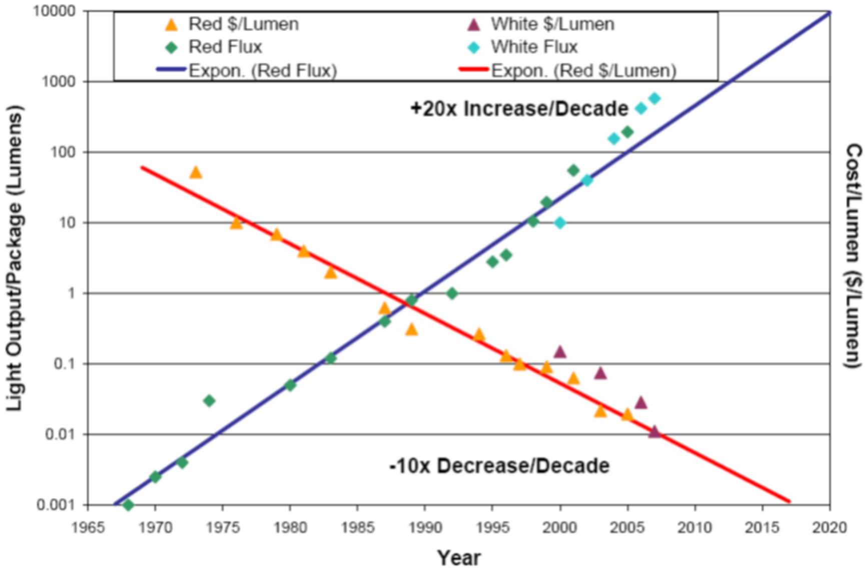


Figure 1.3: *Haitzs Law: LED Light Output Increasing / Cost Decreasing*

cost of SSL systems will be much lower than the current lighting technologies. It is due to the lower energy consumption and longer lifetime. SSL devices cost per lumen has been predicted by Haitz's law to decrease as the technology is being improved (Fig. 1.3).

The third advantage of SSL lighting is being an environmental friendly technology. Fluorescent lighting systems which are one of the most efficient lighting systems before SSL, contains mercury which is not disposable. In contrary with fluorescent lighting devices, LEDs are semiconductor devices which are free of toxic materials. The dream of having a completely environmental friendly lighting system can be achieved by replacing the electronic components with lead-free devices[2].

SSL technology can be interesting for designers and consumers in many other ways. One example is the design flexibility that enables SSL technology to be quickly adopted into different lighting systems markets. LEDs are semiconductor devices that their light intensity can be easily controlled. They can be in theory dimmed up to 100% but their drivers technologies are still not completely

[2]There is an argument about this claim which refers to this fact that in this discussion the effect of production phase to the environment has been ignored.

compatible with current dimmers in the market [6]. The SSL devices turn-on time is almost zero in contrary to the Fluorescent lighting system turn-on time which is more in the order of seconds. Furthermore, the ease of color changing of SSL systems makes SSL appealing for special applications such as entertaining lighting systems or shopping center lighting systems. Due to the narrow emission bandwidth of LEDs, there is no infra-red or ultra-violet light emission from SSL devices which is very important for a very good and sharp spot-lights [1, 3].

As mentioned in the above discussion, there can be a wide variety of applications that SSL devices are very good replacements for traditional lighting systems. In-door lighting, spot lighting, street lighting, and lighting for automotive applications are just some of the many examples. There are also lots of new applications which have been introduced to the market like decorative outdoor/indoor lighting. The examples of these new age lighting systems can be seen in many historical buildings, bridges and conference centers all around the world [7, 8]. Fig. 1.4 shows some examples of the application fields for SSL devices: indoor lighting, outdoor/street lighting, and automotive lighting. Besides the traditional shapes and applications, due to the capabilities of SSL lighting, many new application fields for lighting are being introduced for example in the health care field [9].

(a) Indoor lighting. (b) outdoor street lighting. (c) automotive lighting, which in this figure is the headlamp of the car.

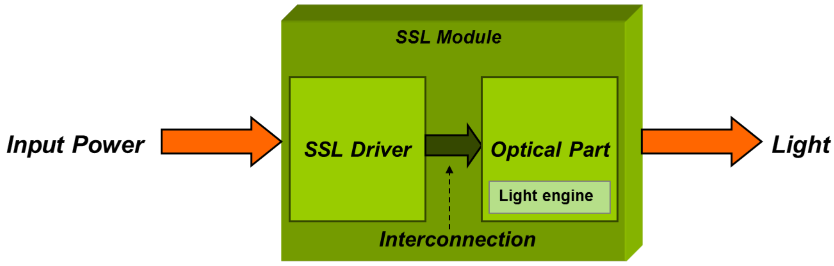
Figure 1.4: *Three examples for different application fields of SSL devices.*

1.3 Solid State Lighting System Architecture

An SSL system is constructed from one or more lighting modules which provide the required light for a specific application. Each lighting module is an SSL device which include three major parts; optical part, LED electrical driver (It will be referred to as "SSL driver" in the rest of this thesis), and interconnections between the latter two parts (Fig. 1.5(a)). In each SSL device, all these three parts are important in order to have a functional system. Fig. 1.5(b) shows an example of a lighting module for which the optical part and the driver part are separated. Thus we can easily differentiate between the parts of an SSL device. The interconnection between these two parts is a cable. In the following paragraphs, the function of each part of the system will be explained [10]. IES standardization in "ANSI/IESNA RP-16-05 Addendum A" [11] has standardized the names for different parts of an SSL system, but there are still disagreements between different manufacturers in how to call different parts of an SSL system.

Optical part is the closest part of the system to the user. This part includes the light engine and non-electrical optical parts. Light Engine is referring to a part of an SSL device that includes one or more LEDs connected to the load side of SSL driver. Electrical, optical, and mechanical components may also be part of it and it does not contain a power source. Non-electrical components are such as phosphor layer, reflectors, and lenses. Application usually defines the required light intensity and color(s) of the light. The designer chooses the type and number of LEDs based on the application requirements, the design of the SSL driver, and manufacturers concerns.

If the light intensity of the lamp requires more than one LED in the system, then the LEDs are connected to each other either in series, in parallel or a combination of them. This depends on the concerns in electrical driver design and the LEDs reliability. In case the most common failure mode of the LED is short circuit, the proper interconnection between LEDs is series connection. Because with one LED failure, the whole chain of LEDs will not fail. The system will keep functioning but with lower light intensity. In case that the most common LED failure mode is the open circuit, then it is best to connect LEDs in parallel with the same reasoning.



(a) An SSL device general block diagram. The three major parts are represented: optical part, SSL driver, and interconnection. SSL driver is the interface of the SSL optical part and the input power of the system.

(b) An example of an SSL device with external driver [12].

Figure 1.5: *Block diagram and an example of an SSL device.*

SSL drivers prepare the regulated power from input main power supply in order to drive the LEDs in the light engine (Fig. 1.5(a)). Types of LEDs, number of LEDs, and the way they are connected to each other will be defined by the design requirements. In each application the input power to the system can be different. In general purpose lighting systems, the input power is the city power plugs which is 220V_{AC} 50Hz (or 110V_{AC} 60Hz). For automotive applications, it is the power from the car battery which is 12V_{DC} to 24V_{DC}. SSL systems for replacement of halogen lamps have a power rating of 12V_{AC} 100kHz [1, 13].

The primary and fundamental task of the SSL driver is to provide the electrical power to the optical part of the system. However, there are lots of other functionalities that can be defined and implemented in an SSL driver. Dimming and color changing capabilities are two examples which already can be found in many commercial products. Examples of added functions that are still in the development phase are built-in sensors, wireless communication, and processing capacity for having a smart lighting network [14, 15].

Interconnections between optical part and SSL driver is the last integral part of the system. Their responsibility is to provide the electrical connection between the driver and the optical part. Their design varies from the simplest case of two wires or two tracks on the printed circuit board, to the more complex types with shielded cables for power and control signals.

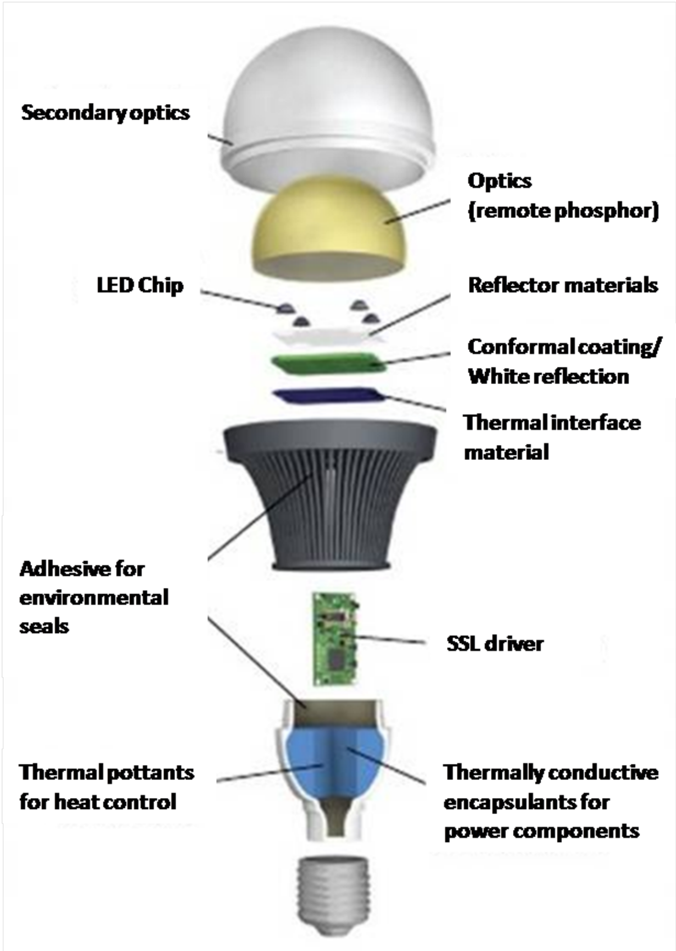
Each of the mentioned three parts of the system can have non-electrical parts for different purposes like optical lenses, heat spreaders, and enclosures. Their shapes and their materials are chosen based on electrical, optical, and mechanical requirements of the application field. In Fig. 1.6 the constructed parts of an SSL devices as an example is shown. More details and background information about SSL system architecture are in Chapter 2.

1.4 Product Design and Manufacturing Phases

Looking at the history of the electronic devices design and manufacturing shows that the procedure started in a serial manner. Each step was happening after the other in series: first design, then manufacturing, and finally testing. Gradually through time the procedure of the product design, manufacturing, and test got more complex with a lot of feedback from each stage to the other ones. V-model is an example of these types of system development tools [16]. Although in the recent years most of the manufacturers make use of these new approaches for having a higher quality product, but still reliability assessment has an isolated place at the end of the process. In most cases the reliability assessment can be very little help to guide the designers in order to improve the design quality.

Design for Six Sigma (DFSS) is a recent method for system development and project management which has a focus on the customer needs [17]. In this work we will talk about this system development approach regarding to SSL products. In this approach, we define several steps related to reliability throughout an SSL product life-cycle. In Chapter 3 of this thesis will be a more detailed introduction on DFSS and SSL product life-cycle phases with respect to DFSS approach.

(a) SSL retrofit lamp.



(b) SSL retrofit lamp disassembled.

Figure 1.6: *One example of SSL devices: Philips MASTER LED retrofit lamp.*

1.5 Reliability Theory and Practice

The word reliability originates far sooner than most would guess [18, 19]. In 1816, Samuel Taylor Coleridge [20] used it in one of his poems obviously not having the same meaning to as we nowadays do so. He more used the word from a psychological perspective where reliability refers to the inconsistency of a measure. A test is considered reliable if we get the same result repeatedly. The history of reliability as we know it now goes back to the 1950s, when electronics played a major role for the first time. During the 1950s, there was a great concern within the US military where half of the vacuum tubes were estimated to be down at any given time. In these days, many meetings and ad hoc groups were created to cope with the problems. In 1952, as an initiative between the department of defense and the American electronics industry [21], a study group was initiated under the name Advisory Group on the Reliability of Electronic Equipment (AGREE) [22]. This group recommended the following three items for the creation of reliable systems:

1. The need to develop better parts.
2. Establishing quantitative reliability requirements for parts.
3. Collecting field-data on actual part failures to determine their root cause.

It may seem strange today but at that time there was considerable resistance to recognizing the stochastic nature of the time to failure, and hence reliability. With the basics ready, Shewhart and Weibull [23] already published their techniques, statistics as a tool for making measurements would become inseparable with the development of reliability concepts. During this period, 1950s to 1960s, several working groups and conferences were held to discuss the reliability topic; examples are the IEEE Reliability Conference, the Reliability Society, Rome Air Development Center (RADC) and the already mentioned AGREE committee. Recommendations included running formal demonstration tests with statistical confidence and running longer and harsher environmental tests that included temperature and vibration. All led to the well known Military Standards, such as MIL781 and MIL217 [24]. In this decade, reliability was driven by the demand from the military industry.

From the 1960s onwards to the 1970s, the complexity of electronic equipments began to increase significantly, and new demands were placed on reliability. Semiconductors came into more common use as small portable transistor radios appeared. This decade brought a heightened interest in system-level reliability and safety of complex engineering systems. In order to do so, people began to use the Weibull function and the further developed Weibull analysis methods and applications [25, 26].

During the decade of the 1970s, reliability had expanded into a number of new areas; examples are the use of Failure Mode and Effect Analysis (FMEA) [27], risk management through the use of reliability statistics, system safety and software assurance. For the latter one, the first primary models originate from this period in time [28]. System safety was introduced by the railway industry, driven by the need for timely arrivals of its travelers.

The largest changes in reliability development occurred in the 1980s. Televisions had become all semiconductors, automobiles rapidly increased their use and communication systems began to adopt electronic switches. Standards became worldwide accepted and implemented. During this decade, the failure rate of many components dropped by a factor of 10. Thus, by the decade end, dedicated reliability programs could be purchased for performing FMEAs, reliability predictions, block diagrams and Weibull analysis. It was also the decade in which the people at home were confronted with a disaster that had a clear reliability nature: the Challenger disaster[3], which occurred on January 28, 1986. This disaster caused people to re-evaluate how to estimate risks.

By the 1990s and beyond, the pace of IC development ramped following the well-known Moores law (number of transistors doubled every 18 months). It quickly became clear that high volume produced components often exceeded the reliability demands that came from the military specifications. Many of these military specifications became obsolete and best commercial practices were often adopted. Most self-respected industries developed their own reliability standards, examples are the JEDEC Standards for semiconductors [29] and the Automotive Standard Q100 and Q101.

The turn of the decade started with a well-known software reliability problem: Y2K[4]. The Year 2000 problem was a problem some questioned whether the relative absence of computer failures was the result of the preparation undertaken or whether the significance of the problem had been overstated. We will never know,

[3]The Space Shuttle Challenger disaster occurred on January 28, 1986, when Space Shuttle Challenger (mission STS-51-L) broke apart 73 seconds into its flight, leading to the deaths of its seven crew members.

[4]The Year 2000 problem (also known as the Y2K problem, the Millennium bug, the Y2K bug, or simply Y2K) was a problem for both digital (computer-related) and non-digital documentation and data storage situations which resulted from the practice of abbreviating a four-digit year to two digits.

but it brought reliability failures and the cost of them closer to the consumer. Product development times decreased to periods below 12 months. This meant that reliability tools and tasks must be more closely tied to the development process itself.

Nowadays, products with high failure rates are logged on the web leading to bad reputation for a company. In many ways, reliability is part of everyday life and part of consumer expectations [30]. The word reliability is extensively used by the general public and the technical community, as illustrated by the following: there are over 3000 published books whose title or keywords contain the word reliability; the web of science lists some ten thousand technical papers with reliability as a keyword (since 1973); and the popular search engine Google lists over 12 million occurrences of reliability on the world wide web [31, 32, 33]. The following definition of reliability is commonly used:

Reliability: *The probability that a system will perform its intended function under its life-cycle conditions for a specified period of time without failures.*

1.6 Reliability Issues in Solid State Lighting Technology

Reliability is one of the major concerns of high-tech industries. It is one of the important aspects in system integration besides cost, efficiency, and size. Not enough spending resources on reliability issues can lead to direct financial losses of global annual industrial revenue. Looking at the warranty costs of some of the big industries is an example of a great financial loss related to reliability of products [34]. It is also the reason for delayed product release, liability issues, and reduced consumer confidence. SSL technology as the novel lighting technology is not an exception. Due to the fact that SSL is a relatively new technology, research on its reliability issues and also systematic methods for design improvement is lacking.

As with any other types of products, a reliability study informs both consumers and producers about lifetime and performance of the product. Consumer uses reliability information deduced mainly from the product warranty in order to compare between different products. For the manufacturer, this information is much more insightful, in addition to providing warranty information; reliability information can be used for giving feedback to the design department. This information will not only help them for designing a more reliable product but also will assist them to formulate their maintenance and logistic plan. Therefore, a reliability study for any product is essential.

The SSL system life-cycle includes all stages of a life of a product from manufacturing, storing, handling, and operation. In some studies, the life of a product after its complete failure and component recycling also is counted as a part of the life-cycle span [35]. In this discussion the main focus is on the devices operational phase. Reliability talks about the survivals, thus the reliability curve is the reverse of the failure curve. Fig. 1.7 shows an example of a failure curve and a reliability curve. At the meeting point of these two curves half of the devices have failed. A system can be classified whether it is functional or not from the measurable inputs/outputs of the system. In this case, the measurable parameters of a basic SSL system are its light output intensity, color of the light, and consumed input power.

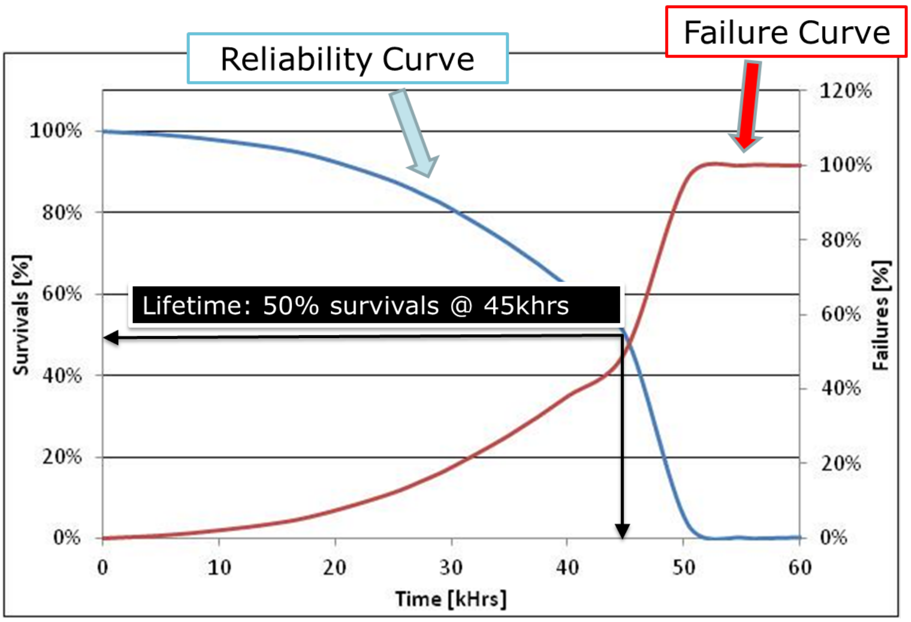


Figure 1.7: *An example of failure and reliability curve.*

There are some factors that make SSL reliability distinguished from the other lighting systems. First of all, SSL systems are new technology with very few existing field information. The second issue is the long lifetime of SSL devices, over 20,000hours, which makes testing till the end of its lifetime before releasing the product into the market almost impossible. The third factor; the more complex a system is the more failure modes evolve. For examples in a fluorescent lamp about 7 to 8 different failure mode can happen, such as broken glass and gas leakage. Above 30 to 40 different failure modes ca happen in an SSL device (Fig. 1.8). These failure modes include the catastrophic and light depreciation failure modes. In light depreciation failure mode, the device is counted as failed when the light intensity goes below a certain percentage (70% is commonly used based on "ASSIST test recommendation") of its initial light intensity [36].

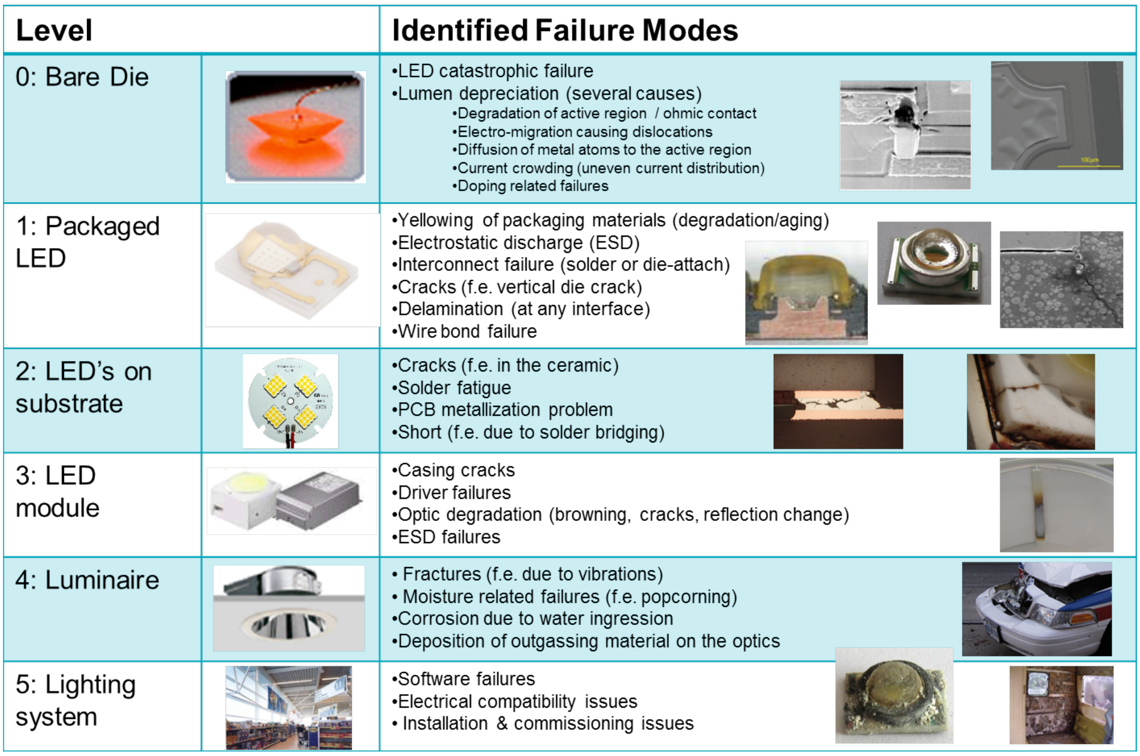


Figure 1.8: *Identified critical failure modes in different levels of a general SSL device [37].*

Due to the mentioned reasons, there is still a big need for research on reliability of SSL devices. SSL system manufacturers are still in the learning curve. In many cases the claimed lifetime for SSL devices is based on just LED's lifetime and the rest of the system has been ignored. The LEDs lifetime test results are not completely comprehensive, they are mostly a direct translation from the methods which are applied for common semiconductor devices [38] which is not sufficient. In principal, a system's lifetime depends on all its components and not just one or two of its components. Each component exhibits its own failure modes and mechanisms. Interactions of the components over each other should be taken into account for having a valid reliability study.

1.7 SSL Drivers and Their Reliability Issues

SSL driver is one of the major parts of an SSL system which has not got enough attention regarding to its reliability. The current state of the art is that the reliability of light engines have received far more attention than the electronic driver [39, 40]. One example is the work of Moon-Hwan Chang et al. [41] from CALCE Center from University of Maryland which is thorough review over the reliability of light engines in SSL products. Therefore there is a concern that SSL electronic driver may not be able to satisfy the performance and lifetime expectations. SSL drivers as a part of the system which their failures can lead the whole system to fail can become the bottle neck of the system reliability. In 2008, IESNA standard organization published two standard methods for testing HB LEDs: LM-80-08 and LM-79-08 [42, 43, 44]. But the focus in these standards is on testing of the whole SSL device. They are unable to provide information about SSL driver reliability individually. The work in this thesis introduces a systematic approach on how to deal with the reliability of SSL drivers.

In Chapter 2 there is discussion about different reliability methods and which of those methods are the best choice for studying reliability of SSL devices and more specifically in this thesis, reliability study of SSL drivers.

1.8 Research Objectives

Following the previous sections discussions, SSL is a new technology for lighting and it is evolving very rapidly. Reliability of SSL devices are a challenge due to the fact that it is a new technology and specially because a long lifetime is expected from these devices. SSL drivers as a part of SSL devices play an essential role in the reliability of the whole device. This thesis is focusing on SSL driver reliability. Besides the latter mentioned challenges, a third challenge should be mentioned. SSL driver design varies with respect to the application criteria. It means SSL driver as one term, refers to a big category of devices. The question is how to tackle these challenges toward understanding the reliability of SSL drivers. This thesis is about to answer this question with a "Systematic Approach to Address the Reliability of Solid State Lighting Drivers".

The objectives of this thesis are to find answers for the following challenges:

I. What is the most suitable reliability assessment method for SSL drivers?

II. Implementing a system-level reliability assessment methodology integrated in the design phase.

III. Implementing a multi-physics reliability assessment methodology in order to be able to predict the devices thermal / electrical behavior and consequently predict its lifetime.

IV. What happens in real life to the electrical and thermal performance of a device when it ages (Experiments on a case study)?

V. How to apply "design for reliability" for SSL devices?

1.9 Outline of the Thesis

This thesis is divided into five main chapters which describe the overview for the SSL driver technology and choosing the suitable reliability prediction method, introducing the new system-level reliability methodology, introducing a multi-physics reliability simulation, experimental results on sample SSL devices, and design for reliability for SSL devices.

Chapter 2 describes the function of SSL drivers, and their different architectures. The succeeding part is about different reliability prediction methods which are currently used for any kind of electronic devices or systems. This is followed by a discussion about how to apply each method regarding to SSL drivers. At the end, the one which is the most suitable method is chosen which will be the foundation for the rest of the work in this thesis.

Chapter 3 discusses the system view and what the best method is in order to start with reliability examination of an SSL driver. The aim is to introduce a new system-level methodology to study the reliability of SSL drivers. This methodology integrates all aspects of an SSL driver such as electrical, thermal together in order to be able to understand the behavior of the device through its lifetime and eventually being able to predict device's lifetime. After an introduction about design for six sigma (DFSS), it will be discussion about how DFSS is applied for the case of SSL drivers.

Chapter 4 follows the methodology explained in Chapter 3, by introducing a multi-physics reliability simulation method to study the reliability of an SSL driver. This method has the capability of predicting the thermal/electrical behavior of an SSL driver under study during its lifetime. This information is very valuable for design improvement. This method is explained in details. Succeeding part of this chapter is about the implementation of this simulation for a case study.

Chapter 5 presents the experimental results on an SSL driver of a halogen replacement SSL lamp. Electrical and thermal test setups are explained. Thermal and electrical performance of new samples and aged samples are reported and discussed.

Chapter 6 describes the concept of design for reliability for SSL devices. Based on this concept an SSL device is designed. The details of this design and how it can be put into operation is explained.

Chapter 7 summarizes the findings of this thesis and presents perspectives for the future work.

Chapter 2

Reliability Prediction Methods for SSL Drivers

This chapter explains about different aspects of SSL drivers reliability study. First part introduces different parts and different application fields of SSL drivers. Reliability study is meaningless without having knowledge about the device's environmental conditions. This information is defined by the SSL driver application field and the device form factor. Thus, the succeeding part is about SSL driver different topologies and application field induced criteria. It is followed by discussing the different common reliability prediction methods and their advantage/disadvantages for applying them for SSL drivers. More details on the preferred methods are explained.[1]

[1]This chapter is reproduced from the following publication: [S. Tarashioon, **Chapter: "Introduction to SSL driver reliability"**, Solid State Lighting Reliability book: Components to System, Edited by van Driel, Willem Dirk and Fan, X.J. ISBN 978-1-4614-3066-7, 2012, Springer]

2.1 Introduction

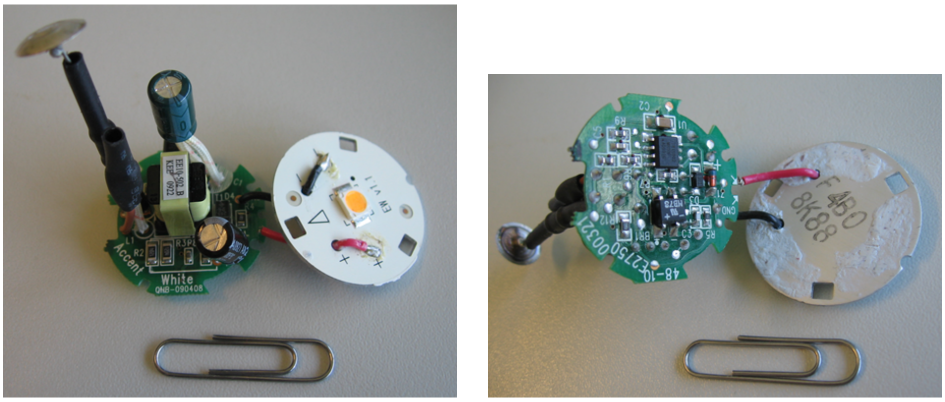
SSL drivers as one of the major parts of an SSL device plays an important role in the reliability of the whole device. SSL driver is a term which refers to more than one type of device. It can be as simple as a transistor and some passive components in case of linear topologies [13] . It can be as complex as a power converter with filters and protections including sensors and microcontroller. SSL driver design depends on its application, required light output, and manufacturer demands for size, weight, and cost. This variety makes the discussion of reliability for SSL drivers very challenging.

In this chapter, SSL driver technology and its different functional blocks are explained. Afterwards different reliability prediction methods and what method is preferred for SSL drivers are discussed. The discussions give information about important issues to know before starting a reliability analysis, and what the options are for reliability analysis. In Appendix A all standards related to SSL testing and safety are listed.

2.2 SSL Driver Functions

Regarding the "ANSI/IESNA RP-16-05 Addendum a" standard, the definition of an SSL module's electronic control circuitry is: *"electronic components located between the power source and the LED array designed to limit voltage and current,to dim, to switch, or otherwise control the electrical energy to the LED array. The circuitry does not include a power source"* [11]. In other words, an SSL module's electronic control circuitry (in this text "SSL driver") is the electrical interface to control the electrical energy between the SSL module's input power source and the SSL modules light engine.

The SSL driver input is the input power of the SSL module which is defined by the application. For example the input power for a retrofit lamp is 220Vac to 240Vac 50Hz (in European standard) and for a halogen lamp is 12Vac 100kHz. The SSL driver output is the required power input for the optical part, which is defined by the LED type, number of LEDs, and topology of LED connections. Topology of LED connection can be series, parallel, and combination of the two.



(a) Top part of the boards; the optical part is one high brightness LED.

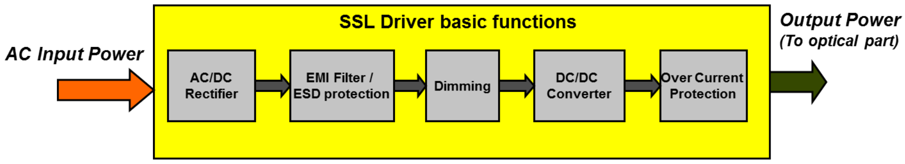
(b) Bottom part of the boards.

Figure 2.1: *SSL driver and LED board of a commercial SSL retrofit lamp. Its external enclosure and non-electrical optical parts have been removed and are not shown here.*

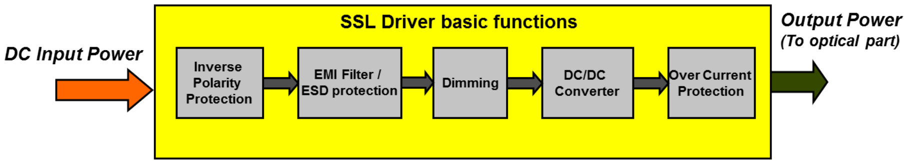
2.2.1 Basic Functions

The basic functions of an SSL driver can be defined by knowing the basic functionalities of its SSL device. SSL devices are lighting devices and therefore the very basic expected functionality is to be able to switch the light ON and OFF. The very basic function of any kind of SSL driver is to provide the proper electrical power for switching a series of LEDs ON and OFF. Fig. 2.1 shows an example of an SSL device (a retrofit lamp) which provides this very basic function. In the figure, the SSL driver and the optical part are shown. The enclosure and nonelectrical optical elements are not shown in this figure. The second functionality is dimming capability. The dimming function can be provided by the SSL driver either directly or indirectly by having dimming capability by means of an external dimmer.

Fig. 2.2 shows the major building blocks of an SSL driver with basic functionalities. The input block of the SSL driver is different based on the type of input electrical power which can be alternating current (AC) or direct current (DC). In case the input power is AC, the first block is an AC/DC converter which converts the source of alternating current (AC) to a direct current (DC) (Fig. 2.2(a)). Example for an application with AC input power is SSL retrofit lamps. In case



(a) When the input power is alternating current (AC) the input block is an AC to DC converter.



(b) When the input power is direct current (DC) the input block is an inverse polarity protection circuit.

Figure 2.2: *The block diagram of an SSL driver with its basic functions. Regardless of the input block, the rest of SSL driver building blocks are the same.*

the input power is DC, the first block is inverse polarity protection (Fig. 2.2(b)) which protects the circuit in the occurrence of inverse polarity assembly.. Example of SSL devices with DC input power is in automotive applications. The rest of the blocks in SSL drivers with AC input power or DC input power are the same:

- *EMI filter*: to filter the unwanted effects of electromagnetic interferences (EMI).
- *ESD protection*: to protect the device from Electrostatic discharge (ESD) which is the sudden flow of electricity caused by contact.
- *Dimming*: A circuitry which provides the dimming capability for the SSL device.
- *DC/DC converter*: to convert a source of direct current (DC) from one voltage level to another
- *over current protection*: to protect the device against over current which is a situation where a larger than intended electric current flows through the circuit.

SSL drivers in their simple designs do not include all the above mentioned blocks. The simplest driver for the case of AC input power includes only two blocks: AC/DC converter and DC/DC converter, and the simplest configuration for the case of DC input power is just a DC/DC converter.

DC/DC converter is counted as the core of any SSL diver. It is so important that the SSL driver type is mostly called after its own DC/DC converter topology. For example an SSL driver which has a buck DC/DC converter is called buck SSL driver. In the following section some of the most common and well known DC/DC converters used in SSL drivers are shortly explained.

2.2.1.1 DC/DC Converters Topologies

There are two categories of electronic circuit topology for DC/DC converters based on their conversion method: linear converters and switching converters [45, 46, 13]. Each DC/DC converter can be step-down, step-up converter or both. A step-down converter is a a converter which can provide output power voltage which is lower than its input voltage. In reverse, a step-up converter provides an output power voltage which is higher than its input voltage. The maximum voltage level in step-up converter is limited and defined by the values of components in the converter.

Linear converters: The basic of a linear converter's operation is based on providing the required voltage on each LED and dissipating the excess power on a resistive element such as transistor or resistor. Fig. 2.3(a) shows a simple illustration of this topology. Transistor Qn in this illustration is the resistive element which the excess power is dissipated on. From this explanation two facts can be deducted: first, the power dissipation rate can be pretty high and consequently it can have thermal problem. Second, this topology is a step-down converter. The advantage of this topology is its design simplicity and producing no electromagnetic interferences (EMI). Its disadvantage is having quite low efficiency which makes it the least favorite converter topology for SSL drivers.

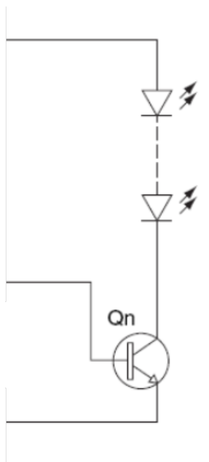
Switching converters: The basic of a switching converter operation is regulating either output voltage or output current by switching ideal storage elements, like inductors and capacitors, into and out of different electrical configurations.

Its major advantage with respect to the linear topology is higher efficiency and possibility of making a smaller size circuit. Its disadvantage is producing electromagnetic interferences (EMI). Switching converters make it possible to provide voltage both lower and higher than input voltage. In this text we will discuss three well known switching converters: buck converters, boost converters, and boost-buck converters. These three topologies are non-isolated which means the input and output voltages share a common ground. There are many other topologies such as fly-back converter which is an isolated topology, and charge pump converter which all of its energy storage components are capacitive.

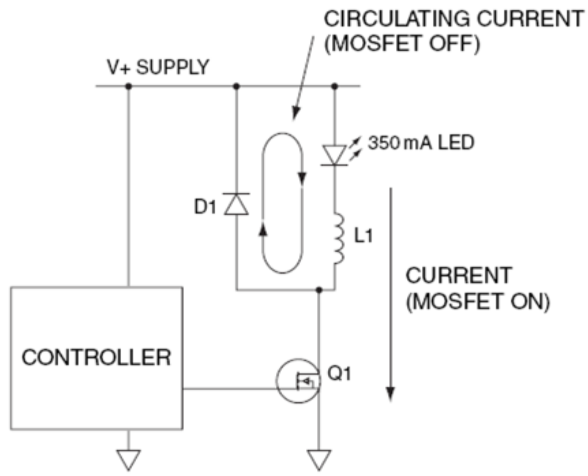
buck converter: is the simplest of the switching converters which is a step-down converter. Fig. 2.3(b) shows a simplified representation of this topology. Transistor Q1 plays the role of a switch which is being controlled by the controller. This switch is constantly goes ON and OFF. The energy is stored in the storage element -inductor L1- while the switch Q1 is conducting (ON). The stored energy is released while the switch Q1 is not conducting (OFF).

boost converter: is ideal for the case that requires output voltage greater than the input voltage (step-up). Fig. 2.3(c) shows a simple schematic for boost converters. Transistor Q1 is the switching element in this configuration which constantly goes ON and OFF. Inductor L1 and capacitor Cout are the energy storage elements.

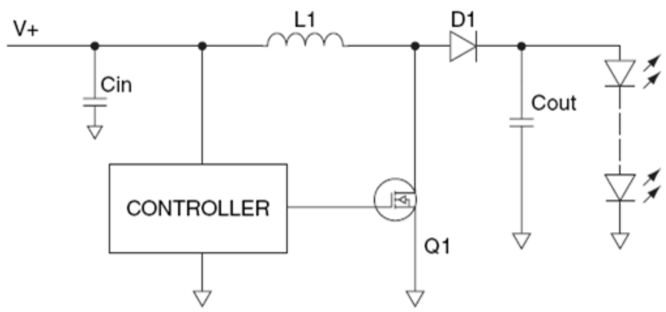
boost-buck converter: is cascade of boost converter followed by a buck converter. The advantage of this topology is that it can act as both step-up and step-down converter. One of the applications of such a topology is when the input voltage is not constant, like when the input power is from a battery. When the battery is fully charged voltage is higher than required output voltage, and otherwise its voltage is lower than required output voltage. Car headlamp which is supplied by the car battery is an example of such a case. Fig. 2.3(d) show a simplified electronic schematic for this topology. Transistor Q1 is the switching element which constantly goes ON and OFF. Energy storage elements are inductor L1 and L2, and capacitor C1.



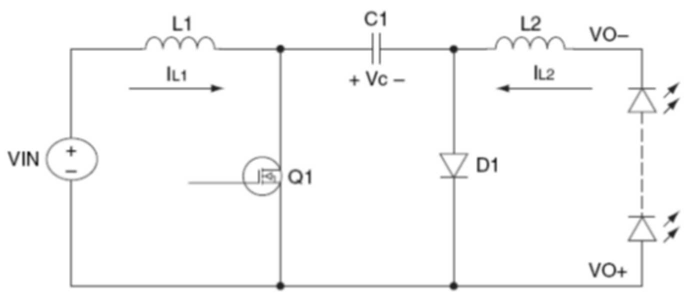
(a) Linear converter



(b) Switching converter: Buck



(c) Switching converter: Boost



(d) Switching converter: Boost-buck

Figure 2.3: *Simplified electrical schematics of DC/DC converters topologies*

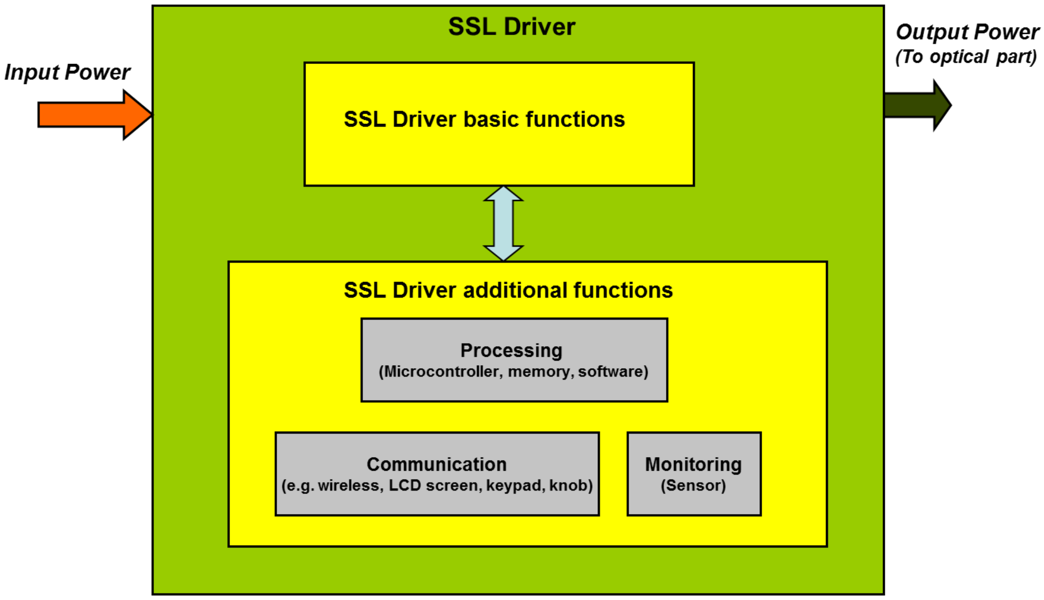
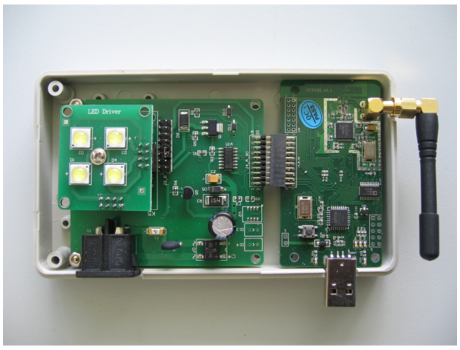


Figure 2.4: *Block diagram of an SSL driver with basic functions and additional functions.*

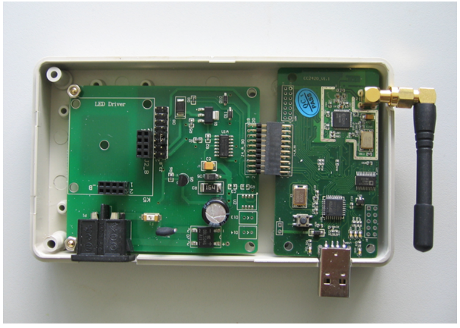
2.2.2 Additional Functions

An SSL device can be more than just a lamp. One existing example is devices equipped with motion sensors for the purpose of energy saving. In the case of not sensing any movement in their field of vision for a specific time period, the lights are turned off. These kinds of devices have some additional functionality other than the basic ones which were explained in the previous section. Generally, we can categorize the additional functions of SSL drivers into three major categories: processing, monitoring, and communication (Fig. 2.4). In the following paragraphs these three parts are explained with application examples. An example of such an SSL device with these additional functions is shown in Fig. 2.5 [47, 48, 49]. This design with details is explained in Chapter 6.

The monitoring part is a collection of sensors for monitoring environmental and internal conditions of an SSL device. The sensors for monitoring environmental conditions are mostly implemented to make smart decisions to control the light. One example is the lighting device equipped with a motion sensor. Another example is using a light sensor to measure the ambient light in order to dim the light in case of high ambient light. The sensors for monitoring the internal



(a) Complete device with optical part and SSL driver.



(b) just the SSL driver.

Figure 2.5: *An example of an SSL device with additional functions such as microcontroller, sensors,and wireless communication capability [49, 50].*

conditions of device are used for device health monitoring purposes [35, 51].

The communication part makes the communication possible between individual SSL devices, and between SSL devices and the users. SSL device can have different levels of communications for different users. The capability for dimming the light or changing the light color can be the type of the communication between the end user and the SSL device. Higher level users like system managers and maintenance people can configure the device or access data in the device's memory. Depending on the type or complexity level of communication between the device and the user, the communication part in an SSL driver can be different. It can be just a single wire connected to a switch or a screen which shows the device's status, or wireless communication for large-scale systems [15].

The processing part is a microprocessor or a microcontroller with memory which includes the software. This part controls the communication part, reads data from the monitoring part, and controls the light based on the data from monitoring part and communication part. In the mentioned example of a lighting device equipped with a motion sensor, the data from the motion sensor are processed in the processing part and the command for turning off the light is sent.

2.3 SSL Driver in Different Application Fields

Talking about reliability is meaningless without knowing the conditions that the device faces in the application field environment. Reliability study also requires to know the criteria for performance in that specific application field. Table 2.1 shows examples of application-induced criteria and product requirements. Product requirements are defined based on application fields requirements or manufacturers internal decisions. These criteria and product requirements can be divided into five categories: environmental conditions, user operation profile, performance expectation, cost, and reliability.

Environmental conditions include all the conditions that the surrounding environment forces on the device. There are four major categories of environmental conditions: electrical, physical, mechanical, and chemical (Table. 2.1). Talking about the environmental conditions for the components of a system refers not only to the ambient conditions but also the conditions that the device itself is forcing on its own different parts. For example in a retrofit lamp, the temperature of SSL driver is affected by the light engine temperature. Another example is mechanical tensile or compressive stresses on the SSL driver PCB board due to the different thermal expansion coefficients of the enclosure and the PCB board.

"Electrical conditions" are conditions such as input electrical voltage/current, frequency of switching, any undesirable electrical signals like input voltage surges and noises. As Example of an application field with harsh electrical conditions is an industrial environment with many electrical motors. The electromagnetic noise level in the environment will be high and it can affect the SSL driver with switching converters.

The two most important subcategories of "physical conditions" are temperature and humidity. High temperature and high level of humidity, and their combination are the most common failure causes for electronic circuits [52], and SSL drivers are not any exception. Examples of harsh environment regarding physical conditions is street lighting. In this application the device could be installed in a rainy, hot region and thus experience a high level of humidity and temperature. Also it could be installed in a region near a desert, which can face temperature cycling with very large temperature changes from day to night [53, 38].

Table 2.1: *Some of the application induced criteria and product requirements.*

Environmental conditions	Electrical conditions	Input voltage/current
		Noise/interferences
	Physical conditions	Humidity
		Temperature
	Mechanical conditions	Vibrations
	Chemical conditions	Chemical agents
User operation profile	ON/OFF cycle per day	—
	Electrostatic discharge	—
Performance expectations	Electromagnetic performance	Max allowed electromagnetic emission
	Thermal performance	Max allowed temperature
	Spatial performance	Power density
		Surface area
		Airflow area
	Electrical performance	output inrush current/voltage
		output current/voltage ripple
		Efficiency
Cost	—	—
Reliability	Lifetime	—
	Reliability Level	—

"Mechanical conditions" like vibration can be the kind of mechanical stresses that devices can experience. One of the application fields in which mechanical conditions become critical is the automotive application. SSL devices designed for automotive applications must tolerate a high level of mechanical stress of both vibrations from the engine source and due to driving conditions. For automotive applications the standard ISO16750-1 to ISO16750-5 help performing suitable tests regarding these conditions [54].

"User operation profile" includes all the conditions which are induced on an SSL device because the way users handle the device. Examples are how many times per day the device is turned ON and OFF and electrostatic discharge (ESD) from user touching the device.

"Performance expectation" differs from one application to another one. One of the parameters which defines the performance expectation is safety. For example, for an indoor lighting we may tolerate a systemic decrease in the light. But in an automotive headlamp, decrease in the light output decreases the level of visibility of the road for the driver, thus it decreases the level of safety. Some of the performance expectation parameters are defined in the standards and recommendations such as in classes of FCC which defines the limits for electromagnetic compatibility of the device, or ASSIST which defines the minimum accepted device's light output [36]. The electrical performance parameters for SSL drivers are the efficiency, output voltage/current level, and ripple level in the output [46]. The performance expectations for SSL drivers are usually derived from performance expectations of SSL device, for example SSL device light output expectation is translated to the required power output for SSL driver [55].

It may appear that the criteria induced from an application field should be clear before even starting the design of product. But mostly this is not the case. Referring to the US department of energy SSL manufacturing roadmap [4, 5]:

"The lack of driver standards, lack of standard reporting of driver performance, and the lack of availability of high current drivers were all identified as manufacturing roadblocks to luminaire[2] production. This is likely the result of the

[2]A complete LED lighting unit consisting of a light source and driver together with parts to distribute light, to position and protect the light source, and to connect the light source to

rapidly evolving performance of LEDs, particularly in terms of their input power requirements, and the variety of luminaire architectures, which all have different incoming power requirements. This results in the problem of most power supplies/drivers being specialized or custom products, which makes them difficult to specify and expensive. This difficulty is compounded by the varied performance reporting of the power supplies/drivers."

Table 2.2 shows an example of environmental conditions and user operation profile [3] for internal and external SSL drivers. Internal SSL driver is a built-in part inside the SSL device. External SSL driver has a separate enclosure and can be installed in a different place than the optical part.

2.4 SSL Driver Reliability Analysis

2.4.1 Reliability Prediction Methods

There are many different approaches for executing a reliability study. We can divide them into four categories. Reliability prediction methods based on "field data", "test data", "handbooks", and "stress and damage models". In this section, first there is a short explanation about each method, and afterward a discussion about how each of the methods can be used for SSL drivers. For more extensive information about different prediction methods, refer to standard IEEE1413.1 [57].

2.4.1.1 Prediction Based on Field Data

This method is the oldest method for reliability study of any kind of devices. Field data are directly representative of the device operation in device life-cycle conditions. The major challenge of prediction based on field data is how to collect the data. Three types of information are required: initial operation time, operating conditions, and failure time for the failed devices. In complex systems

a branch circuit [11].

[3] Environmental conditions plus user operation profile is usually referred to as the "mission profile" by industries.

Table 2.2: *Example of environmental conditions and user operation profile for internal and external SSL drivers.*

Item		Attribute	Unit	Internal driver	External driver
Physical conditions	Operating ambient temperature	Minimum	°C	25	-20
		Maximum	°C	85	85
		Cycles/24h		1	1
		# of operating	h/day	12	12
		# of operating	h/year	4000	4000
	Relative humidity	Minimum	%RH	30%	30%
		Maximum	%RH	60%	95%
Electrical conditions	Electrical stress (mains)	average voltage	V	230	
		range	V	110 - 277 (-6%, +8%)	
		over voltage	%	-10%, +10%	
		interrupts, spikes, surge	-	EN 61000-4-11 [56]	
Chemical Conditions	Dust	IP-class	-	NA	IP66
User Operation Conditions	Power Scheme	cycles/day	-	1	
		ON/OFF (mains)	-	ON/OFF (No dimming)	
		stand by	-	No	
		total operating	hours/day	12	

with regular maintenance and monitoring, collecting data is easier. But in home appliances we rely on information from the returned products which is not always the best representative of the whole population.

2.4.1.2 Prediction Based on Test Data

Test data are the data which are collected as the result of tests in the manufacturing environment. The value of tests depends on how much the test environment is close to the actual operational environment. Thus reliability tests should be planned very carefully. Generally, there are two types of reliability tests: non-accelerated and accelerated.

In non-accelerated one, tests are conducted under nominal load (stress) conditions. These conditions can be of any conditions that the device will face in the real operational environment. But as the conditions in the real operational environment is not always completely known, it is sometimes difficult to plan the test. The results replicate the failures found in real-life conditions. Choosing which part of the device to monitor depends on different parameters: the best point to show the functionality, the fastest point to detect failure, or the easiest point based on measurement methods and instruments.

Accelerated testing is a reliability prediction method performed within a short period of time. The length of test time is usually much shorter than the lifetime of the device in its life-cycle environment. The goal in the accelerated testing is to accelerate the damage accumulation rate for relevant wear-out failure mechanisms. Performing accelerated tests are not possible without knowing about the major failure causes. Defining the acceleration factor is very essential because if we accelerate the stress too much, the sample may fail due to a failure mode which never happens in the device life-cycle conditions. Some examples of models that can be used to derive acceleration factors are the CoffinManson inverse power law model, Rudra's inverse power law model, Peck's model for temperature - humidity, and Kemeny's model for accelerated voltage testing [31, 58].

2.4.1.3 Prediction Based on Handbooks

Handbook prediction methods can be used for reliability prediction for electronics and electrical components and systems when the failure mode is standard and previously established. The data in these handbook methods are based on historical data collected from field testing or lab testing, usually from different manufacturers of the components. For system-level reliability calculations, most of the handbook methods assume that the components fail independent from each other. All handbook prediction methods contain one or more of the following items [57]:

1. Tables of operating and/or non-operating constant failure rate values arranged by part type.

2. Multiplicative factors for different environmental parameters to calculate the operating or non-operating constant failure rate.

3. Multiplicative factors that are applied to a base operating constant failure rate to obtain non-operating constant failure rate.

The oldest reliability handbook is MIL-HDBK-217 [59] which was published in the 1960s. Examples of some popular and more updated ones are RIACs 217PLUS, Telcordia RS332, RDF 2000/2003-IEC62380, and FIDES 2009. In order to choose the proper one for the specific product there are a number of items to consider, such as age of the handbook, typical aimed products , if it contains the part count/part stress methods, if it contains the multiplicative/additive factors, and if it has any system-level considerations.

2.4.1.4 Prediction Based on Stress and Damage Model

The objective of a reliability prediction based on stress and damage model is to assess the time-to-failure and its distribution for a system and its components, evaluating individual failure sites which can be identified and modeled based on the construction of the system and its anticipated life cycle. The stress and damage model approach is based on the understanding of system geometry, material construction, operational requirements, and anticipated operating and environmental conditions [57].Fig. 2.6 is the flowchart of the stress and damage model methodology which involves:

- Reviewing geometry and materials of the constructed parts of the system.
- Reviewing loads and stresses which are being induced in the system like voltage, temperature, humidity.
- Identifying failure modes that the system can experience due to these stresses (failure causes), e.g. electrical short circuit or open circuit.
- The sites of possible failure will be specified.
- Identifying the mechanisms of the failures like corrosion, fracture, fatigue. A system is a construction of different parts and due to the loading conditions all constructed parts can fail. The ones which have a higher probability of failing sooner and will lead the system to fail are important to study. In order to distinguish the dominant failures we can use the experiences from similar systems and highly accelerated life test (HALT) [60].
- Identifying physics of failure[4] models like Arrhenius, Eyring, and Coffin-Manson models [61] for evaluating the time-to-failure for the identified failure mechanisms.
- Estimating time-to-failure for the identified failure mechanisms, by means of PoF models.
- Distinguishing the dominant failure mechanism based on time-to-failure of different failure mechanisms.

[4]Physics of Failure (PoF) is a technique under the practice of Design for Reliability that leverages the knowledge and understanding of the processes and mechanisms that induce failure to predict reliability and improve product performance.

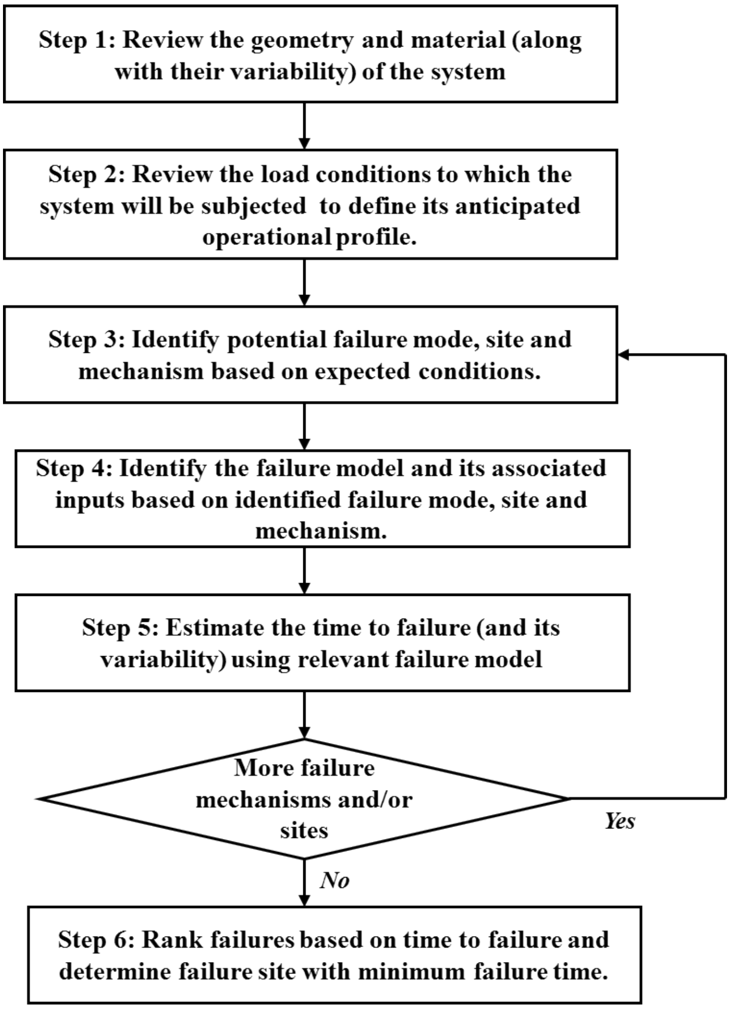


Figure 2.6: *Generic process of estimating the reliability of an electronic system based on stress and damage model [57]*

2.4.2 Comparison of Reliability Prediction Methods for SSL Drivers

In above discussions we introduced four reliability prediction methods. Applying each method for SSL drivers has advantages and disadvantages. Table 2.3 shows the general comparison between these methods. In the following paragraphs we discuss the advantages and disadvantages of each method for SSL drivers. Finally, we conclude with the most suitable method(s) for SSL driver reliability prediction.

***Reliability prediction based on field data*:** The advantage of prediction based on field data for SSL drivers is the same for every other kind of product; it is a prediction based on operation in their real life-cycle conditions. SSL is a relatively new technology with a longer lifetime with respect to other lighting technologies. The disadvantage of this method for SSL drivers is the absence of enough field data. Therefore, due to the lack of information, this is at the present not the best method for reliability prediction for SSL drivers.

***Reliability prediction based on test data*:** Illuminating Engineering Society (IES) [62] has introduced LM-80-08 standard which is an approved method for measuring lumen maintenance of LED light sources. This method covers the measurement of lumen maintenance of inorganic LED-based packages, arrays, and modules [44]. This method is a non-accelerated test method which needs the complete device to be able to run the test: optical part plus the SSL driver. The results show the behavior of the complete device and it is hard to distinguish the role of the SSL driver. The other drawback of this method is that due to very long lifetime of the SSL module and SSL driver, it will take a long time to run the test. For accelerating tests, research is still going on.

***Reliability prediction based on handbooks*:** Handbook prediction methods are still one of the most commonly used methods to predict the electronic circuits' reliability. For SSL drivers, it is also broadly used by manufacturers and designers. Appendix B is an example of using a handbook method for reliability prediction of an SSL driver for an automotive application. Using handbook method is favorable due to the fast development of SSL devices and lack of enough field information. The other reason is that manufacturers want to introduce their new products very fast to the market and prediction methods based on test data

Table 2.3: Comparison of reliability prediction methods [57].

	Field data	**Test data**	**Handbook methods**	**Stress and damage models**
Are sources of uncertainty in the prediction results identified?	Can be	Can be	No	Can be
Are limitations of the prediction results identified?	Yes	Yes	Yes	Yes
Are failure modes identified?	Can be	Can be	No	Yes
Are Failure mechanisms identified?	Can be	Can be	No	Yes
Are confidence levels for the prediction results identified?	Yes	Yes	No	Yes
Does the methodology account for material, geometry and architectures that comprise the parts?	Can be	Can be	No	Yes
Does methodology allow incorporation of reliability data and experience?	Yes	Yes	Yes	Yes (some)
What probability distributions are supported?	Not limited	Not limited	exponential	Not limited
Can it provide a reliability prediction for non-operational conditions?	No	Yes	No(except PRISM)	Yes

can be very time consuming.

The disadvantage of using handbook methods for SSL drivers is that each handbook give different results for the same product. The other disadvantage is that handbook method results do not provide any helpful feedback to the designers in order to improve the device's reliability. A further disadvantage is that the stress conditions (e.g. temperature or electrical stresses) that we can apply in handbook methods are limited. For example in the Telcordia RS322 handbook [63], the temperature can be defined but it assumes that the temperature during the lifetime of the device is constant. Therefore it is not valid for applications with temperature cycling in their lifetime, like in street/road lighting. The last but not least, the effect interrelation of the components on reliability of the whole system is not taken into account in this method. The conclusion is that although this method is often applied due to its ease of use, it is not the best choice for studying the reliability of SSL drivers.

***Reliability prediction based on stress and damage model*:** This model not only has the capability of predicting the device's time to failure, but also the potential of providing valuable information to the designers for the device's reliability improvement. This method is a very good candidate for SSL driver reliability prediction. The disadvantage of this method is that it requires much more research, and at the present time it is not able to provide a fast answer for the reliability of an SSL driver.

***Concluding statement*:** Using reliability prediction based on test data after reliability prediction based on handbooks is the most common approach in industries. The common procedure in applying reliability prediction based on test data is, after lifetime test or other tests such as HALT or temperature cycling tests [60], failed devices are examined in order to explore the failed component(s). In order to improve reliability of the device, this component(s) is being replaced with a more robust types. This is a trial and error way towards having a more reliable device. Even if the result is satisfactory, the final product may become more expensive or bigger in size.

Making use of the advantages of both reliability prediction based on stress and damage model and reliability prediction based on test data is the best choice for reliability prediction of SSL drivers. These two approaches can be applied in parallel and make use of each other's outcomes. In reliability prediction based on stress and damage model, the dominant failure mechanism based on time-to-failure of different failure mechanisms is distinguished. Based on this information and physics of failure of dominant failure mechanism, suitable accelerated tests can be planned. On the other hand, physics of failure models can be verified or extracted from the results of test data.

2.5 Conclusions

The goal of this chapter is to cover the general information for studying the reliability of an SSL driver, and to distinguish the most suitable reliability prediction methods. There are four common reliability prediction methods. Reliability predictions based on handbooks have been criticized due to their lack of accuracy. Reliability prediction based on field data is not applicable yet because of long lifetime of the SSL and it being a relatively new technology. Reliability prediction methods based on stress and damage models and based on test data are the most suitable ones for the case of SSL drivers. The method based on stress and damage models can not only give estimation about lifetime of the driver, but also include valuable information for designers to improve the design regarding reliability issues. The disadvantage of this method is that it is not a fast solution. It takes time to understand and develop a proper model for every product.

Chapter 3

Towards a System Approach for Driver Reliability

The product design procedure of an SSL device based on design for six sigma (DFSS) is the opening for discussions of this chapter. A new method for partitioning an SSL driver which is introduced in this work is the foundation of a new system-level methodology to study the reliability of SSL drivers. This methodology integrates all aspects of an SSL driver such as electrical and thermal together in order to be able to understand the behavior of the device through its lifetime, and eventually being able to predict the device's lifetime. [1]

[1]This chapter is reproduced from the following publication: [S. Tarashioon, W.D. van Driel, G.Q. Zhang, **System Approach for Reliability of Low-power Power Electronics; How to Break Down into Their Constructed Parts**, CIPS 2012, 7th International Conference on Integrated Power Electronics Systems March, 6th - 8th, 2012 Nuremberg / Germany, ISBN: 978-3-8007-3414-6]

3.1 Introduction

The components reliability is not the major concern anymore in reliability of a device [64]. The components reliability has been greatly improved during the previous years. The way to tackle the reliability issues of the devices is to look at it at the system-level. There is plenty of research regarding the component level, but there are very few works on the system-level, specially on the interactions of the components in the system [65]. Reliability study on the system-level means exploring the effect of the system components on each other and consequently on the whole system reliability. In this thesis the focus is on studying the reliability of SSL drivers at the system-level. The best way to enter this discussion is to look at the big picture of a product design. We talk about the product design procedure of an SSL device based on design for six sigma (DFSS). Then we will point at the blocks which are the concern of this thesis.

The rest of this chapter discusses about a system approach toward reliability assessment of SSL drivers. In order to study a complex system, the first step is partitioning the device[2]. It means to break down (not physically) the device into its constructed parts, then study each partition and finally put all data together to be able to talk about the whole device. In this method the interactions of different parts of the system is a major criteria.

3.2 A Summary on Design for Six Sigma

Design for Six Sigma (DFSS) is an emerging business-process management methodology related to traditional Six Sigma. DFSS is a design methodology that focuses on quality and is used within in the development process. DFSS is applied to new products and processes with the goal of improving the designed product in terms of customer value, quality, reliability, and cost [17]. For the people familiar with the traditional six sigma method, the interesting information is to know the differences between them. Although both Six Sigma and Design for Six Sigma have their similarities, and DFSS can be seen as the predecessor of Six Sigma, there are some important differences between the two methods [66]:

[2]This term should not be confused with partitioning term in disk partitioning in computers.

- Six Sigma is intended for existing products or services, while DFSS is for new products, services or processes.
- Six Sigma is more focused on reacting, detecting and resolving problems, while DFSS is a more proactive approach as a means of preventing problems.
- Six Sigma is based on manufacturing or transactional processes and DFSS is focused on marketing, research, and development and design.
- Six Sigma projects allow for a more quickly quantification of financial benefits, while DFSS financial benefits are more long term as well.
- DFSS involves a greater cultural change than Six Sigma. It represents a major change in roles since there is a cross-functional team and for all members it is important to be involved in all aspects of the design process, from market research to product launch.

DFSS can be defined as "a disciplined process that provides the user with a structured methodology for the efficient commercialization of new products, processes and services" [67]. In this definition a product is an entity which can be sold to a company or consumer for use. A process is the manufacturing or transactional process to create a product. A service is a value added activity which is provided by the company to make the use of the product easier for the customer. DFSS spreads over the whole product life cycle process from identification of customers needs to the launch of the commercialized product or service. The main goal of DFSS is to do things right such that the scope of the project does not have to be changed later in the process where it will cost a lot more.

According to estimations only 60% of new products launched are a success and about 45% of resources spent in developing and commercializing new products go into products that are killed or fail to generate sufficient revenue [68]. According to the Product Development Management Association (PMDA) of every eleven ideas evaluated by a company only three enter development and only one of those three succeeds [69]. One of the main causes for the above is inadequate understanding of customer needs, which will never put a company in the position to create a product that will bring value to those customers [67]. **Reliability is**

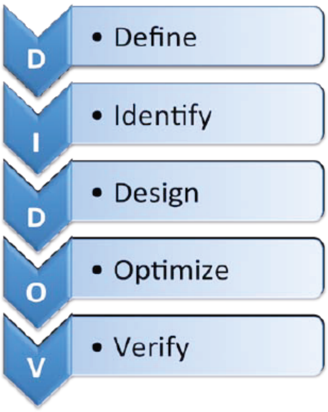


Figure 3.1: *DIDOV roadmap of design for six sigma.*

always one of the requirements that customer asks for a product. This problem occurs in lots of companies. The engineers have not directed all their thinking toward the goal of customer satisfaction. This holds especially in the situation when engineers are working on a small sub-project where the link with the end product is not that easy to see. What happens is that in a team everyone thinks inside his own field of responsibility.

DFSS however is making use of a cross-functional team that represents all relevant areas of the business. People from different functional groups and with different experiences and skills cooperate towards the goals. This enables a synergy maximizing the output of each individual, which is brought to the project. Everyone should have a specific and clearly defined role with consequences or rewards linked to the execution of task. Also, all relevant knowledge and information are made available to the teams such that they can make decisions based on data instead of personal judgment. The DFSS approach ensures that the products and services to be developed meet customer requirements while enabling the business to reduce time, improve quality and benefit financially [66, 70].

There are different roadmaps for the execution of the DFSS. They differ up to a certain extent, but they do go through similar steps towards the same basic goals [67]. One of these roadmaps is DIDOV: Define, Identify, Design, Optimize, and Verify (Fig. 3.1).

The "Define step" is the foundation of all other steps to come. The project charter is created in this step which clearly defines the scope and goals of the project, a schedule, milestones and deliverables as well as a justification on the business case. This will serve as a contract within the team, which will be set up in this step as well to execute the project, stakeholders and the company itself.

Next, the "Identify step" starts in which the customer is the important subject. Efforts will be undertaken to identify the customer and his needs. These are gathered and translated into measurable and verifiable specifications and requirements.

After collecting the requirements several ways to fulfill the customers need while complying with his requirements are researched in the "Design step". The several alternatives are evaluated and a best solution is chosen. The best solution should not only have the highest probability to meet the requirements, but also be free of failure potential.

Choosing the best alternative will be followed by an optimization of the design in the equally named "Optimize step". The design is optimized in such a way to get the best out of the selected concept while still confirming that all requirements are met. Statistical tools are used to predict the quality, performance, and reliability of the product. The design is optimized as much as possible taking into account all requirements.

In the "Verify step" confirmation is sought whether the design is working as expected as it should address the customer needs while complying with all requirements. The design will be verified, the process will be validated, prototypes are built and tested and of course all of the lessons learned have to be captured and documented.

3.3 Different Phases in SSL Product Life-Cycle

By learning from DFSS about a disciplined process for a new product, in this section we will have a helicopter view of different phases of an SSL device life-cycle with focus on reliability. In Fig. 3.2 different phases of an SSL device's life cycle is illustrated. A product's life-cycle is the period of time that begins when

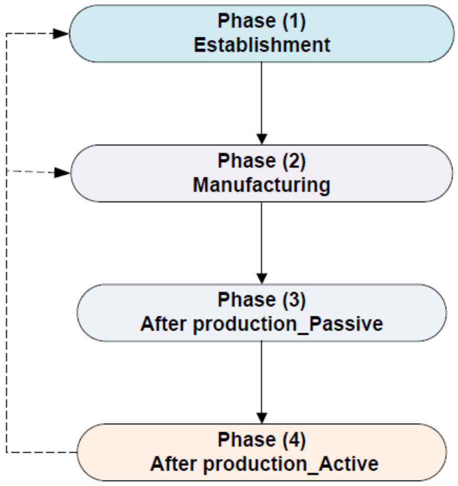


Figure 3.2: *Four major phases in SSL system's life-cycle. Phase (1) is establishment phase. Phase (2) is manufacturing phase. Phase (3) is after production Passive phase, it includes all activities after manufacturing till the time the system becomes operational for the first time. Phase (4) is after production Active phase, in this phase the system can be operational, standby or under maintenance.*

a system is conceived and ends when the system is no longer available for use[3] [57].

A device's life-cycle includes all stages from project initiation till end of its lifetime: establishment phase, manufacturing phase, after production passive phase, and after production active phase. In the following paragraphs these four steps are explained with more detail with focus on the reliability.

3.3.1 Establishment Phase

The establishment phase for a new SSL product shown in Fig. 3.3 starts by either a new idea or a requirement in the market. It is started by defining the application requirements such as the light output intensity, size, form, input power. The next step is to define the product life-cycle profile such as temperature level in operational field. This matter has been discussed in the previous chapter with details. Based on the requirements, the product's first design is accomplished. Then reliability assessments which include FMMEA (Failure Mode Mechanism and Effect Analysis) and reliability virtual assessment are performed on the design. After reliability virtual assessment, if the results are not satisfactory, design should be modified and go through the same procedure again. After assessment,

[3] Some literature mention the product recycling as the very last phase of a product's life [35]

if the results are satisfactory the design is continued by adding a monitoring part for prognostics and health management (PHM) purposes which will be explained with detail in Chapter 6 of this thesis. Then a prototype is made, and functionality and reliability tests are performed on the samples. In case of success this phase is finished and the design is adequate for mass production. The three reliability related blocks in the flowchart in Fig. 3.3 will be covered through this thesis:

- In the following sections of this chapter the procedure of applying FMMEA on a general SSL driver is explained.
- Chapter 4 of this thesis introduces a new methodology on virtual reliability assessment (reliability simulation).
- Chapter 6 of this thesis is about the design for reliability in SSL systems, how to put prognostics and health management discipline into practice for an SSL device, and an SSL system is designed with such a capability.

3.3.2 Manufacturing Phase

Details of manufacturing phase shown in Fig. 3.4 depends on chosen technology during establishment phase and is outside the scope of this thesis. We can shortly mention that devices are manufactured and tested in this phase before being released into the market. Test procedures come from standards, establishment phase, and after production active phase (in case data from previous versions of the device exists).

3.3.3 After Production Passive Phase

After device manufacturing, each product will undergo periods of storage, handling and installing (Fig. 3.5). These three phases are also part of the device's lifetime where failures may occur. However, the failures occur during these periods are usually ignored due to the difficulty of monitoring the devices status.

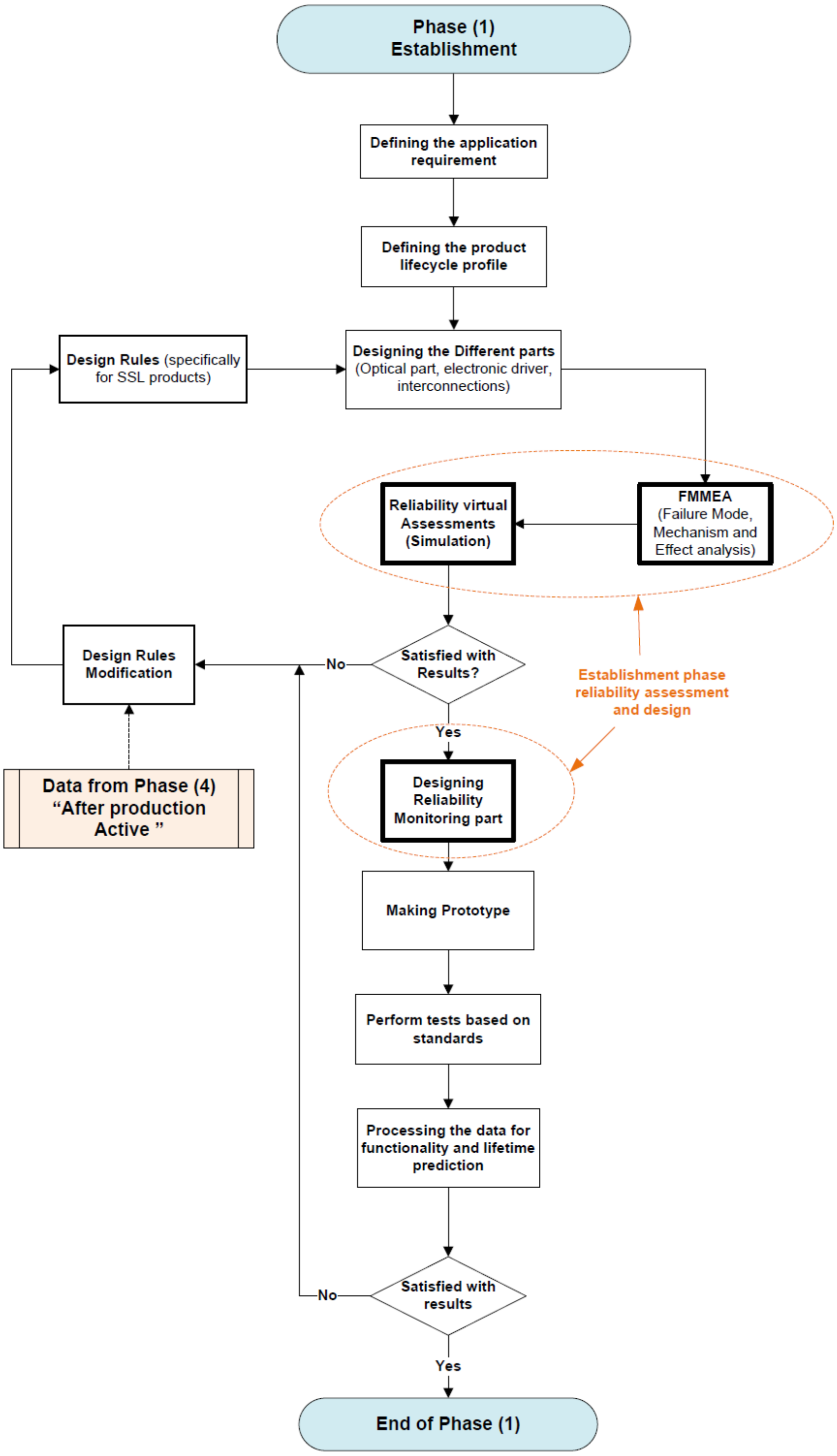


Figure 3.3: *Establishment phase for the SSL products. (The blocks with thicker lines are related to or affected by the reliability examination process.)*

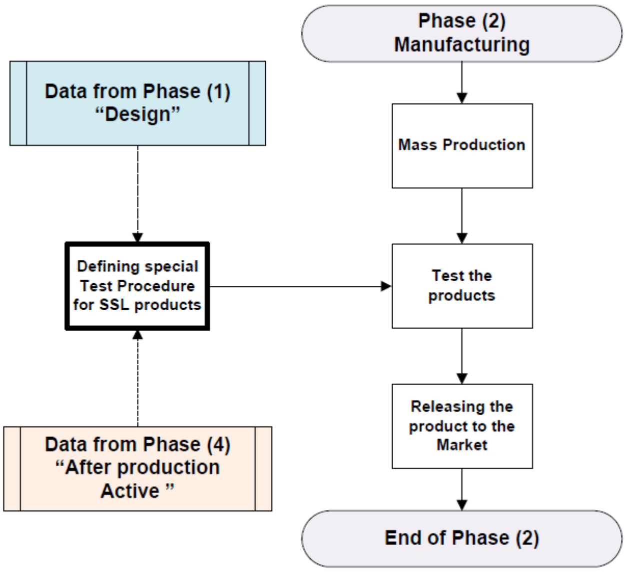


Figure 3.4: *Manufacturing phase for the SSL products. (The blocks with thicker lines are related to or affected by the reliability examination process.)*

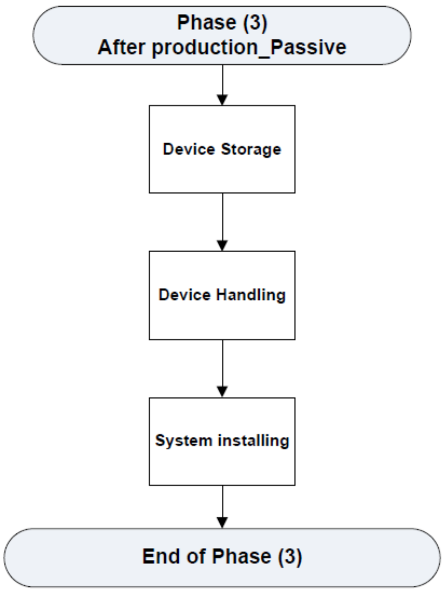


Figure 3.5: *After production passive phase for the SSL products.*

3.3.4 After Production Active Phase

This phase includes the stages that the device is put in operation, when it fails, and when it is maintained[4] (Fig. 3.6). The conventional method for failure detection of the device is either by random inspection like for in-door applications, or by regular maintenance visual inspections like for out-door applications. A novel method for failure detection is prognostics and health management.

The monitoring part can be any kind of sensor such as light sensor, temperature sensor, and humidity sensor. The type of sensors and their locations are defined by the reliability assessment in the establishment phase. The data collected from the sensors are then processed in order to define the status of the system and consequently the lifetime of the device. The system should have a processing capability for accomplishing this task. An example of this approach is in the work of Jianfei Dong et al.[72]. In Chapter 6 of this work there is an example of an SSL device design with capability of system prognostics and health management.

After the failure or degradation of the system is detected, the system should be able to compensate for the failure through self-maintenance or reporting the failure to the maintenance operator. Self-maintenance methods are methods during device operation which can keep the device functional for longer time. One good utilization for this capability is being able to elongate the lifetime until the arrival of maintenance operators. In critical applications such as automotive lighting and street lighting, these methods can increase the level of safety. The device should be able to predict its end of lifetime. One of the most well known design techniques in design for reliability is redundancy. Redundancy is the duplication of the critical components or functions of a system with the intention of increasing reliability of the system. It means that if one part of the system fails, there is an alternate success path, such as a backup system.

[4] In some of the reliability engineering studies the end of lifetime of the device is when it fails for the first time [71].

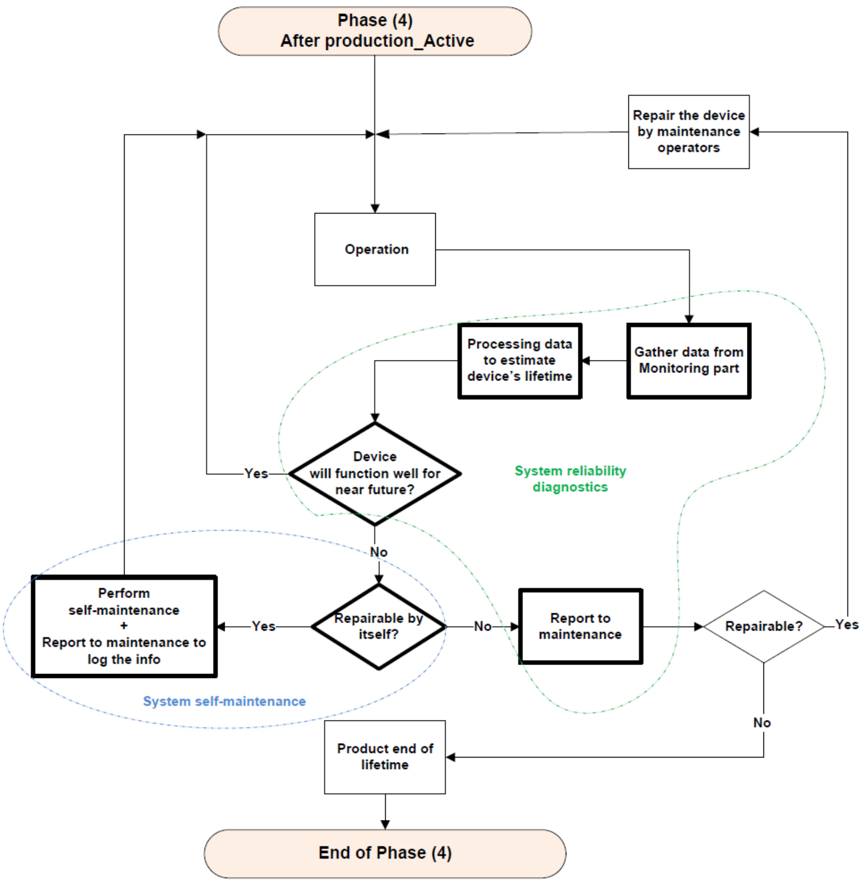


Figure 3.6: *After production active phase for the SSL products. (The blocks with thicker lines are related to or affected by the reliability examination process.)*

3.4 Partitioning an SSL Driver into its Constructed Parts

Discussing about reliability of a complex device is not possible unless we start with distinguishing its least complex elements. After studying the reliability of these elements, we can put them together to have a reliability model for the whole device. This act of distinguishing less complex elements of a system is called partitioning in this thesis. Partitioning is the act of breaking down (not physically) the device into its constructed parts for the purpose of reliability study. A smart way of partitioning the device makes the reliability study easier and more accurate.

The existing partitioning methods will be discussed in this section under the category of traditional partitioning methods. A new method for partitioning SSL drivers will be introduced in this work. Based on this new method, the foundation of structured reliability study of an SSL driver is established. It is followed by explaining how to apply this method during a reliability assessment.

Performing the partitioning on any device requires a good knowledge over the device itself. In Chapter 2, SSL driver technology is explained. Its different constructed blocks and their functionalities are reviewed. But shortly here to refresh the memory: SSL drivers which provide power for the optical part of SSL devices are Low-power power electronics which work in power range of few watts to few hundred watts. The majority of devices in this power range use printed circuit boards (PCB) for the electrical interconnections and mechanical support for the components. Depending on the components and power dissipation, power components may have been assembled on heat sinks for better thermal dissipation. The rest of the components are cooled by air convection or in some less common cases by active cooling. Depending on the device application field conditions, the whole assembly is enclosed in an enclosure made of metal, silicon based materials or epoxies for protection [73, 74, 75].

3.4.1 Traditional Partitioning Methods

There are two existing common approaches used by reliability engineers for partitioning an SSL driver. The tree structure[5] of these two methods are shown in Fig. 3.7. Both methods are used by reliability engineers.

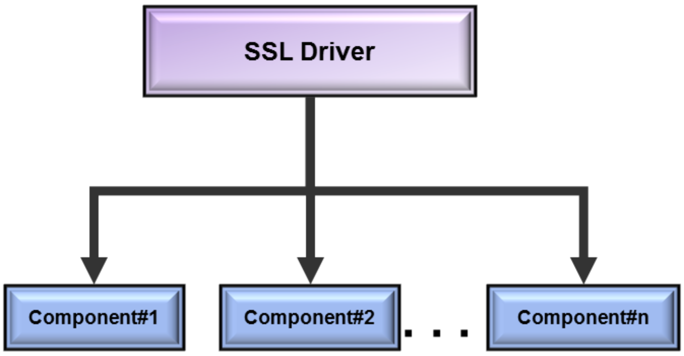
The first method shown in Fig. 3.7(a) is partitioning the device into its physical components, like high power transistors, diodes, capacitors, and inductors. The components in this discussion refer to the products that can be directly soldered on a PCB board, for example an off-the-shelf transistor. Fig. 3.8 shows some example of these components. This method is mostly used in reliability assessments based on handbooks such as MIL-217 or Telcordia [59, 63]. In reliability handbook methods, there are lookup tables of the FIT rates [6] for different components. By adding up the FIT rates of all components together we can have the FIT number of the whole device. Appendix B shows an example of applying one of such a handbook method on a case study.

In the second partitioning method shown in Fig. 3.7(b), the device is divided into its major subsystems and then each subsystem into its components. Subsystems are a part of a bigger system and they perform a specific function. Examples of subsystems in SSL drivers are filter, AC/DC converter, over current protection, DC/DC converter. The components in this discussion are the same as in the first method; such as high power transistors, diodes, capacitors, inductors including their packagings. One of the good examples of when this method is applied, is in an FMEA (Failure Mode and Effect Analysis) [76, 77]. The FMEA method gives some information about the potential failures of the system but no specific number for failure rates. FMEA identifies potential failures of different components, their effect on the system-level, and finally suggesting a level of severity for this failure. This method of partitioning the system helps to define the risk of each component's failure into the whole device's failure.

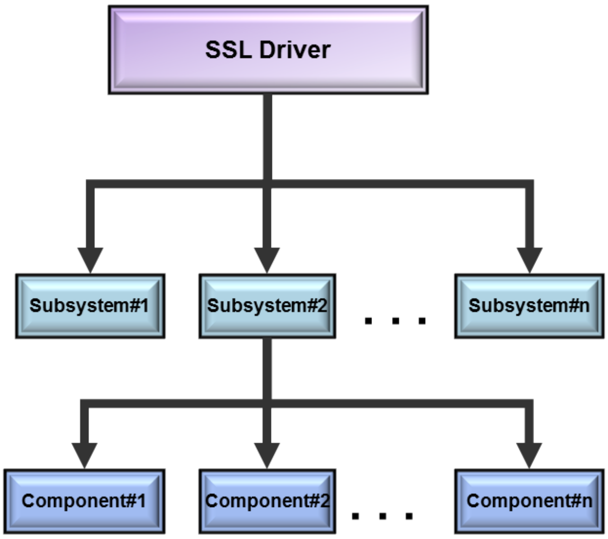
In both above mentioned methods shown in Fig. 3.7, the lowest elements are

[5] A tree structure is a way of representing the hierarchical nature of a structure in a graphical form. It is named a "tree structure" because the classic representation resembles a tree, even though the chart is generally upside down compared to an actual tree, with the "root" at the top and the "leaves" at the bottom.

[6] The Failures In Time (FIT) rate of a device is the number of failures that can be expected in one billion (10^9) device-hours of operation.



(a) Used in reliability handbook methods.



(b) used in reliability method based on test data and stress and damage model.

Figure 3.7: *Tree structure for two common methods of partitioning the device for reliability purposes. Both methods end with physical components (refer to Fig. 3.8).*

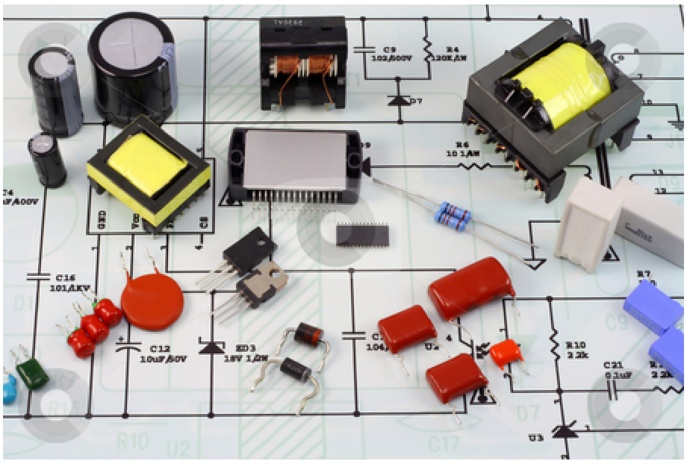


Figure 3.8: *Examples of components used in an SSL driver.*

complete physical components including their packaging. Distinguishing these components is very straight forward. Performing standard physical reliability tests like thermal cycling, HAST, and JEDEC has been defined for these physical components [78]. The drawback of these traditional methods is their limited capacity of usage in a system reliability study while taking into account the interactions between components. The new partitioning method has the capability to tackle such limitation.

3.4.2 New Partitioning Method

The new partitioning method for SSL drivers is based on the functionality that each element performs in the device. Fig. 3.9 shows this new partitioning method for an SSL driver with switching converters. Linear converters are not discussed because they are rarely used in SSL drivers (refer to Chapter 2). This method has been used by J. Popovic [79] for the different purpose of discussing the level of integration in power electronics. As it can be seen in Fig. 3.9, the device has been divided into two major parts which are functional elements and packaging elements.

Functional elements discussed in this work, as mentioned above, are only valid for SSL drivers with switching converters. Understanding the switching topology for converters helps with understanding the functional elements in this discussion.

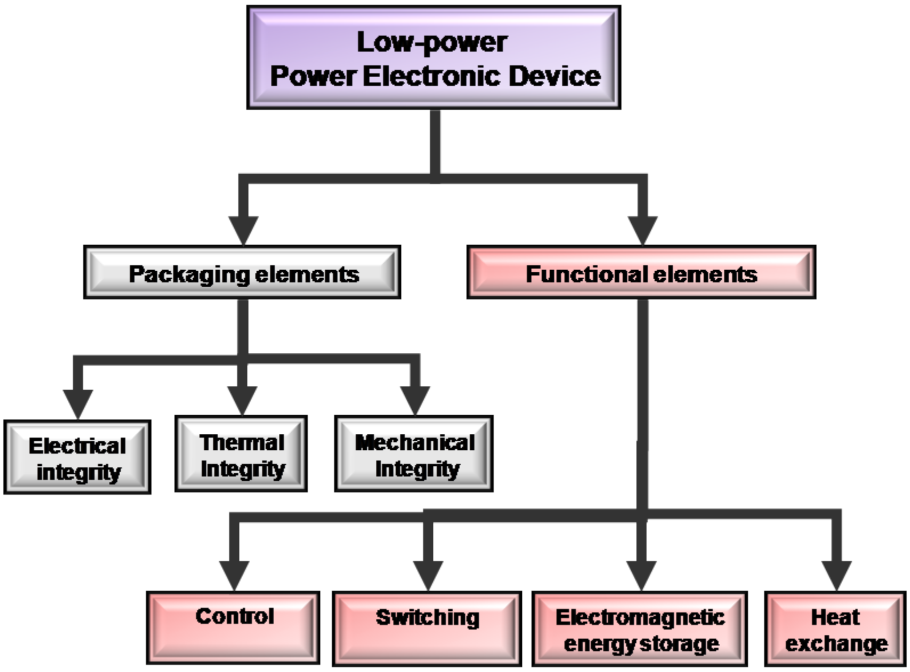


Figure 3.9: *Tree structure for the new method introduced in this chapter for SSL driver partitioning for reliability purposes. The end results are elements of different parts which are categorized based on the function they perform.*

The functional elements are control part, switching part, energy storage, and heat exchange part. For the case of SSL drivers with linear topology the functional elements are different. We can add more parts to the functional elements with respect to the applications and designs. Packaging elements include three parts; electrical integrity, thermal integrity and mechanical integrity.

3.4.2.1 Functional Elements

The main functionality of an SSL driver is embodied in the following functions. It should be mentioned that in this part the additional functions that were discussed in Section 2.2.2 are not taken into account [74]:

- Switching function: Controls the flow of electromagnetic energy through the converter.
- Control function: Enables the required relationship among the previous functions.

Table 3.1: *Typical functional elements in SSL drivers.*

Fundamental Function	**Functional elements**
Switching	Power semiconductor die (MOSFET, diodes)
Control	Control semiconductor die (Silicon die)
Electromagnetic energy storage	Magnetic core Magnetic wire and planar copper conductors Metalized foil Metalized ceramic layer
Heat exchange	Heat sink Heat pipe Fan

- Electromagnetic energy storage function: Provides the continuity of energy when interrupted by the switching function.
- Heat exchange function: Provides the exchange of the heat dissipated in the converter with the environment.

These functions will be referred to as "fundamental functions". In Table 3.1, the typical functional elements in SSL drivers are shown.

3.4.2.2 Packaging Function Elements

Packaging function elements are necessary since they provide the connection between fundamental functions and also gives integrity to the whole device[79].

- Functions that provide electrical integrity:
  - Electrical interconnections: Providing electrical path for power and signals.
  - Electrical insulations: Providing integrity of electrical signals.
- Function that provides thermal integrity: Provides heat paths for the dissipated heat from the dissipated part to the heat exchanger in order to ensure that these parts operate in their allowed temperature range.

- Functions that provide mechanical integrity:
  - Mechanical support: Provides mechanical support, rigidity, and ductility.
  - Environmental protection: Provides protection of the parts and assembly from damaging due to handling and environmental effects, especially moisture.

These functions will be referred to as "packaging functions". One element in the device can provide more than one of the functions, e.g. copper traces on the PCB board act as electrical interconnections and thermal integrity. In Table 3.2 the typical packaging elements in SSL drivers are mentioned.

3.4.2.3 Case Study

In order to clarify this new partitioning method, functional elements and packaging elements of a case study shown in Fig. 3.10 will be explained. This case study is an SSL driver with step-down buck topology DC/DC converter. The components of this case study are as follows:

- Film resistor R as the input resistor
- Metalized film roll capacitor C1 as the input capacitor
- Controller IC as the control part for the switching converter
- Diode D as the switching element (or freewheeling diode)
- Transistor MOSFET Q1 as the switching element
- Inductor L as the electromagnetic energy storage element
- Capacitor C2 as the energy storage element

Functional elements and packaging elements of the case study components are shown in Fig. 3.11 and Fig. 3.12.

Table 3.2: Typical packaging elements in SSL drivers.

<table>
<tr><th colspan="2">Packaging function</th><th colspan="2">Packaging elements</th></tr>
<tr><td rowspan="4">Electrical Integrity</td><td rowspan="2">Interconnection</td><td>Component level</td><td>Wire bonds
Semiconductor lead frames
Bobbins (pins)
leads</td></tr>
<tr><td>Assembly level</td><td>Copper tracks
Via holes
Copper bus bars
pins</td></tr>
<tr><td rowspan="2">Insulation</td><td>Component level</td><td>Wire insulation</td></tr>
<tr><td>Assembly level</td><td>Dielectric carrier (PCB dielectric, ceramic)
Dielectric tapes, adhesives</td></tr>
<tr><td rowspan="4">Mechanical Integrity</td><td rowspan="2">Mechanical support</td><td>Component level</td><td>Leads and lead frames
bobbin</td></tr>
<tr><td>Assembly level</td><td>Circuit carrier
Base plate
Bus bars</td></tr>
<tr><td rowspan="2">Protection</td><td>Component level</td><td>Polymer case (molded plastic, epoxy coating)</td></tr>
<tr><td>Assembly level</td><td>Silicon gel
Metal housing</td></tr>
<tr><td colspan="2" rowspan="2">Thermal integrity</td><td>Component level</td><td>Cases, lead frames</td></tr>
<tr><td>Assembly level</td><td>Thermally conductive circuit carrier
Thermal interface materials</td></tr>
</table>

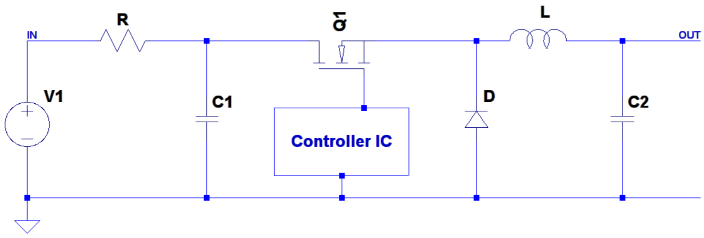


Figure 3.10: *Case study: a switching DC/DC buck converter.*

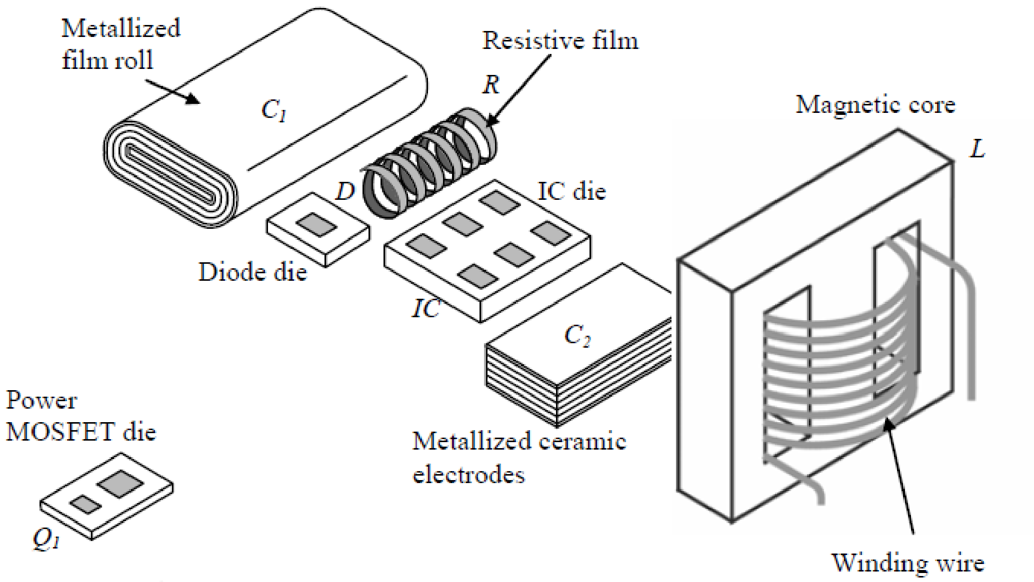


Figure 3.11: *Functional elements in the SSL driver components of the case study in Fig. 3.10 ([75]).*

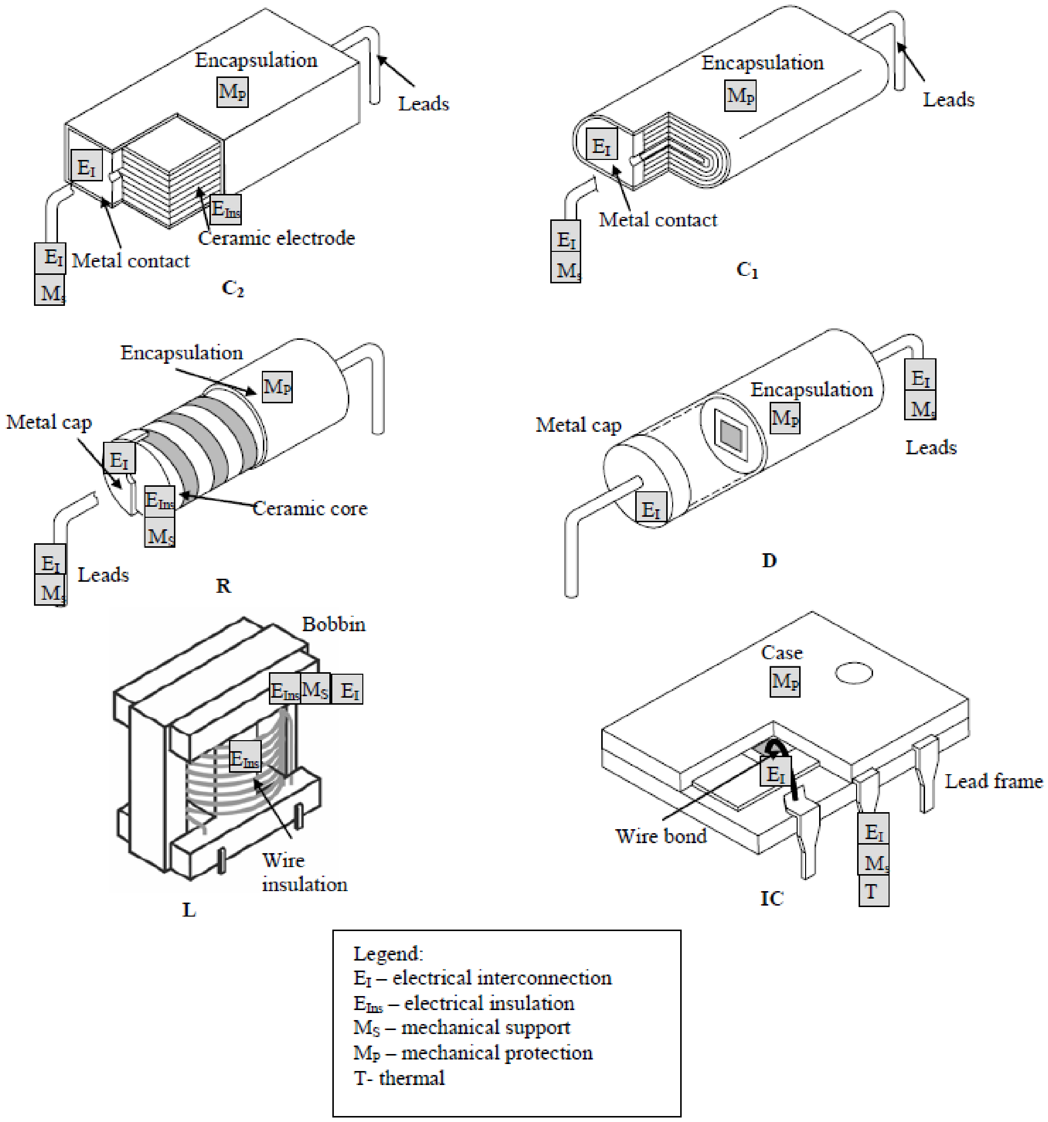


Figure 3.12: *Packaging elements in the SSL driver components of the case study in Fig. 3.10 ([75]).*

3.4.2.4 Discussions on the New Partitioning Method

During any component's design and production phase, different aspects such as electrical and thermal has been taken into account. Also during the reliability study, attention is required for every single aspect. In other words, the same fields of profession needed for the design and production, is also needed to understand its reliability.

In case of SSL drivers or any other electrical product, the main function of the product is designed by an electrical professional. Its enclosure is designed by a mechanical professional. A thermal professional helps with the thermal issues in the electrical circuit and also the enclosure part. At last, if there is any concern about electromagnetic interferences, a professional in that field helps out with all stages of the design. The preferred reliability study should engage the same four professionals.

There are several advantages in employing this method with respect to the traditional partitioning methods. First, prioritizing the failure modes in order to distinguish the dominant mode is easier. For example a small crack in the enclosure of a lamp for indoor applications may have no harm to the device's reliability, though the same crack in a lamp for street lighting which faces high percentages of humidity can be fatal. Second, this methodology helps with having more structured reliability study procedure and therefore make it more possible applying it into a computer program [80, 81]. Last but not the least, this partitioning method establishes the foundation of a multi-physics reliability simulation which will be introduced in the next chapter.

3.5 Apply New Partitioning Method for Reliability Prediction

Reliability assessment based on stress and damage model was discussed in Chapter 2 as the most suitable method (Accompanying with reliability assessment based on test data) for studying the reliability of SSL drivers. In this method after distinguishing the different constructed elements of an SSL driver, we can discuss the potential failure modes, mechanisms, and failure causes. Eventually, this partitioning method is used as a tool to reach the goal to perform a virtual reliability assessment.

3.5.1 Potential Failure Modes, Mechanisms and Failure causes

In the generic process of reliability prediction of a device based on stress and damage model (refer to Chapter 2), it is required to identify the potential failure mode, site, and mechanism according to the load conditions. In previous section, it was explained how to partition an SSL driver. Some potential failure causes, modes, and mechanisms of different parts of an SSL driver are identified based on the existing literature.

Different stress loads on an SSL driver can be the "failure causes" for SSL driver failure, such as thermal, electrical, and mechanical stresses. There are four major categories for failure causes. The focus is on environment induced failure causes and how we can affect the design process induced failure causes.

- Design process induced failure causes
- Manufacturing process induced failure causes
- **Environment induced failure causes**
- Operator/maintenance failure causes

A "failure mode" is the observed electrical or visual symptom which generally describes the way the failure occurs. Failure modes can range from catastrophic to slight degradation, and they are typically categorized as functional, parametric shifts (which results from degradations), or visual. An example of catastrophic failure mode in electrical components can be short circuit or open circuit.

"Failure mechanisms" are physical, chemical, or other processes that cause a failure. Different types of failure mechanisms can lead to the same failure mode. As examples of failure mechanisms we can mention electromigration (EM) in interconnections and dielectric breakdown in transistors [82, 53].

After partitioning an SSL driver some of their typical failure modes, mechanisms, and causes are explained. In Table 3.3 there is a list of the functional

Table 3.3: *Examples of potential failure modes and mechanisms, and their causes for functional elements in SSL drivers [35, 54, 65].*

Fundamental Function	**Functional elements**	**Potential Failure Mode / Failure Mechanism**	**Failure Causes**
Switching	Power semiconductor die (MOSFER, IGBT, diodes)	Time dependent dielectric break down	Voltage, Temperature
Control	Control semiconductor die (Si die)	Fatigue in Die attach, Fatigue in wire bonding, Corrosion in metallization, EM in metallization, time-dependent dielectric breakdown (TDDB), fatigue in solder leads	Temperature, Current density, Humidity, Voltage cycling, Mechanical stress
Electromagnetic energy storage	Magnetic core,Magnetic wire and planar, copper conductors,Metalized foil, Metalized ceramic layer	Wire corrosion, dielectric breakdown, Termination break, Fracture in ceramic dielectric, internal delaminations or void, silver migration	Voltage, Temperature, Mechanical stress
Heat exchange	Heat sink, Heat pipe,Fan, Thermal Pads, copper planes	Fatigue in bond pads, thermal paths and traces	Mechanical stress, Voltage

elements and their potential failures. It is followed by the list of typical failures of packaging elements of an SSL driver in Table 3.4.

Table 3.4: Examples of potential failure modes and mechanisms, and their causes for packaging elements in SSL drivers [35, 54, 65]

Packaging function		Packaging elements		Potential Failure Mode / Failure Mechanism	Failure Causes
Electrical integrity	Interconnections	Component level	Wire bonds,Semiconductor lead frames,Bobbins (pins)leads	Fatigue in wire bonds, fatigue in lead frames, electromigration	Temperature cycling, Voltage, Humidity
		Assembly level	Copper tracks,Via holes,Copper bus bars,pins	Delamination and crack in copper tracks, solder joint fatigue / cracking	Voltage, Temperature, Mechanical stress, temperature cycling, vibration
	Insulation	Component level	Wire insulation	insulation melted	Temperature
		Assembly level	Dielectric carrier (PCB dielectric, ceramic) Dielectric tapes, adhesives	Fracture in dielectric	Temperature, Voltage
Mechanical integrity	Mechanical support	Component level	Leads, lead frames,bobbin	Substrate cracking, underfill cracking	Temperature cycling
		Assembly level	Circuit carrier,Base plate,Bus bars	Circuit carrier cracking	Mechanical stresses, vibration
	Protection	Component level	Polymer case (molded plastic, epoxy coating)	Package cracking	Temperature cycling, Voltage
		Assembly level	Silicon gel,Metal housing	Package cracking, Void, Water penetration	Temperature cycling, Mechanical stresses
Thermal integrity		Component level	Cases, lead frames	Case cracking, fatigue in lead frames	Temperature cycling, Mechanical stresses
		Assembly level	Thermally conductive circuit carrier,Thermal interface materials	Crack in circuit carrier	Mechanical stresses

3.5.1.1 The Weakest Links in SSL Drivers

The first failures of elements or components which lead the whole device to fail are called the weakest links in the system. In reliability based on stress and damage model, the last step is to rank failures based on time-to-failure and determine failure site with minimum failure time. To define the weakest link in the SSL driver, the second parameter to study about failures is how much each failure can affect the whole SSL driver reliability. Some failure modes may not affect the device performance and reliability; one example is when there is a small crack in the SSL driver enclosure for an indoor application. Since one of the important enclosure's main functions is to protect the device from moisture, being inside an environment with very low level of humidity does not affect the performance and reliability of the device. Nevertheless some elements failure can be fatal to the device, like failure of the switching function element; there will be no output power for the SSL driver and consequently there will be no light output from the SSL device.

Based on experimental results from literature, capacitors as the energy storage elements in the SSL drivers show high rate of failure. Capacitors, especially electrolytic capacitors are one of the most common monitored failed component. Other components which have been monitored with a high rate of failures are switching elements. The high-power electrical energy passes these two parts and they also face ON and OFF cycles with a relatively high frequency. Power transistor dielectric (gate oxide) can fail due to high temperature and temperature variation. High voltage can be another reason for its failure. The other common source of failures is in interconnections parts, solder joints and copper pads in PCB boards due to temperature, humidity, and mechanical stresses. Cracks produced in solder joints and copper pads are delaminated from the PCB [83, 84, 85, 86].

3.5.2 Reliability Virtual Assessment

The introduced method for partitioning an SSL driver is the foundation of a new method for performing reliability virtual assessment. A proper reliability virtual assessment is an assessment which includes all different aspects of an SSL driver.

It means its electrical, thermal, mechanical, and electromagnetic. This assessment should put all these four aspects together, and assess how the performance of each of the four can affect the other performances and the whole device performance. Each aspect requires its own related type of analysis:

- Reliability electrical analysis
- Reliability thermal analysis
- Reliability electromagnetic analysis
- Reliability mechanical analysis

In this way, instead of dealing with a big and complicated problem, we deal with many smaller problems which are more feasible to solve. The reliability analysis with a mix of different analysis looks like an impossible task to tackle. But here it is divided into four analysis with known nature. The same sort of analysis which is performed during the design phase, will now be performed for reliability assessment purpose. By this action, we break down one problem with an unknown nature into many smaller problems with known natures. Each of the above analysis needs different expertise that can rarely be found in one reliability engineer. In most cases the reliability engineer is expert in one out of four mentioned analysis and he/she has very limited knowledge in the other fields. This method proposes a way to help people with different expertise being able to connect the results of their work together toward the common goal of reliability assessment of an SSL driver[7]. Referring to the DFSS:

"When people from different functional groups and with different experiences and skills cooperate towards the goals."

Each of the four above mentioned reliability analysis due to their nature are concerned about some of the device's elements (refer to Table 3.1 and Table 3.2). These are the elements that an expert in each of the four fields (electrical analysis, thermal analysis, mechanical analysis, and electromagnetic analysis) takes into account in her/his analysis (analytical, experimental, or simulation). In the following paragraphs these elements are listed for each analysis.

[7]This way of approaching the goal of reliability assessment by involving people with different skills can be introduced as a new framework in any electronic device's reliability assessment.

Reliability electrical analysis:

- From functional elements:
  - Control
  - Switching
  - electromagnetic energy storage
- From packaging elements:
  - Electrical integrity
    * Interconnections
    * Insulation

Reliability thermal analysis:

- From functional elements:
  - Heat exchange
- From packaging elements:
  - Thermal integrity

Reliability electromagnetic analysis:

- From functional elements:
  - Switching
  - Electromagnetic energy storage
- From packaging elements:
  - Electrical integrity

Reliability Mechanical analysis:

- From packaging elements:
  - Mechanical support
  - Protection

Fig. 3.13 shows these four reliability analysis which exchange information with each other via a central block called reliability core processor. Each of four analysis blocks besides the above mentioned elements, should receive the related environmental conditions. Examples of environmental conditions for thermal

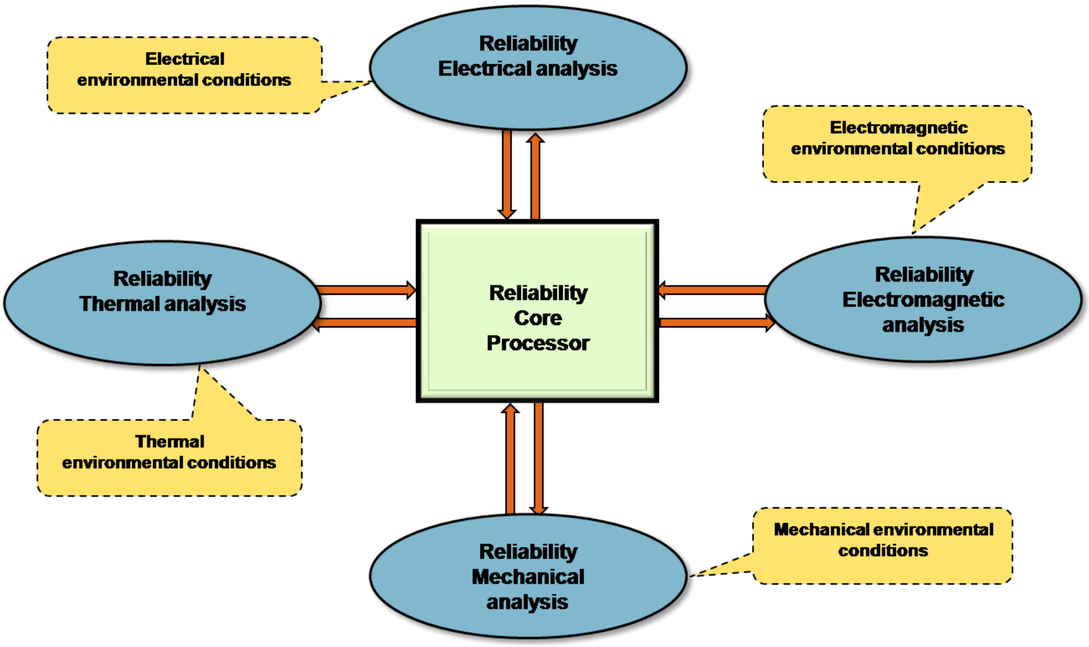


Figure 3.13: *How four different aspects of reliability analysis connected to each other.*

analysis are steady-state temperature, temperature gradients, temperature cycles, and time-dependent temperature changes [87]. Examples of environmental conditions for electrical analysis are electrical current flowing through components, electrical voltage, and electrical power. Reliability core processor is required to serve two main purposes. First, it interprets the results of each analysis to the proper information type usable for the other analysis. Second, it routes the required information from one analysis to the other analysis. In this thesis, reliability thermal analysis, reliability electrical analysis and their interactions are discussed.

3.6 Conclusions

We make use of perspectives in Design For Six Sigma (DFSS) process in order to provide a system-level approach to address SSL driver reliability. In the DFSS process, people from different functional groups and with different experiences and skills cooperate towards the goals, which one of the goals is producing a satisfactory level of reliability in the product.

In this chapter a new partitioning method for SSL driver for reliability purpose is introduced. This method distinguishes the device's functional elements and packaging elements. There are advantages and disadvantages for this new partitioning method. The disadvantage of this method is that lots of traditional reliability information of the components will be hard to use. The reason is that they mostly refer to failure rate for the whole component. As advantages of this method, we can mention the followings; different part which share different functions share the same failure modes and thus makes the reliability study easier. It makes finding the dominant failure mode easier. And finally, due to categorizing different parts due their functions, the design can be assigned to different professionals to examine its reliability performance.

Based on the introduced partitioning method, the reliability study is divided to four categories which exchange information with each other. They are electrical, electromagnetic, thermal, mechanical reliability analysis. It is a more structured reliability procedure and therefore makes it more possible to be applied in the computer programs. Next chapter is about implementing a multi-physics reliability simulation based on this chapter's work.

Chapter 4

Multi-physics Reliability Simulation

This chapter introduces a multi-physics reliability simulation approach for SSL drivers. This work explores the system-level degradation of SSL drivers by means of applying its components reliability information into a system-level simulation. Reliability information of the components such as capacitor, inductor, etc. defines how a component electrical behavior changes with temperature, and also with time. The purpose of this simulation is to understand the thermal-electrical behavior of SSL electronic drivers through their lifetime. Once the behavior of the device during its lifetime is understood, the real cause of the failure can be distinguished and possibly solved.[1]

[1]This chapter is reproduced from the following publication: [S. Tarashioon, W.D. van Driel, G.Q. Zhang, **Multi-physics Reliability Simulation for Solid State Lighting Drivers**, Journal of Microelectronic Reliability, Vol. 54, Issues 67, JuneJuly 2014, Pages 1212 - 1222, doi: 10.1016/j.microrel.2014.02.019.]

4.1 Introduction

There are many circuit level reliability simulation and prediction tools, some examples are FaRBS [81], RELY [88], BERT [89], ARET [90], HOTRON [91]. These tools attempt to access one or more failure mechanism with the focus on VLSI[2] circuits / transistors. FaRBS is one of the most recently introduced methods. It is a failure rate based SPICE[3] reliability model which makes use of handbook methods benefits [81]. It adds the correlation of failure rates with transistor electrical operating parameters into a SPICE model. None of the above mentioned circuit level reliability simulation tools can take passive components into account. SSL drivers are low-power power converters where passive components play a very important role in their reliability. Thus none of these methods can be a proper method for reliability assessment of an SSL driver. In this chapter a new system-level reliability simulation methodology is introduced.

In the previous chapter a new system-level methodology to study the reliability of SSL drivers was introduced. This new system-level methodology provides a way to build in reliability into the design phase. It integrates all aspects of an SSL driver (electrical, thermal, mechanical, and electromagnetic) together in order to understand the behavior of the device through its lifetime and eventually be able to predict the device's lifetime. More importantly, it provides helpful information to the designers for design improvement. This chapter is applying this methodology into a multi-physics simulation which involves electrical and thermal aspects.

This work explores the system-level degradation of SSL drivers due to the components' specification degradation through time [93]. It introduces a multi-physics simulation approach in order to understand the thermal-electrical behavior of SSL drivers through their lifetime. It is a computer aided reliability assessment tool which applies components reliability information into the system electrical and thermal analysis. There are four outcomes of this simulation. First,

[2]Very-large-scale integration (VLSI) is the process of creating integrated circuits by combining thousands of transistors into a single chip.

[3]SPICE (Simulation Program with Integrated Circuit Emphasis) is a general-purpose analog electronic circuit simulator. It is a program to check the integrity of circuit designs and to predict circuit behavior [92].

information about thermal and electrical behavior of the device through its lifetime. Second, which component will fail first. Third, the cause of failure, either electrical or thermal. Fourth, which part(s) of the device contributes the most to the failure cause.

This method helps understanding the fact that interactions play an important role in the reliability of an SSL driver. The component which fails first is not always the source of the problem. The source of the problem can be in other component(s) which contributes the most to produce the over-stresses on the failed component. This method can not only help with predicting the lifetime of the circuit, but also provides valuable feedback to the designer about the sensitivity of electrical and thermal characteristics of the device to its components. In the following sections, the methodology is introduced and applied on a case study. At the end of the chapter, the advantages and limitations of our proposed method are discussed.

4.2 Methodology

In this section different steps of our new multi-physics reliability simulation methodology are explained. Fig. 4.1 is the main block diagram of our proposed method. Reliability core processor as the core of this reliability multi-physics simulation tool receives the input data and by integrating three different analysis -electrical, thermal, and sensitivity- produces the output results. Each of these parts will be explained in details in the following sections.

Although the discussion is about SSL drivers, the SSL light engine will be mentioned in many steps of this reliability simulation. This is required due to the nature of the method, where focus is on interactions between components in order to make a statement about the whole system. The light engine is a part of the system which electrically and thermally[4] affects the SSL driver. Electrically: it is the electrical load for the SSL driver. Thermally: its temperature with respect to its distance affects the temperature of the SSL driver. Therefore studying reliability of SSL driver is not accurate if we do not take the light engine into

[4]In reality light engine can affect of all aspects of the system which are electrical, thermal, mechanical, and electromagnetic, but in this work the focus is on electrical and thermal aspects.

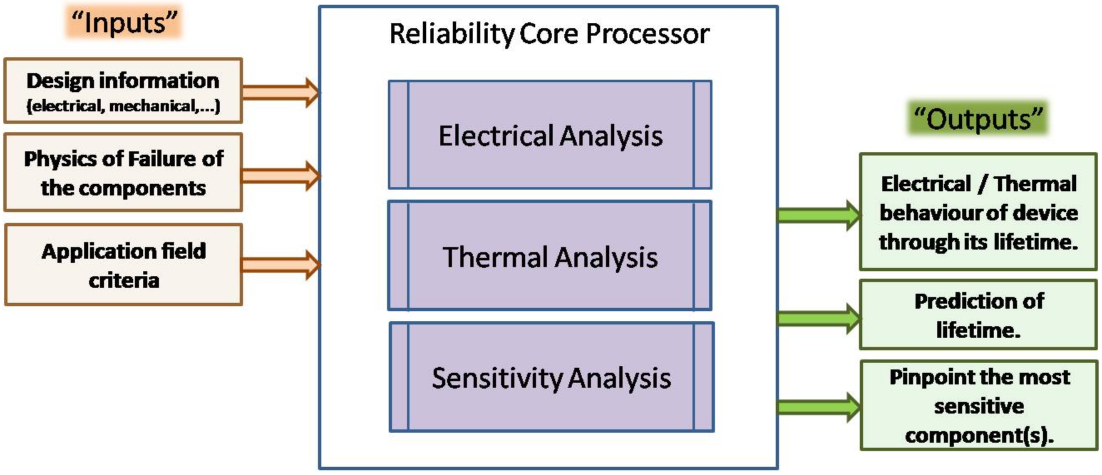


Figure 4.1: *The block diagram of the proposed multi-physics simulation method to assess the reliability of SSL drivers. Electrical, thermal, and sensitivity analysis are performed in their individual environment and just being configured and run by reliability core processor.*

account.

4.2.1 Input Data to the Reliability Core Processor

Let's start with the details of this multi-physics reliability simulation methodology with discussing what input data is required:

- Design information
- Non-ideal models of the components
- The components physics of failure (PoF) information
- Application field criteria

Design information: Design information can be obtained from designers of any SSL product. Design information consists of the device electrical and mechanical design information:

- Electrical bill of material (BOM) which is the list of all electrical components with their details from manufacturer. This information consists of the exact type of the device and its operational conditions.

- Electrical diagram or electronic schematics which is a simplified conventional graphical representation of an electrical circuit.

- Mechanical bill of material which is the list of all mechanical components with their details. This consists of mechanical specification of each components. In SSL drivers, electrical components are installed on a printed circuit board (PCB) which is installed in an enclosure. Information about each part's size and material is included.

- Mechanical diagram which is how different mechanical components are assembled together.

Components non-ideal models: For the purpose of this multi-physics reliability simulation, the electronic schematic of the SSL driver should be modified by replacing the ideal model of each component with its non-ideal model. Defining the non-ideal model of components by itself is a very challenging subject. It needs understanding of how a manufactured component behaves in real life and comparing it with the expected behavior from an ideal component. The non-ideal model of each component with respect to its operational conditions may differ. For example the operational frequency can make a big difference in the non-ideal model of components such as capacitors, inductors and transistors [94]. Some of the electronic components manufacturers publish the non-ideal model of their products. In order to clarify the discussion about non-ideal model of the components, there are explanations about non-ideal model of the passive components used in SSL drivers in Appendix C.

Components physics of failure (PoF) information: Physics of Failure (PoF) concept is based on the understanding of the relationships between requirements and the physical characteristics of the product and their variation in the manufacturing processes, and the reaction of product elements and materials to loads (stressors) and interaction under loads and their influence on the fitness for use with respect to the use conditions and time [95]. In this work some of the physics of failure information of each components are used as the inputs to the reliability core processor. This data is One of the essential inputs to the reliability core processor:

- The maximum electrical and thermal stress each component can tolerate, or in the other word electrical and thermal conditions that make the component fail.
- How the electrical functionality of each component changes with temperature.
- How the electrical functionality of each component changes while it degrades with aging.

The temperature and the degradation models of some of the components can be found in literature, some good examples are the work of I. Bajenescu et al. "Component reliability for electronic systems" [96] and B. W. Williams "Power electronics: Devices, Drivers, Applications, and Passive Components" [97]. Components manufacturers sometimes provide this information as well [98, 99, 100]. Although there is plenty of research about the components failure analysis and their value dependency to different stresses, finding information for every device's component is still a huge challenge. By paying more and more attention in the recent years to the physics of failure approaches for reliability assessment of electronic devices, hopefully in the future physics of failure information for different components will be more accessible. The goal of this work is to apply this information into the system-level and finally to be able to make an statement about the whole system.

Application field criteria: Device's application field criteria provides information such as ambient temperature, maximum input power fluctuation, maximum accepted temperature of the enclosure and minimum accepted light output [48]. No reliability assessment is possible without knowing the conditions and criteria from the device application field. More details are discussed in Chapter 2. In most of the cases the application criteria defines the conditions and specification for the SSL device and not specifically for the SSL driver. One of the tasks is interpreting the conditions and specification of the SSL device into the conditions and specifications for the SSL driver.

4.2.2 Reliability Core Processor

The reliability core processor is the core of this reliability analysis simulation, which connects three analysis together: electrical, thermal, and sensitivity analysis. It provides input data to each of the analysis and receives their output results back. It is implemented in MATLAB [101]. In the following sections, the three analysis and their input data and output results are discussed in detail.

4.2.2.1 Electrical Analysis

Electrical analysis is the process of finding the voltages across and currents through every component in the electrical circuit. Electrical analysis can be performed theoretically and experimentally. In this multi-physics reliability simulation, the theoretical analysis is advantageous in order to integrate it inside the simulation. Theoretical analysis is either done by solving electrical equation of the circuit components or numerically integrated inside the electrical circuit simulation programs. In case of SSL driver due to being a complex circuit, the second choice is preferred.

Electronic circuit simulation is using the electrical analytical models to replicate the behavior of an actual electronic circuit. For the purpose of multi-physics reliability simulation, electronic circuit simulation can be called at any time by the reliability core processor. There are many software programs available for the electronic circuit simulation. 'LTSPICE IV' implemented by semiconductor manufacturer Linear Technology, which is a specialized simulation program for switching power supplies, is the choice of this work. LTSPICE IV is freeware computer software implementing a SPICE simulator of electronic circuits which provides a schematic capture and waveform viewer with enhancements and models to speed the simulation of switching power supplies. This analysis requires the following data:

- Input data which are set just one time at the beginning:
  - The electronic circuit schematics
  - Non-ideal models of the components
  - The model for each component's value with respect to the temperature

    - The model for each component's value degradation with time

- Input data which are set by reliability core processor at each time of running this analysis:
    - Device's temperature (Used in order to update the components values)
    - Current time (This is the time on the life span of the device, it is used in order to update the components values)

The electronic circuit schematics is drawn in LTSPICE IV. Each component model is modified to its non-ideal model. Finally, the components constant values are replaced with a model which is a function of time and temperature. The electronic simulation for the SSL driver under test is performed, and the output results of this electronic circuit simulation are processed by the reliability core processor. These output results are:

- Voltage across each component
- Current through each component
- Power consumption of each component which is the product of voltage and current
- Total power consumption of the SSL driver

4.2.2.2 Thermal Analysis

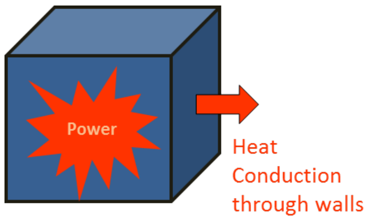
Thermal analysis is often used as a term for the study of heat transfer through structures. It is possible to perform thermal analysis both theoretically and experimentally. Thermal analysis performed inside this multi-physics simulation is a theoretical analysis. The theoretical analysis can be analytical or numerical. Analytical solutions is the method of using the heat transfer equations and calculating the temperature of different parts of the system. Numerical solutions are used in the thermal analysis simulation programs such as COMSOL Multiphysics [102] and ANSYS [103]. They are many studies about thermal analysis of the electronic devices such as work of C.J.M Lasanece [104, 105]. The input data required for thermal analysis are as follows and the output results of the thermal analysis is temperature of each component in the system.

- Mechanical diagram of the enclosure
- Information of the printed circuit boards (PCB). This contains the information of mechanical dimensions of electrical components and how they are physically located on the PCB board.
- Material properties of different parts of the system
- Ambient temperature
- Power dissipation in of each of the electrical component

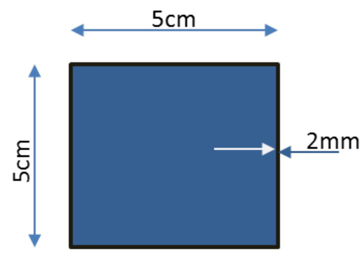
In this study, the analytical solution for a simplified version of the system is chosen. The reason for this choice is to avoid making this simulation too complex by joining three software programs together. By choosing the simplified model for thermal analysis, the required input data is more abstract. It is assumed that temperatures of all components of the device are the same and the enclosure is a cube with the device located in its center. Thus the output result of the thermal analysis is the system's temperature instead of each individual component's temperature. The required input data for the thermal analysis then becomes:

- Mechanical diagram of the enclosure which is dimensions of the cubical enclosure.
- Material properties of the enclosure
- Ambient temperature
- Total power dissipation information of the SSL device

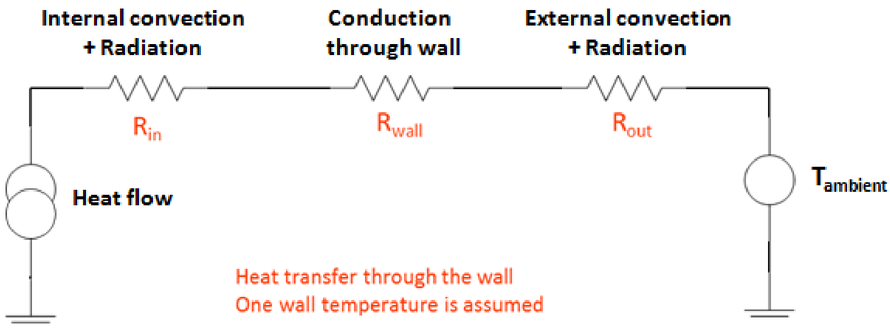
In this simplified thermal model, it is assumed that the enclosure of the SSL lamp is a sealed cube which is filled with air and the device is in the center part of this cube. It is assumed that the whole device which is located in the center of enclosure has the same temperature. Fig. 4.2(a) and Fig. 4.2(b) show



(a) Simplified closed box or sealed enclosure.



(b) 2D dimensions of the enclosure.



(c) Thermal-electrical analogue of the sealed enclosure.

Figure 4.2: *Simplified model for an SSL driver for thermal analysis.*

the dimensions of this enclosure. It is a $5cm \times 5cm \times 5cm\times$ cubical enclosure with the walls with thickness of 2mm. The electrical power dissipation of the device generates heat. This heat transfers through the walls of the enclosure by conduction. Knowing the ambient temperature and device electrical power dissipation, makes it possible to calculate the device temperature.

Thermal-electrical analogy is used to show the path that heat will pave from device to the ambient. Thermal-electrical analogy is a method to draw an equivalent electrical circuit for a thermal problem [106, 107]. Each thermal phenomenon has its equivalent in electrical analogy:

- Temperature drop ($^{\circ}C$) is the equivalent of electrical voltage drop [V]
- Heat flow [W] is the equivalent of electrical current [A]
- Steady state temperature is the equivalent of DC (direct current)
- Heating/cooling [K/W] is the equivalent of electrical resistance [ohm]
- Thermal capacity [J/K] is the equivalent of electrical capacitance [Farad]
- Ohm's law stays valid ($voltage = current \times resistance$)

Using thermal-electrical analogy makes a complicated heat transfer analysis much simpler by creating an equivalent electrical circuit and solve the electrical circuit problem. Fig. 4.2(c) shows the thermal-electrical analogy of the sealed enclosure for this work. The heat is being transferred inside the enclosure toward the walls by means of radiation and convection. It passes through walls by means of conduction and it goes out to the ambient air by means of radiation and convection. Each of these three stages has their own thermal resistances: R_{in}, R_{wall}, and R_{out} respectively. R_{in} and R_{out} are convective thermal resistances from a surface to a fluid and they can be calculated as in Equation 4.1.

$$
\begin{aligned}
&R_{in} = 1/(A \times h_{in}) = 1/(0.015 \times 10) = 6.66[K/W] \\
&R_{out} = 1/(A \times h_{out}) = 1/(0.015 \times 10) = 6.66[K/W] \\
&A : box\ area\ transferring\ heat\ [m^2] \\
&h_{in} : heat\ transfer\ coefficient\ inside\ the\ box\ [W/m^2K] \\
&h_{out} : heat\ transfer\ coefficient\ outside\ the\ box\ [W/m^2K]
\end{aligned}
\tag{4.1}
$$

R_{wall} is a thermal resistance between surfaces, it can be calculated as in Equation 4.2.

$$
\begin{aligned}
&R_{wall} = t/(A \times k) = 0.002/(0.015 \times 0.23) = 0.58[K/W] \\
&A : box\ area\ transferring\ heat\ [m^2] \\
&t : wall\ thickness\ [m] \\
&k : wall\ thermal\ conductivity\ [W/mK]
\end{aligned}
\tag{4.2}
$$

In the equivalent electrical circuit, the three resistors are in series, thus the total resistance is the addition of the three resistors values as it is shown in Equation 4.3.

$$
R_{th(total)} = R_{in} + R_{out} + R_{wall} = 13.9[K/W] \tag{4.3}
$$

The dissipated electrical power in the device turns into heat. It is shown as the current source in the thermal-electrical model as the heat flow. Ambient temperature behaves like a voltage source in the equivalent electrical circuit. The device temperature is the parameter which should be calculated. Its equivalent in thermal-electrical circuit is the voltage across the current source. The device's temperature can be calculated as follows:

$$
\begin{aligned}
&T_{device} = P_{dissipation} \times R_{th(total)} + T_{ambient} = P_{dissipation} \times 13.9 + T_{ambient} \\
&P_{dissipation} : power\ dissipation\ in\ device\ [W] \\
&T_{ambient} : ambient\ temperature\ [K]
\end{aligned}
\tag{4.4}
$$

4.2.2.3 Checking the Device's Health Condition

Device's health condition is used with meaning of 'Device has failed' with its functioning. Thus it can refer to either the situation that one of the device's components has failed or the device has failed to operate in the range of its specifications. The second situation is more tangible when we think of an example such as a car headlamp where working with lower light output endanger the safety. In other words, the device's health depends on the following conditions:

1. The health of each and every component in the system. The health condition of each components is defined by checking its maximum tolerance due to electrical and thermal stresses. Components tolerances are defined by manufacturers. The temperature here refers to the steady state temperature.

   - The electrical voltage across the component should be lower than its maximum allowed operational voltage.
   - The electrical current through the component should be lower than its maximum allowed operational current.
   - The electrical consumed power of the component should be lower than its maximum allowed operational power.
   - The component's temperature should be lower than its maximum operational temperature.

2. Comparing the device functionality with the defined specification, such as minimum and maximum required power output and maximum device temperature.

In the first case, when the component(s) condition exceeds its allowed operational range, it fails and leads the device to fail. This is a catastrophic failure. In the second case, due to any reason such as components degradation, the device does not satisfy the required specification. An example of this case is when the power output of an SSL driver drops below the required value, then the light output of the SSL device drops. In this case the failure is due to the lumen depreciation of the SSL device. The time when any of the above conditions is not met, is a good estimation of the end of the device's life. The output results of "checking the device's health condition" are:

- Lifetime of the device
- The cause of the device's failure

4.2.2.4 Sensitivity Analysis

Sensitivity analysis is used to determine how sensitive a system is to changes in the values of different system parameters. It is also called parameter sensitivity. Parameter sensitivity is usually performed as a series of tests in which different parameter values are changed in order to see how the system behavior changes [108]. The system in this work is the SSL device and the parameters are the component's values. The components value can change due to:

- Its manufacturing tolerances which is always mentioned in the datasheet of the product
- Device's temperature variations due to ambient temperature change or effect of adjacent components temperature
- Degradation through lifetime of the component

Simplest method for defining the sensitivity of a system to certain parameters is to change one parameter at a time while keeping the other parameters fixed. By changing just one parameter at a time, we may never get the valid results, since mostly a certain system behavior changes due to the changes of more than one parameter at the same time. Therefore this method is unreliable and may

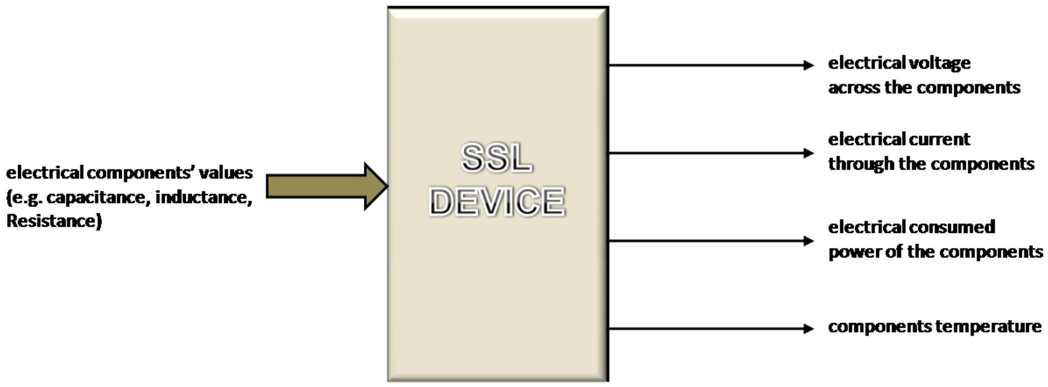


Figure 4.3: *Illustration of a SSL device for design of experiment.*

produce false results. Design of experiments (DoE) is a method to cope with this problem [109, 110].

In order to properly understand designed experiment, it is essential to have a good understanding of the system under study. System is the transformation of inputs to outputs. In performing a designed experiment, the inputs to the system are intentionally changed in order to observe corresponding changes in the output results. Fig. 4.3 illustrates inputs and outputs of an SSL driver for performing DoE. As it can be seen the inputs are the electrical components values such as capacitance, and the outputs are components electrical voltage, current, power, and components temperature. By getting the data from "checking the device's health condition" about what was the cause of the device's failure, one or more of the mentioned possible outputs for design of experiment are chosen.

The purpose of sensitivity analysis is to find out which component(s) has the most contribution to the failure cause. For example if the device's high temperature caused failure in one of the components (in other word if temperature is the failure cause), it is investigated which of the component(s) has the most contribution to the increase the device's temperature. Another example is when device has failed satisfying the required specification for the output power. Then the DoE experiments investigate which component(s) contributes the most in output power variations. This information can be extremely helpful for design modification and the device reliability improvement.

The most commonly used methods for DoE are fractional designs at two levels and three levels. The number of levels defines the possible values that each input parameter gets during the tests. In this work two level factorial is used which is the most commonly used.

Factorial designs allow us to study the effect of each input parameter on the output result, as well as the effects of interactions between input parameter on the output result. There are two types of factorial designs: full factorial and fractional factorial. Full factorial designed experiment consists of all possible combinations of levels for all input parameters. When the number of input parameters is k at two level, then the number of experiments are 2^k. When there are many input parameters, the number of experiments tend to become too large. Fractional factorial designs are experimental designs consisting of a carefully chosen fraction of the experiments of a full factorial design. The fraction is chosen in the way that the most important feature of the problem is studied. For the same case of having k input parameters, the number of experiments in fractional factorial design is 2^{k-p}. $\frac{1}{2^p}$ represents the fraction of the full factorial 2^k. In this work a fractional factorial design with two level for the input parameters is used. Our experiment is actually simulation results by means of electrical analysis and thermal analysis which are run within the reliability core processor.

In this work a two level designed experiment is performed. These two levels are the minimum and maximum values that each input parameter can have. 50% less and 50% more than the nominal value of each of the input parameter is assigned as the minimum and maximum values. These values differ from component to component and it needs a very thorough knowledge about all of the components. Here the same rule is used for all input parameters. This number is a bigger percentage than the common percentage of variation in components value tolerances due to manufacturing processes [111, 112, 113]. The reason is to include the variation of parameters due to temperature change and its degradation as well.

Our automated SPICE approach allows to perform sensitivity analysis on certain parameters within the model. For running each of the $2^{(k-p)}$ experiments, the input parameters, which are the electrical components values, are modified and the electrical analysis is performed. The chosen output results from the sensitivity analysis can be either electrical or thermal (refer to Fig. 4.3). In case of thermal output results, besides the electrical analysis the thermal analysis should be performed as well. After each run of the experiment, the desired output results and the correspondence input parameters are stored in a table in an Microsoft Excel file. After running all $2^{(k-p)}$ experiments the table in the Microsoft Excel is imported into Minitab software [114]. Minitab is a statistical analysis software package. One of its applications is to design the sets of experiments in factorial design and processing the results.

Pareto plot is a powerful tool to find which input parameters (or the combinations of them) has the biggest role in the variation of the output results. It displays the absolute value of the effects, and draws a reference line. Any effect which passes the reference line is potentially important. After distinguishing the potentially important parameters on the output result, this effect can be analyzed with more depth by means of counter plot or surface plot. Minitab software Design of Experiment package offers a lot more different tools in order to look into the results of such a study.

4.2.2.5 Performing the Reliability Simulation

In the above sections, four major blocks of the multi-physics reliability simulation were explained. Electrical analysis, thermal analysis, checking the device's health condition, and sensitivity analysis. The role of the reliability core processor is to connect these blocks together and produce the final results of the multi-physics reliability simulation. Fig. 4.4 shows the flowchart which is run inside the reliability core processor.

They are two loops in the flowchart of the reliability core processor in Fig. 4.4. First one is in order to converge to the device temperature in each time. It is called LOOP1 for the ease of the future reference. Device temperature is calculated in each repetition of this loop by means of power dissipation which is applied into the thermal analysis. Best way to explain this part is that it behaves like the turning-on time in its real life. At the moment of turning-on the device, it is operating in the same temperature as the ambient temperature. As the time goes on due to the power dissipation of SSL device, its operating temperature

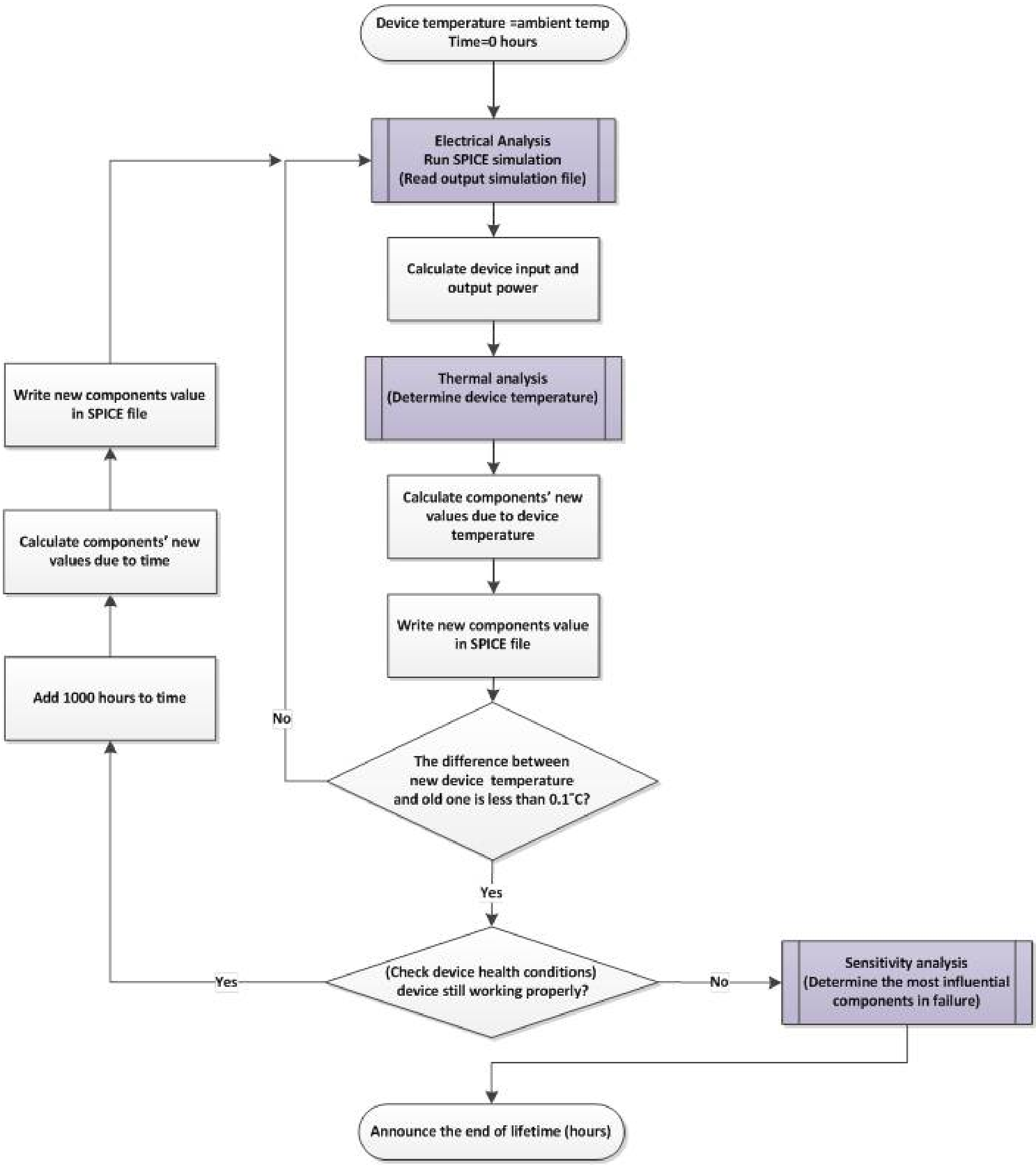


Figure 4.4: *Detailed flowchart for the reliability core processor.*

increases to a certain temperature and then stabilizes. Within the simulation this act (LOOP1) is simulated through the following steps:

1. The components values are set with their values in ambient temperature.
2. Total electrical power dissipation is defined by the output results of the electrical analysis.
3. Based on the total electrical power dissipation, the device's temperature is defined by the output results of the thermal analysis.
4. The values of the device components are modified based on the new device's temperature.
5. Electrical analysis block analyzes the device with the modified values of the components, and calculates the total power dissipation of the device.
6. Thermal analysis block analyzes the device and based on the total power dissipation and calculates the device's temperature.
7. Repeat steps 4, 5, and 6. Comparing the Last calculated device temperature with the previous one, if the difference is below 0.1 degree it means that the device temperature has stabilized. This temperature is the device's operational temperature.

The device's operational temperature stays the same till the time that due to the degradation one or more of the components' values changes. Then the device goes through the same loop which was explained above to obtain the device's new operational temperature. In order to simulate this phenomenon, each of the components' degradation model is checked every 1000 hours in order to see if there is any change in its value. 1000 hour is chosen as the optimum time span based on the author's observation of the component's value changing due to the degradation. In case of choosing bigger time span some of the changes of the components may be missed. In case of smaller time span, the simulation will take a very long time. This leads us to the second major loop in the flowchart of the reliability core processor in Fig. 4.4 is going through time, meaning that time hour is increased in each repetition. In this process the device's thermal and electrical characteristics is simulated through time until the device fails. Within the simulation this act is simulated through the following steps:

1. At the time 0 hour, the device's thermal and electrical characteristics is calculated and logged in the memory. This is done inside LOOP1 of the simulation.

2. At the time 1000 hours, the component's values are checked due to their degradation models. The values of the device components are modified.

3. the device's thermal and electrical characteristics are calculated and logged in the memory.

4. The "checking the device's health condition" investigation is performed. In case of monitoring failure, the end of the lifetime of the device and the failure cause are known. The device's lifetime is 1000 hours and perform step 8. In case that the device is healthy and in proper functioning status, the simulation continues.

5. Adding 1000 hours to the time of the system and checking the component's values due to their degradation models. The values of the device components are modified.

6. the device's thermal and electrical characteristics are calculated and logged in the memory.

7. The "checking the device's health condition" investigation is performed. In case of monitoring failure, the end of the lifetime of the device and the failure cause are known. The device's lifetime is the time of the system in hours and perform step 8. In case that device is healthy and in proper functioning status, steps 5 to 7 are repeated.

8. perform sensitivity analysis.

The end results of the multi-physics reliability simulation introduced in this work are as follows:

- Device's lifetime
- The component(s) which their failure made the device fail
- failure cause (e.g. high temperature, over voltage, over power, or deviating from one of the device's specifications)
- Illustration of the device's temperature versus time
- Illustration of the device's electrical characteristics (Voltage, current, power) versus time
- The component(s) which they contribute the most in failure cause

These results not only define the lifetime and the failure cause, but also give a very good insight to the designer about the condition of the device during its lifetime. During the case study in the following section, the way of applying this is practiced.

4.3 Case Study

SSL driver case study in this work is a DC/DC switching buck converter which steps down battery power to the proper power for a series of three high power LEDs, with an expected light output of 250lumen. Device control/information part is an integrated circuit and the rest are discrete components. The device is designed in the way that keeps the output power to the LEDs as constant as possible. The lamp is installed in a luminaire with ambient temperature of +40°C.

Fig. 4.5 shows a simplified schematics of this case study. In this schematics D1 is the series of three high power LEDs. Q1 is a transistor that operates as the main switch of this switching converter which its state (ON or OFF) is being controlled by the 'controller'. Inductor L1 and Capacitor C1 are the energy storage elements which hold and release the stored energy inside themselves in cycles of switching of Q1. While the Q1 switch is ON, the electrical current flows from battery through Q1 and is stored in L1 and C1. As the Q1 switch is turned

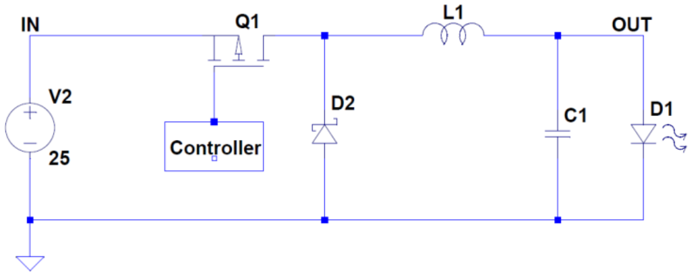


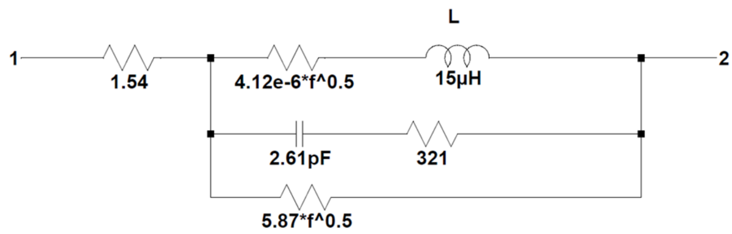
Figure 4.5: *The simplified electrical schematics of the SSL driver case study.*

OFF, the energy stored in L1 and C1 are released and D2 diode which works as the other switching element of this circuit allows the current flow. By controlling the switching duty cycle of Q1, the voltage level on the LEDs are controlled. The switching frequency in this design is 850KHz.

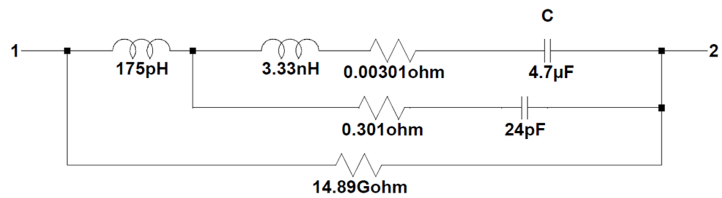
Device's health conditions: In this application the minimum accepted lumen output is the 70% of the initial lumen output of the device. The optical parts are assumed to be ideal: no change with the thermal conditions and no degradation with time. Thus this specification can be interpreted as: the minimum accepted power output of the SSL driver is 70% of its initial power output. The device's health condition is when the output power is above 70% of its initial power, and when the conditions for output like the maximum temperature, maximum current/voltage, maximum electrical power are not overridden.

Electrical schematics: Electrical schematics of this circuit implemented in LTSPICE is illustrated in Fig. 4.7. The controller in this driver is an LT3517 chip LED driver from Linear Technology. It is a current mode DC/DC buck converter with an internal 1.5A, 45V switch specifically designed for driving LEDs [115]. LT3517 combines a traditional voltage loop and a unique current loop to operate as a constant-current source.

Replacing the components ideal models with non-ideal models: The focus in this example is on the components in the main switching loop which are capacitor and inductor as energy storage elements, high power transistor and diode as switching elements. In the schematics shown in Fig. 4.7 the non-ideal model of these components are replaced with their ideal models. The model of each component is defined by the text under the schematics which is defined by



(a) 15H inductor with ceramic/ferrite core from Colicraft Inc., the value of two resistors in this model are frequency dependent [98].



(b) $4.7\mu F$ ceramic SMD capacitor from KEMET [100].

Figure 4.6: *Electronic schematics of non-ideal models of energy storage components used in the case study.*

the reference name written next to each of the component's symbols. The non-ideal model of the Inductor L1 and capacitor C1 are from their manufacturer's information package. Fig. 4.6 shows the equivalent schematics of the non-ideal model of these two components. The non-ideal model for the diode D2 and LED D1 are ideal diode and a series resistor. The non-ideal model of the switching transistor is a resistor in the ON state of the transistor instead of an ideal switch.

Temperature and time dependent components values: Next step is to add the dependency of each of the L1, C1, D1, D2, Q1 components (refer to Fig. 4.7) to changes in temperature, and their degradation models with time. These models are the result of searching in different sources of information such as component's datasheets, manufacturers' technical papers, publications of research results from different research centers, and simplifying assumption of author for the components models [97, 116, 117, 118, 119, 120, 121, 122, 123]. The components values dependent on time and temperature is assumed linear. Therefore the models used in this case study are not perfect models for the components, and therefore it is more to satisfy the purpose of clarifying how to apply the methodology. In order to have results which are very close to reality of the device's behavior, there is need for having better models for device's behavior. This requires performing thorough research on the component level physics of failure for every component in the device.

Each of the components values listed in Table 4.1 are a function of the following parameters. The names of the parameters are the choice of the author and can be seen in the electrical schematic in Fig. 4.7.

- The components nominal values which are mentioned in the component's datasheets [124, 125, 98, 126, 127]
- TMP: SSL driver's temperature at each time [$°C$]
- thour: the time on the life span of the device [hours]
- REFTMP: Ambient temperature (it is set to $+25°C$ for ordinary room temperature)
- Acoef: aging coefficients are the slope of the linear curve of the components values with respect to time
- Rth, Cth, Lth: The slope of the linear curve of the components values with respect to the temperature

Distinguishing the failure cause and lifetime The procedure mentioned in the methodology section in this work is applied on this case study. Fig. 4.8(a) shows how the device power input/output varies in time. As mentioned before, this device is designed with feedback loops to keep the output power (power to LEDs) as constant as possible. It can be seen even though the output power is kept constant, the input power is increasing with time. However, at about 75000 hours, the output power suddenly starts dropping. This is the point that the device's components has been deviated from their nominal value such that the converter goes out of its specification. At this time the device can still operate.

Table 4.1: *Definition of the variable used in Fig. 4.7 schematics, and their reference names used in the sensitivity analysis.*

Component	**Name in Schematics**	**Variable Description**	**Reference in Sensitivity analysis**
inductor L1 energy storage element	D603PS-153k(L1)	Inductance value (μH)	perLL1
	D603PS-153k(R2)	series resistance value (Ω)	perRL1
capacitor C1 energy storage element	MDC10-475k50A52P3(C1)	capacitance value (μF)	perCC1
	MDC10-475k50A52P3(R1)	series resistance value (Ω)	perRC1
switching transistor Q1	FDS4685-MO(Ron)	drain-source on resistance (Ω)	perQ1
LEDs D1	LXK2-PW14-MO(Rs)	Series resistance (Ω)	perD1
Switching diode D2	MBRS360-MO(Rs)	Series resistance (Ω)	perD2

After a short while at 80000 hours it reaches the health condition of 70% of initial power. This is the end of the device's life. The device's efficiency decreases from about 77% to about 67% during device lifetime. For applications with limited source of energy, this 10% dropping in efficiency is not an ignorable value (Fig. 4.8(b)).

In Fig. 4.8(c), the device temperature versus time is shown. From 0hour device till 75000hours, device temperature increases from +70°C to some degrees over one hundred. But no temperature health limit for any component is exceeded at the time of failure in 80000hours.

Table 4.2: *Variables in sensitivity analysis of the case study (refer to Fig. 4.5 and Table 4.1)*

Variable Name	**nominal value**	**Variation**	
		Min.	Max.
perLL1 (μH)	15	7.5	22.5
perRL1 (Ω)	1.54	0.77	2.31
perCC1 (μF)	4.7	2.35	7.05
perRC1 (Ω)	0.0031	0.00151	0.00452
perQ1 (Ω)	0.027	0.0135	0.0405
perD1 (Ω)	0.752	0.0376	1.13
perD2 (Ω)	0.042	0.021	0.063

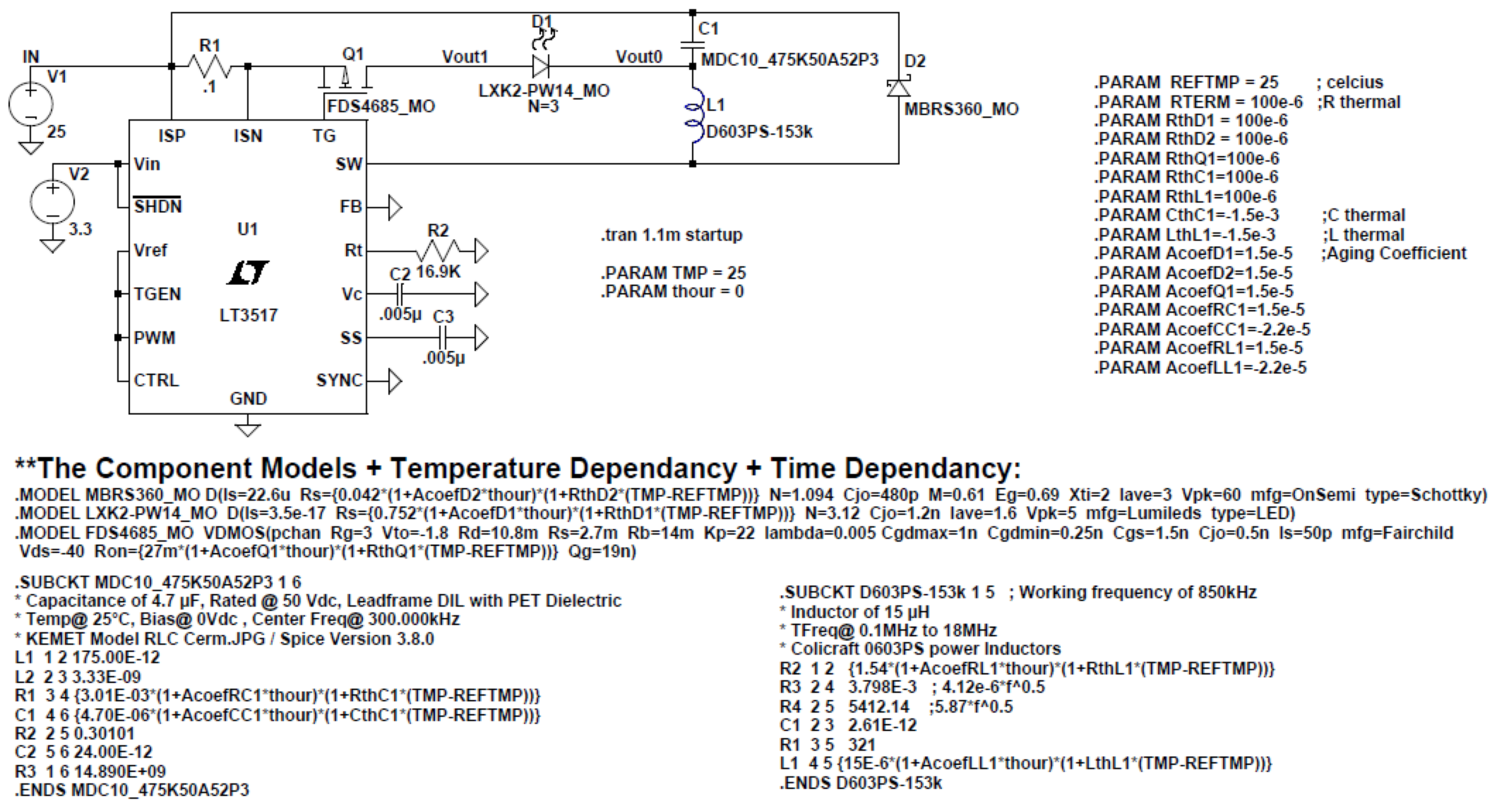
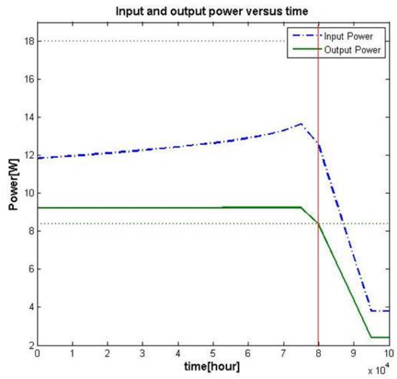


Figure 4.7: *LTSPICE schematics of the SSL driver case study, including the components non-ideal models and their dependency to temperature and time. For parameters definition refer to Table 4.1.*

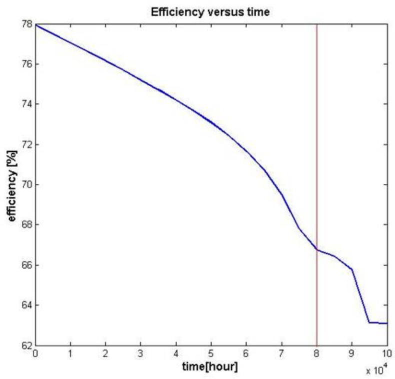
Distinguishing the components which contribute the most to failure cause Sensitivity analysis by means of the DoE method is performed in order to see which component(s) value or their interactions are the most important contributor to the SSL driver failure cause which is the LEDs power drop. The experiments in this sensitivity analysis are the results of simulations and not actual experimental tests on the real device. In this case we take a look at temperature change contributors as well. The explanation of the parameters contributing in power and temperature change in this case study is summarized in Table 4.2. It is a factorial design with 7 parameters which results in 64 runs. Every parameter is varied between -50% and +50% of its standard value.

Fig. 4.9 shows the pareto plot of standardized effect of the device power output. With variation of the components values, the output power changes. The effective parameters are inductance value of the inductor and capacitance value of the capacitor and their interactions (perLL1 and perCC1 refer to Table 4.1). Although in this case study temperature is not the device failure cause, it is one of the most discussed parameter in case of reliability study. Thus the pareto chart of standardized effect of the device temperature is generated as well which is shown in Fig. 4.10. The two most important contributors to temperature variation are inductance and resistance value of the inductor (perLL1 and perRL1 refer to Table 4.1).

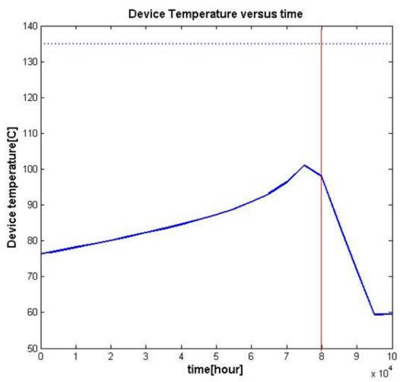
Fig. 4.11 and Fig. 4.12 shows how much the dependency of output power and device temperature is to the two mentioned most sensitive parameters. In case of the device output power the interaction of two parameters, inductance value of the inductor and capacitance value of the capacitor, both play important roles in power output variation. In case of the device temperature the effect of inductance value of the inductor is almost ignorable in comparison with the effect of resistance value of the inductor.



(a) Device output power versus time. Two horizontal lines show the accepted range of output power.



(b) Device efficiency versus time.



(c) Device temperature versus time. The horizontal is the high limit of temperature.

Figure 4.8: *The results for multi-physics simulation for reliability study of the SSL driver case study.*

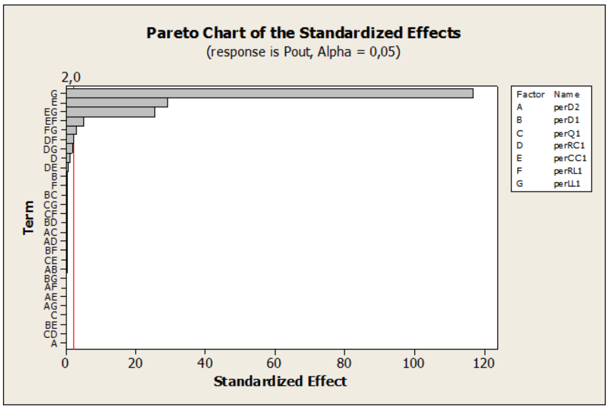


Figure 4.9: *Pareto plot of standardized effect of device output power with respect to the device's components.*

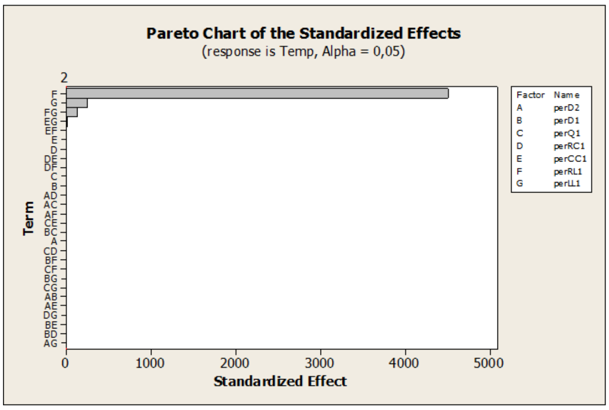


Figure 4.10: *Pareto plot of standardized effect of device temperature with respect to the device's components.*

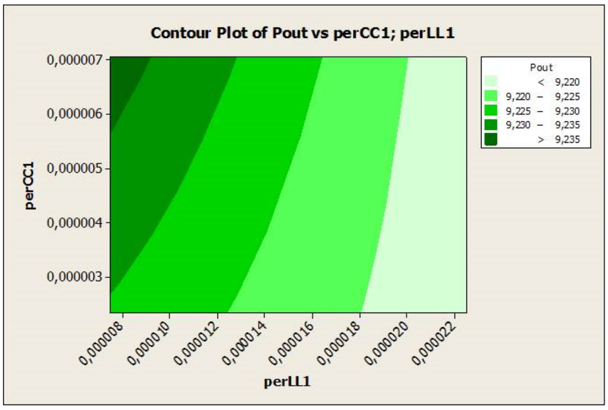


Figure 4.11: *Counter plot of the device's output power with respect to its two most effective circuit parameters perCC1 and perLL1.*

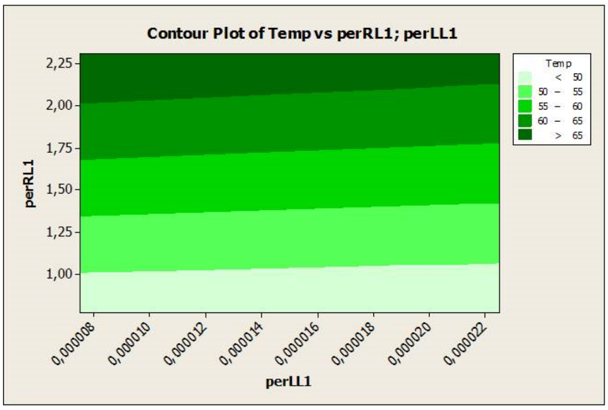


Figure 4.12: *Counter plot of the device's temperature with respect to its two most effective circuit parameters perRL1 and perLL1. Effect of perLL1 is almost ignorable.*

4.4 Conclusions and Recommendations

The method introduced in this chapter is a multi-physics reliability simulation method which helps understanding electrical / thermal status of an SSL driver during its lifetime. This method can be a good complementary tool for experimental tests such as lifetime test. This method uses the component behavior over time and temperature variations in a system-level simulation method, built with SPICE and MATLAB. The results show that our proposed method is able to forecast the lifetime of the driver. Sensitivity analysis indicates the most important parameters on component level that determines the lifetime estimate. Our iterative multi-physics reliability simulation method can be a strong technique to support the design of SSL drivers.

Two limitations can be mentioned for our method. First, like every repetitive simulation method, it can be time consuming. Second, this simulation is strongly dependent on the information from components; the components non-ideal models and their value dependency to temperature and time which should be provided by manufacturers. For complex components such as the controller part, it can be complicated to provide such information. Also for very cheap components such as passive components, manufacturers usually are not eager to spend time and money to provide this information. But the bright side for the later problem is that recently more and more attention is attracted to the physics of failure method as the preferred method for reliability study of the devices. Therefore, more and more research will be done on components physics of failure. Therefore a bright future for such system reliability simulations based on physics of failure of the components can be predicted.

Chapter 5

A Case Study of Reliability in SSL Drivers

This chapter presents experimental results of an actual case study, being a commercially available MR16 LED lamp. Experiments are performed on two groups of fully functional samples: new samples and the samples which are aged to 6000hours under controlled conditions. The goal of these experiments are to study the effect of aging on electrical and thermal performances of the samples. Understanding the performance of an SSL driver during its aging is very valuable information for design improvement.[1]

[1]This chapter is reproduced from the following publication: [S. Tarashioon, W.D. van Driel, Xiu Peng Li, G.Q. Zhang, **Reliability of LED driver in consumer LED lamps**, Proceedings of 9th China international forum on solid state lighting, November 2012, Guangzhou, China]

5.1 Introduction

This work is about thermal/electrical experiments on a commercially available indoor-lighting SSL lamp. It is a 10W SSL lamp which works as a replacement for a 50W halogen lamp. The major parts of this product are light engine, SSL driver, active cooling element (fan), and the enclosure.

The objective of this study is to investigate variations of temperature in SSL driver samples in different conditions: by changing the ambient temperature and by aging the devices. To help understanding the samples behavior with aging, their electrical power consumptions are monitored as well. For this investigation, a group of samples are subjected to degradation experiments at elevated temperature of 45°C for 6000 operational/burning hours (around 8.3 months). Temperature of the enclosure and the critical components of the aged SSL products are measured with comparison to the not-aged samples, as well as electrical power consumption of both groups.

5.2 Introduction to the Case Study

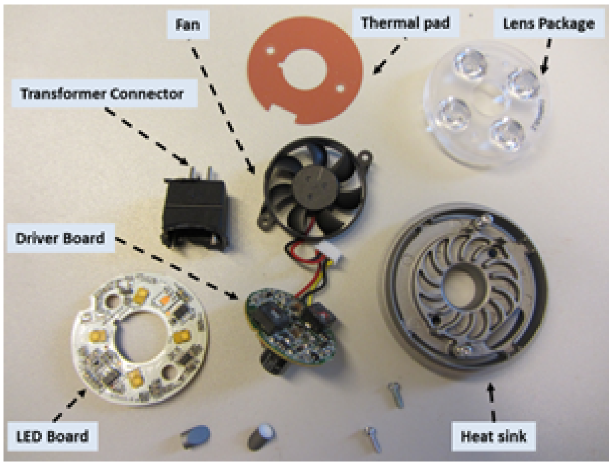
The case study is an SSL driver for a 10W SSL halogen replacement lamp. This lamp is a commercially available replacement for a 50W halogen lamp and compatible with halogen lamp transformers [128]. It is equipped with active cooling (an electrical fan) in order to control the temperature of the light engine and SSL driver. Fig. 5.1 shows the case study lamp and its constructed parts.

The SSL driver's function is to convert the output power from the halogen lamp transformer to the power for both light engine and active cooling element. The power path in this lamp is shown in Fig. 5.2. The light engine is composed of four high brightness LEDs mounted on a PCB board with an optical lens on top of the LEDs. The required voltage and current for the light engine are around $12V_{DC}$ and 700mA-1000mA. This design is capable of providing (almost) constant current to the light engine in order to have constant light output.

The SSL driver in this case study is constructed from different parts as shown in Fig. 5.3. First the rectifier converts AC input voltage into DC. Then a boost-buck power converter converts this DC voltage to the required voltage for the

(a) Case study lamp

(b) Case study: disassembled



(c) different parts of the case study

Figure 5.1: *Case study: 10W SSL halogen replacement lamp [129].*

LEDs in the light engine and the electrical fan. The components with critical roles in the SSL driver are chosen as test points [93]. All these components are located in the critical path of the SSL driver and their failure leads to failure of the SSL driver. These components are as follows. The names in the parenthesis are the reference names of the components which will be used in the rest of this

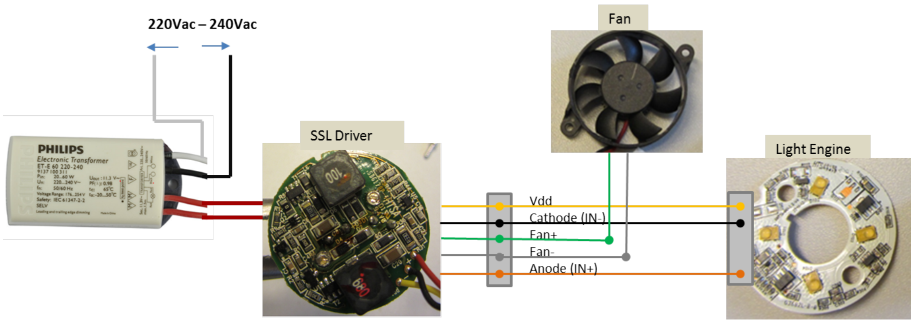


Figure 5.2: *The power path in the case study lamp.*

chapter.

- Diodes in AC/DC rectifier bridge ($D_{1,3}$ rec) and ($D_{2,4}$ rec)
- Transistor in boost converter as the switching element (T_{boost})
- Inductor in boost converter stage as an energy storage element (L_{boost})
- Intermediate capacitor between two stages, as an output stabilizer (C_{interm})
- Inductor in buck converter stage as an energy storage element (L_{buck})
- Capacitor in the output of the driver, as a final output stabilizer (C_{load})

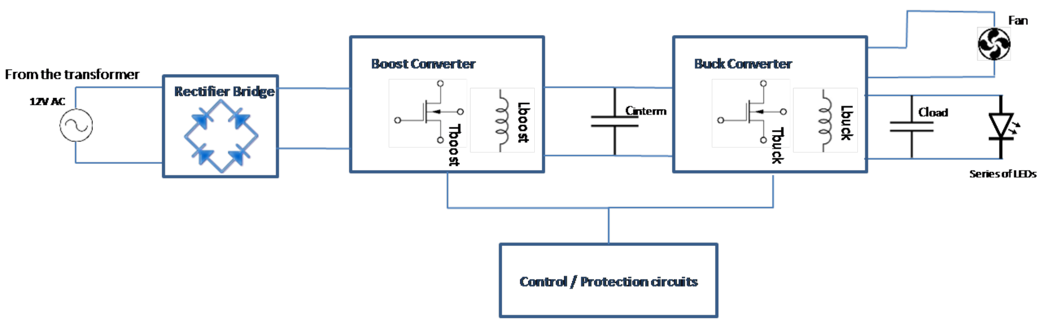


Figure 5.3: *Block diagram of the SSL driver of the case study. The driver topology is a boost-buck which keeps the voltage of intermediate capacitor (C_{interm}) constant. The additional circuitry are designed for accomplishing functions such as over voltage protection, over current protection, driving fan, and dimming function. The current through the LEDs is kept constant.*

5.3 Measurement Methods and Setups

The goal is to compare the thermal and the electrical behavior of the SSL driver. A group of lamps are subjected to degradation experiments by putting the devices in elevated temperature of $45°C$ for 6000 operational/burning hours (around 8.3 months). This condition is imitating the condition that the lamp is facing in its real life condition in the luminaire. These samples are fully operational after 6000 hours. In this text we call these samples 6000-hours samples. The not-aged samples are called 0-hour samples. SSL drivers in 0-hour samples are the reference point for these measurements.

For reaching the goal, temperatures of different parts of the samples and power consumptions are measured. The comparison between 0-hour samples and 6000-hours samples leads us to understand thermal and electrical changes during aging. In this chapter we call these measurements "Effect of aging" measurements. Another sets of measurements is to measure how much ambient temperature can affect the device's temperature. In this chapter we call these measurements "Effect of ambient temperature" measurements.

Temperature of enclosure and critical components of reference samples defines the first collections of measurements [130]. How much aging affects temperature of enclosure and critical components with respect to 0-hour samples defines the second collections of measurements.

In order to cover all desired measurements in "Effect of ambient temperature" and "Effect of aging" in a proper way, first the following issues should be addressed:

- Place and time of measurements
- Thermal measurements test setup
- Electrical measurements test setup

5.3.1 Place and Time of Measurements

Ambient temperature can effect both thermal and electrical measurement results, thus measurements are performed in temperature controlled environments. Three different measurement rooms are provided where the temperature choices are due to the possibilities in our laboratory:

- Test room1 with $10.5°C \pm 0.5°C$ ambient temperature
- Test room2 with $20.5°C \pm 0.5°C$ ambient temperature
- Test room3 with $27°C \pm 1°C$ ambient temperature

All tests of "Effect of aging", both thermal and electrical are performed in test room1 with $20.5°C \pm 0.5°C$ ambient temperature. "Effect of ambient temperature" tests are performed in all three mentioned test rooms.

Proper measurement time is the time that each sample has reached its maximum operational temperature. After that moment, the steady state temperature of the devices can be measured. For this case study, the temperature of a group of samples is monitored to be able to extract the time at which the samples' temperature stabilizes.

5.3.2 Thermal Measurements Test Setup

In both categories of tests "Effect of aging" and "Effect of ambient temperature", thermal measurements are performed in order to measure the temperature of different parts of the samples. The thermal measurement setup includes the following elements:

1. Temperature controlled test rooms: refer to Section 5.3.1 descriptions.
2. Thermocouples: used for constant monitoring of the test rooms temperatures.
3. Infra-Red thermal imager: Fluke Ti10 thermal Imager with temperature measurement range of $-20.5°C\ to\ +250°C$ and measurement accuracy of 2% [131]. Temperature of the sample's enclosures and critical components of the SSL driver are measured by means of this imager.
4. Mechanical holder: used to hold the thermal imager during thermal measurements.

Thermal measurement challenge: The lamps have an active cooling element which is a fan mounted on top of the SSL driver PCB board. In order to measure the temperatures of the SSL driver's components, the lamp should be opened and the active cooling element should be set aside (Fig. 5.4(b)). By bypassing the active cooling element, measurement results show higher temperatures than in real working conditions. The "effect of active cooling" or in other words the correction temperature is calculated by comparing the SSL driver side temperature on samples packaged in two conditions: with or without the active cooling element (Fig. 5.4(a) and Fig. 5.4(b)).

For each sample the following test points are measured:

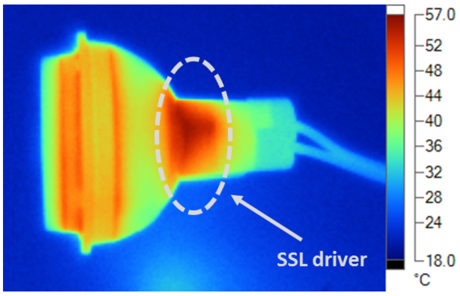
- The temperature at the lamp side where the SSL driver is located as shown in Fig. 5.4(a).
- The temperature at the lamp side where the SSL driver is located while the lamp enclosure is open and the active cooling element (fan) is set aside as shown in Fig. 5.4(b). These measurement results are used to calculate the "effect of active cooling".
- Test points within the SSL driver. These are the critical components which were mentioned in Section 5.2. They are shown in Fig. 5.4(c) and Fig. 5.4(d).

5.3.3 Electrical Measurements Test Setup

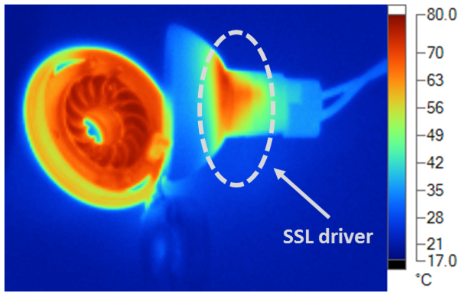
In "Effect of aging" collections of tests, electrical measurements are performed in order to measure the power consumption of different parts of the samples. The electrical measurement setup includes the following elements. The test setup is shown in Fig. 5.5.

1. Temperature controlled test room: all electrical tests are performed in Test room2 with temperature of $20.5°C \pm 0.5°C$ (refer to Section 5.3.1).
2. Digital multimeter[2]: in order to measure electrical currents in the test paths.

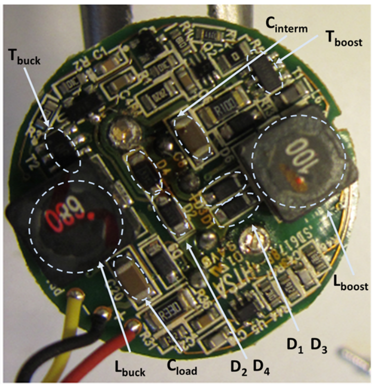
[2]Multimeter is an electronic measuring instrument that combines several measurement functions in one unit. A typical multimeter would include basic features such as the ability to measure voltage, current, and resistance.



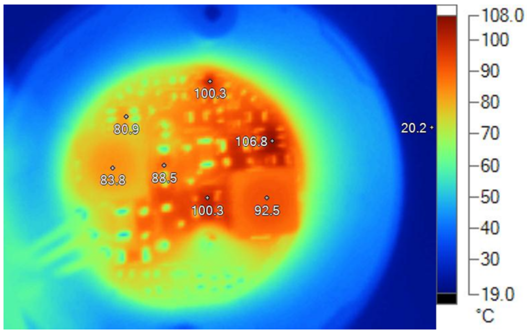
(a) Side of the sample enclosure.



(b) Side of the samples enclosure while the lamp enclosure is open and the fan is set aside.



(c) Top side of SSL driver board.



(d) Infra-Red thermal image of top side of SSL driver board.

Figure 5.4: *Thermal test points on SSL halogen lamps samples. Thermal images are taken by means of an Infra-Red thermal imager.*

3. Digital oscilloscope[3]: in order to measure electrical voltages of the test points.

4. Mechanical holder: in order to hold the samples during electrical measurements

5. Test connector: Due to the very small size of the SSL driver board, in order to ease the measurements and making the test points more accessible an interface connector is prepared.

[3]An oscilloscope is a type of electronic test instrument that allows observation of constantly varying signal voltages, usually as a two-dimensional graph.

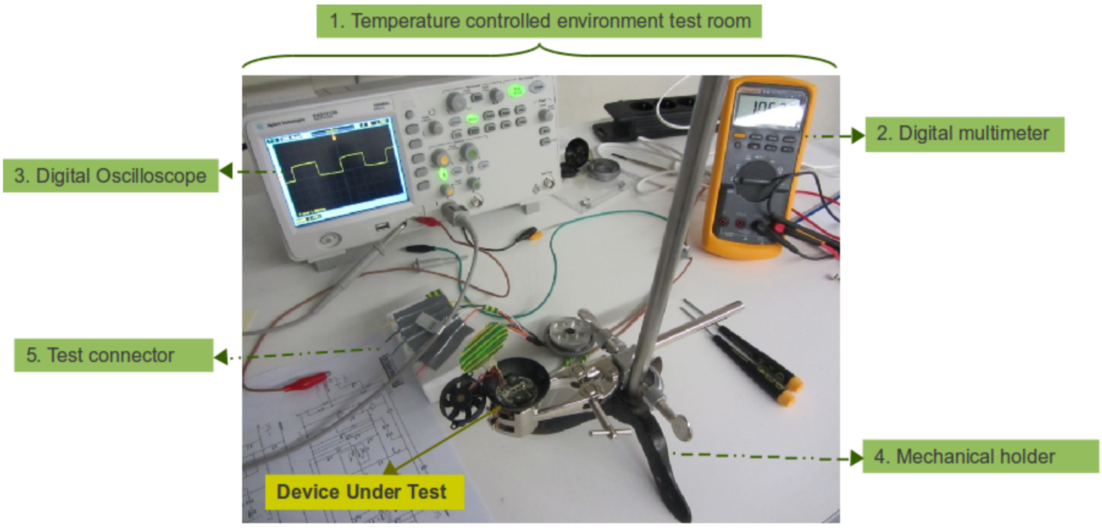


Figure 5.5: *The electrical measurement setup.*

The aim is to monitor the effect of aging on samples' electrical power consumptions and efficiencies. Voltage and the current values at the test points are measured. The input power, the power to the active cooling element (fan), and the power which goes to the light engine part are measured [132]. With this information the power dissipation in the SSL driver and also its efficiency are calculated:

$$
\begin{aligned}
&P_{input} = P_{SSLdriver\ dissipation} + P_{active\ cooling} + P_{light\ engine} \\
&\eta_{SSL\ driver} = \frac{P_{input\ power} - P_{SSLdriver\ dissipation}}{P_{input\ power}} \\
&P_{input} : Input\ electrical\ power\ to\ the\ lamp \\
&P_{SSLdriver\ dissipation} : Electrical\ power\ dissipation\ in\ the\ SSL\ driver \\
&P_{active\ cooling} : Electrical\ power\ dissipation\ in\ active\ cooling\ element \\
&P_{light\ engine} : Electrical\ power\ fed\ to\ the\ light\ engine \\
&\eta_{SSL\ driver} : Electrical\ efficiency\ of\ the\ SSL\ driver
\end{aligned}
\tag{5.1}
$$

5.4 Results

In the following two sections the results of thermal and electrical measurements on samples are presented. Each measurement point shown as a result is an average value over a population of samples. The number of samples in the "effect of ambient temperature" tests is five, and there is eight in the "effect of aging" tests. In order to be certain about the reproducibility of the results, the first two tests in each category of tests are repeated in the following order and the results were compared.

$Sample\ n \Rightarrow Sample\ m \Rightarrow Sample\ n \Rightarrow Sample\ m$

In this way the device under test is tested two times while the procedure of setting its test setup is repeated for two times as well.

5.4.1 Effect of Ambient Temperature

By means of processing the results of thermal measurements with the purpose of effect of ambient temperature, three valuable outcomes are gathered. First, "Effect of active cooling" which is needed as a compensation level for SSL components measurements (refer to Section 5.3.2). Second, how the temperature at the side of the samples changes with ambient temperature. In the other word to fit a curve into the temperature variation at the side of the sample versus the ambient temperature. Third, how the temperature of the SSL driver's components changes with ambient temperature. In the following paragraphs the outcomes are explained.

Effect of active cooling

Table 5.1 shows the "Effect of active cooling" for 0-hour samples and 6000-hour samples. The number of samples is five in this test. These results demonstrate a correction temperature of approximately $13°C$ for 0-hour samples and $12.4°C$ for 6000-hour samples. All results of SSL driver components shown in the rest of this work are the estimation of the temperature by means of applying "Effect of active cooling" in the measurement results.

Effect of ambient temperature at the side of samples

Fig. 5.6 shows the results of the temperature variation at the side of the enclosure of the samples due to ambient temperature changes. Linear regressions

Table 5.1: *Effect of active cooling on 0-hours samples and 6000-hours samples in* $20.5°C \pm 0.5°$ *ambient temperature. The temperature is measured on the side of the samples enclosure (refer to Fig. 5.4).*

		With active cooling ($°C$)	**Without active cooling** ($°C$)	**Effect of active cooling** ($°C$)
0-hours samples	Average temperature	56.0	69.6	-13.0
	Standard deviation	1.4	1.6	
6000-hours samples	Average temperature	59.7	72.0	-12.4
	Standard deviation	1.8	1.7	

are fitted to the measured points of both cases, with active cooling element and without active cooling element, with R-squared value[4] of 0.9. The linear equations are as follows:

$$
\begin{aligned}
&T_{enclosure\ withFan} = 1.18 \times T_{ambient} + 32.8\ [°C] \\
&T_{enclosure\ withoutFan} = 1.18 \times T_{ambient} + 47.1\ [°C] \\
&T_{enclosure\ withFan} : Temperature\ at\ the\ side\ of\ the\ samples\ with\ electrical\ fan \\
&T_{enclosure\ withoutFan} : Temperature\ at\ the\ side\ of\ the\ samples\ while\ electrical \\
&\qquad fan\ is\ set\ aside \\
&T_{ambient} : Ambient\ temperature
\end{aligned}
\tag{5.2}
$$

This data gives a good estimation about the range of ambient temperatures which the device can operate within its specification. One of the specifications of the lamp is defined by the UL8750 standard [133] which is the standard for

[4] R-squared or coefficient of determination indicates how well data points fit a model which is in this case a linear regression.

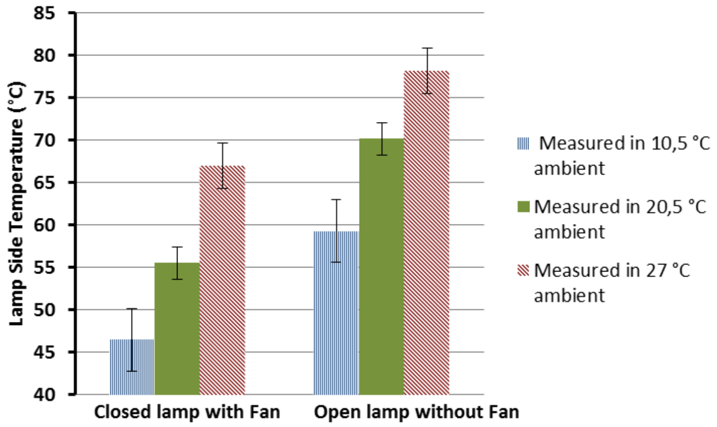


Figure 5.6: *The effect of ambient temperature on side of the samples enclosure. On each bar the standard deviation of the results from different samples is shown.*

safety of light emitting diode (LED) equipment for use in lighting products. In this standard, the maximum temperature of a non-metallic surface of a direct plug-in or through-cord unit is $+75°C$. The maximum ambient temperature for this lamp not to exceed $+75°C$ on its enclosure surface is calculated by means of Equation 5.2 for $T_{enclosure\ withFan}$. At the ambient temperature of $+35.85°C$, the enclosure surface temperature of the lamp reaches $+75°C$ which is its maximum allowed temperature.

Effect of ambient temperature on the SSL driver components

Fig. 5.7 shows the results of temperature variation of the SSL drivers components due to ambient temperature changes. These data are fitted to a linear regression with with R-squared value. In Equation 5.3 the dependency of SSL driver components to the ambient temperature is presented. This data gives a good estimation about the range of the ambient temperatures at which the components can operate without being prone to failure due to the high temperature.

The maximum operational temperature for the components are mentioned in the manufacturers datasheets [134, 135, 116]. The ambient temperature at which the components exceeds their maximum tolerance is calculated by means of Equation 5.3. Inductor L_{boost} is the first component that reaches its maximum tolerance temperature of $+125°C$. This happens at the ambient temperature of

$+67°C$[5].

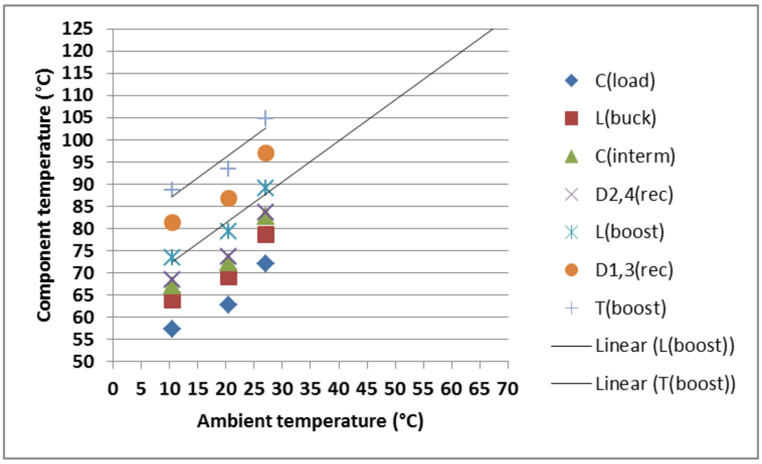


Figure 5.7: *The effect of ambient temperature on samples SSL driver components temperature. L(boost) is the first component which reaches its maximum operational temperature (+125°C). This happens at +67°C ambient temperature.*

$$
\begin{aligned}
&T_{D_{1,3}} = 0.82 \times T_{ambient} + 85.2 \; [°C], (maxT_{D_{1,3}} = +150°C) \\
&T_{D_{2,4}} = 0.82 \times T_{ambient} + 72.4 \; [°C], (maxT_{D_{2,4}} = +150°C) \\
&T_{T_{boost}} = 0.82 \times T_{ambient} + 91.9 \; [°C], (maxT_{T_{boost}} = +150°C) \\
&T_{L_{boost}} = 0.82 \times T_{ambient} + 77.0 \; [°C], (maxT_{L_{boost}} = +125°C) \\
&T_{C_{interm}} = 0.82 \times T_{ambient} + 56.2 \; [°C], (maxT_{C_{interm}} = +125°C) \\
&T_{L_{buck}} = 0.82 \times T_{ambient} + 68.1 \; [°C], (maxT_{L_{buck}} = +125°C) \\
&T_{C_{load}} = 0.82 \times T_{ambient} + 47.3 \; [°C], (maxT_{C_{load}} = +125°C)
\end{aligned}
\tag{5.3}
$$

5.4.2 Effect of Aging

The second collection of tests are measuring the effect of aging on the samples. The temperature of the lamp's enclosure and its critical components after 6000-hour are measured and compared with the 0-hour samples temperature. The

[5]The reader may think that $+67°C$ is too high as ambient temperature to be concerned about it. Due to this fact that as a halogen replacement lamp is installed in the ceiling, it may face such a high ambient temperature.

SSL driver's electrical power consumption and efficiency of 6000-hour and 0-hour samples are measured and compared with each other as well.

Effect of aging on samples temperature

The temperature of the samples' enclosure sides is measured. It increases from $+56.6°C$ in 0-hour samples up to $+59.7°C$ in 6000-hour samples. Fig. 5.8 shows the measured temperature after 0-hour and 6000-hours on the SSL driver components. It shows that during aging the components temperatures increase. As an example, the temperature difference between 0-hours and 6000-hours for the switching transistor of the first level (boost converter) of driver is about $10°C$ (9%), for rectifier diodes about $4°C$ (5%). Unfortunately 0-hour and 6000-hour are the only data points available in these tests, thus trying to fit them in a curve can not be very accurate. In case of having more data points and considering the maximum operational temperature for the components, the lifetime of the device could be predicted. The time at which first components exceeds their maximum operational temperature is an estimation of the whole device's lifetime.

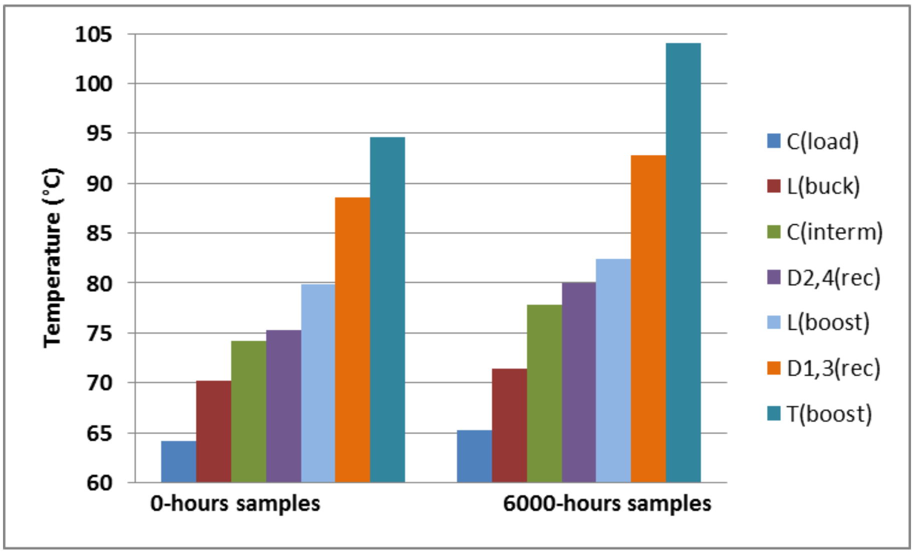


Figure 5.8: *Effect of aging on temperature of the SSL driver components. Bar graphs in each of two categories of 0-hour and 6000-hour from left to right are* C_{load}, L_{buck}, C_{interm}, $D_{2,4}$, L_{boost}, $D_{1,3}$, T_{boost}. *The ambient temperature in these tests is* $20.5°C \pm 0.5°$.

Why NOT to use Arrhenius equation It is a common comment for experiment such as this, to use the Arrhenius equation in order to predict the device's behavior. It is essential to here stress why it is not correct to use the Arrhenius equation for this case study. It is a formula (Equation 5.4) for the temperature dependence of reaction rates which can be used to model the temperature variation of diffusion coefficients, population of crystal vacancies, creep rates, and many other thermally-induced processes/reactions.

$$\begin{aligned} & k = Ae^{\frac{-E_a}{k_B T}} \\ & k: \ rate\ constant \\ & A: \ prefactor \\ & E_a: \ actication\ energy \\ & k_B: \ Boltzmann\ constant \\ & T: \ temperature \end{aligned} \tag{5.4}$$

A complex system such as an SSL driver is constructed from different components which each of them includes different materials. Each of the components can have different modes of degradations due to the temperature which each of them has different activation energy[6]. The degradation of each component changes the system performance (thermally, electrically, etc.). Changing the system performance affects the functionality and degradation process of all its components. Therefore a system like an SSL driver, which is a complex network of different materials with different ways of degrading, cannot be simply modeled by Arrhenius law which is defined for one reaction/process.

Effect of aging on power consumption

Fig. 5.9 shows light engine power, active cooling power, and the dissipated power in the SSL driver (Equation 5.1) changes due to the aging. It is observed that as a result of aging, the power dissipation in the SSL driver increases. The power to the light engine stays almost the same. This is because the SSL driver is designed to keep the power to the light engine part (almost) constant. The SSL driver heats up due to the increase of its power dissipation. This is in agreement

[6] Activation energy is defined as the minimum energy required to start a chemical reaction.

with the thermal tests results which shows the higher temperature for the SSL driver after aging. This is an irreversible change and should not be mistaken for an increase due to increase of ambient temperature. As a consequence of more power dissipation in the SSL driver, its efficiency decreases from 88% in 0-hour samples to 79% in 6000-hours samples (Equation 5.1).

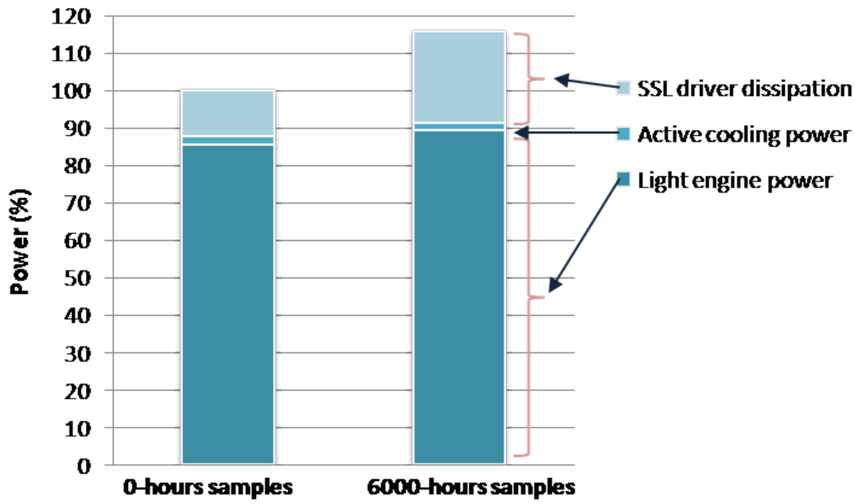


Figure 5.9: *Effect of aging on relative power consumption in samples. There is 15% increasing in SSL lamps total power consumption which is mostly dissipated in the SSL driver.*

5.5 Conclusions

This chapter presents experimental results of an actual SSL lamp case study. The results of thermal and electrical measurements in this chapter helps understanding the reliability of the SSL driver. Two main collections of tests are performed on the samples (all samples are fully functional). The results of the tests are as follows:

- Effect of ambient temperature:
  - The tests results are reproducible.

  - There is linear dependency of the device temperature with the ambient temperature.
  - Application for these tests: these sets of measurements can define the range of ambient temperature in which the device can work properly.

- Effect of aging:
  - The tests results are reproducible.
  - The steady state operational temperature of an SSL driver increases with aging. This is an irreversible change.
  - The electrical power dissipation in the SSL drivers of the aged samples is higher, and respectively the electrical efficiency of the aged samples is lower. This is an irreversible change.
  - Application for these tests: by having enough samples of different age, the dependency between age and temperature/efficiency can be modeled. The device's lifetime can be predicted by means of such models.

Chapter 6

Design for Reliability

Design for reliability is a systematic and concurrent engineering program in which reliability engineering is intertwined into the whole development cycle. Prognostics and health management is a technique under the practice of Design for Reliability. It will be discussed how we can put this concept into practice for an SSL device. For this purpose, an SSL device with extra functionalities is designed in this work. The functions developed makes the device capable of performing prognostics and health management procedures on its own. [1]

[1] This chapter is reproduced from the following publications: [S. Tarashioon, A. Baiano, H. van Zeijl, C. Guo, S. W. Koh, W.D. van Driel, G. Q. Zhang, **An approach to "Design for Reliability" in solid state lighting systems at high temperatures**, Journal of Microelectronic Reliability, doi: 10.1016/j.microrel.2011.06.029]
[S. Tarashioon, C. Guo, H. van Zeijl, W. D. van Driel, G.Q Zhang, **LED in Double function; Light Source and Light Sensor**, Proceedings of 8th China international forum on solid state lighting, November 2011, Guangzhou, China]

6.1 Introduction

Design for reliability is a systematic and concurrent engineering program in which reliability engineering is intertwined into the whole development cycle. This chapter deals with system prognostics and health management as a technique under the practice of Design for Reliability. The concept of Prognostics and Health management (PHM) for electronic systems has been introduced by CALCE center (Center for Advanced Life Cycle Engineering) at University of Maryland [136]. PHM is a method that permits reliability assessment of a product or a system under its actual applications conditions. PHM techniques combine sensing, recording, interpretation of environmental, operational, and performance related parameters to indicate a systems health [35, 137]. This method is based on physics of failure reliability prediction methods. Although applying this capability to an SSL system is costly, it can be very beneficial especially in application fields where maintenance is very expensive or reliability is intertwined with safety. It brings the following benefits:

- Provide advanced warning of failure
- Minimize unscheduled maintenance
- Reducing inspection costs
- Improving qualification

A system with prognostics and health management capability has a set of minimum hardware requirements. This system should be able to sense, record, process, and communicate. Therefore an SSL system with health management capability besides having a basic lamp function, should have additional capabilities as follows:

- *Processing part:* The system should be smart, and therefore it needs a microcontroller[2] with its required peripherals.

[2] A microcontroller is a small computer on a single integrated circuit containing a processor core, memory, and programmable input/output peripherals. Microcontrollers are designed for embedded applications, in contrast to the processors used in personal computers or other general purpose applications.

- *Monitoring part:* is a collection of sensors for monitoring environmental and internal conditions of an SSL device.

- *Communication part:* makes the communication possible between individual SSL devices, as well as between SSL devices and the users.

In this work an SSL device with the above mentioned capabilities is designed. The following parts of this chapter explain the design, the performed tests, and ideas about how PHM discipline can be applied on such a design.

6.2 System Design

In this work an SSL device with health management capability has been designed with the following specifications[3]:

- Basic lamp functions
  - Device can illuminate maximum 200lumen
  - Input power is 200V/50Hz
  - Dimming capability
- Processing part
  - Smart light (microcontroller)
- Monitoring part
  - Equipped with a light sensor
- Communication part
  - Wireless communication capability

[3]The design of the device was accomplished under ENSURE project which was between TUDelft and Philips lighting.

This design satisfies the additional requirement of a system with PHM capability. The original design also included a sensing mechanism in order to measure the LED junction temperature. This design is based on using LED itself to measure its own junction temperature. The details of the design can be found in Appendix D. Fig. 6.1(a) shows the block diagram of the lighting system designed in this work. Each module in this figure is an SSL device with the specifications which was explained above. All modules have the communication capability with the other one and also with the server. Each module can access to all collected data from the other modules' light sensors. Light output can vary from 0% to 100% and it can be controlled by means of both control signals from the server and the module itself.

Fig. 6.1(b) illustrate the block diagram of each module. Its different parts which are microcontroller part and wireless communication part, light engine, driving LEDs, dimmer, and light sensor are explained in the following sections. The final product of modules is shown in Fig. 6.2.

6.2.1 Microcontroller and Wireless Communication Part

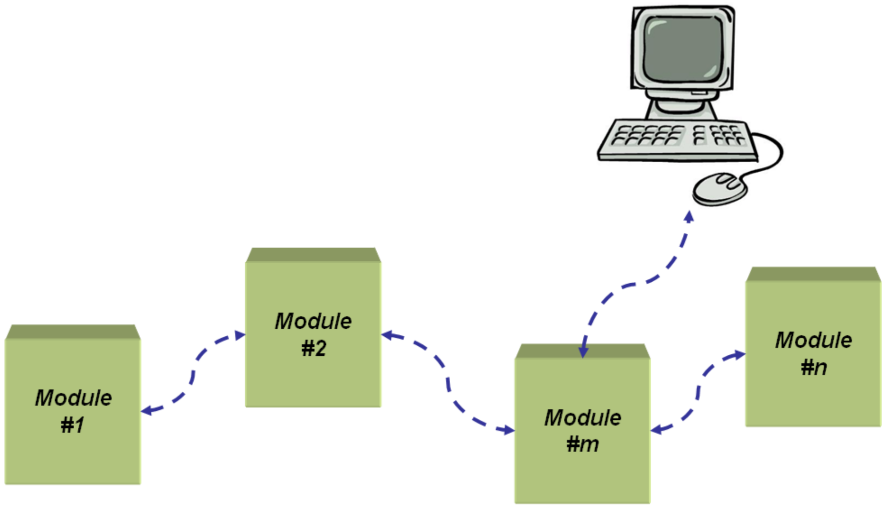
In this design an off-the-shelf microcontroller board (Tmote Sky) with wireless communication capability is used [138]. Tmote Sky is using the 8MHz Texas Instruments MSP430 microcontroller with 10k RAM, 48k Flash memory. It has integrated ADC[4] and DAC[5] and 250kbps 2.4GHz IEEE 802.15.4 Chipcon Wireless Transceiver. It can be programmed and communicate through USB connection as well. The microcontroller is the brain of the system which controls all parts by means of the software it is programmed with. The software is out of the scope of this discussion, It can be found in the works of C. Guo et. al. [14, 139].

6.2.2 Light Engine

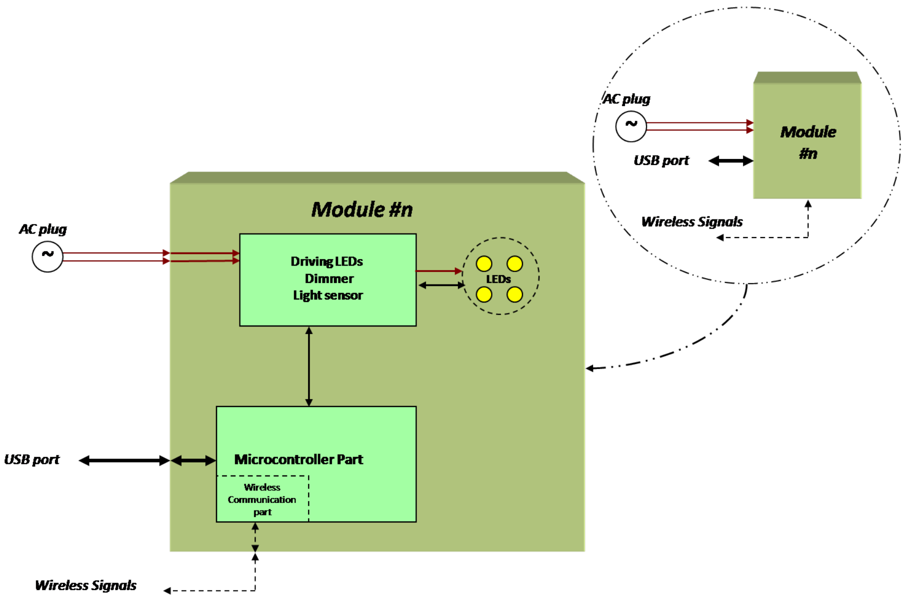
Light engines of any SSL device constructed from one or more LEDs which provides the required light output. The goal in this design is providing maximum

[4]In electronics, an analog-to-digital converter (ADC) is a device that converts a continuous physical quantity (usually voltage) to a digital number that represents the quantity's amplitude.

[5]In electronics, a digital-to-analog converter (DAC) is a device that converts a digital (usually binary) code to an analog signal (current, voltage).



(a) Smart lighting system: different modules can communicate with each other and also with a server through wireless network.



(b) The block diagram of one module. Four LEDs construct its optical part and the rest construct the SSL driver.

Figure 6.1: *The block diagram of the SSL system with PHM capability designed in this work.*

Figure 6.2: *Final product of the designed device. (The right one is the device without the front cover)*

200lumen light output. The basic step for designing the light engine is selecting the LED type. A survey in the high brightness LEDs market shows that there are generally two main categories of HB LEDs: the first category is the LEDs with high operational current and relatively low voltage. An example of this is Philips Lumiled 'Luxeon Rebel' LEDs with 3V/1000mA [140]. The second category is LEDs with high operational voltage and relatively low current, such as Seoul Semiconductor 'Acriche' LEDs with 50V/40mA [141]. In this design the Acriche LEDs from Seoul Semiconductor manufacturer is chosen due to the ease of driving the LED part. The specifications of this LED type are as follows:

- Liminous Flux: 50lumen
- Operating voltage: 63V (max)
- Current: 20mA
- Power rating: 0.76W
- Operating temperature: $-30°C\ to\ +85°C$

The light engine of this device is a PCB which contains four of this LED type connected electrically in serial manner together. A connector connects the light engine to the rest of the device.

6.2.3 Driving LED

Fig. 6.3 shows the electronic schematics for driving the LEDs. Choosing high voltage LED while the input power is 220V/50Hz (V1 in the schematics) gives this opportunity of using linear topology and still having reasonable efficiency. A diode bridge (D7) and a capacitor (C1) converts $220V_{AC}$/50Hz voltage to $310V_{DC}$ signal. A series of four LEDs (D1 to D4) are powered with this DC power. Forward voltage across each LED is about 50V and it is driven with constant current of 50mA. Power transistor (Q1) operates as the current sink to drive the four LEDs, and controls the current flow through LEDs. Applying 0V to the transistor gate ("ON/OFF" signal) turns the LEDs off, and applying 20V to the transistor gate turns the LEDs on. Fuse (F1) and thermistor[6] (TH1) are the protection elements. This design allows to add a fifth LED in series with the other four. In that case the efficiency of the driving part will increase due to less power dissipation on transistor Q1 and resistor R5.

6.2.4 Dimming Part

This part is an addendum to the design of the driving LED part. Applying a range of voltages between 0V to 20V to the 'ON/OFF' control signal in Fig. 6.3, varies the LEDs illumination from its 0% *to* 100% of its maximum illumination. The small series resistor (R5) helps to have a linear changing of current and have a good linear dimming functionality. The goal is to be able to control the LEDs light output from the microcontroller part.

Fig. 6.4 shows the electronic schematics for driving LED part including dimming part. The available signals on microcontroller part is 0V to 3V. An extra circuitry is used to convert the microcontroller 0V to 3V signal to 0V to 20V re-

[6] A thermistor is a type of resistor whose resistance varies significantly with temperature, more so than in standard resistors. One common application of thermistors is inrush current limiter.

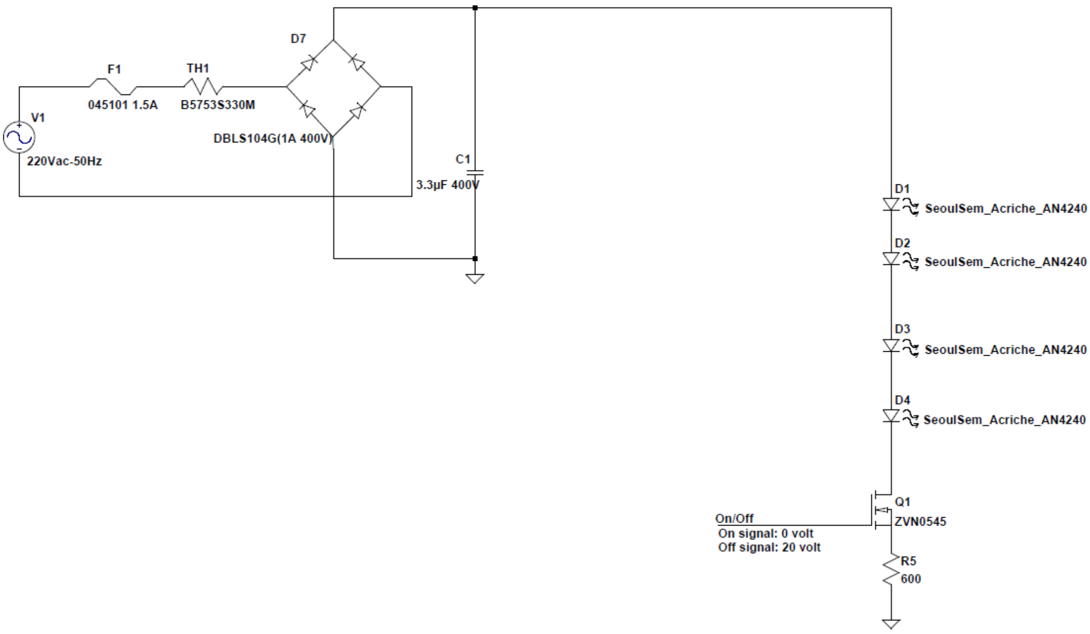


Figure 6.3: *Electrical schematics for driving the LEDs*

quired on Q1 transistor. Operational amplifier (U1A) performs this task. There is an extra challenge here to provide the required power for operational amplifier which is +15V. Due to the very low power consumption of this operational amplifier, a simple structure with a 15V Zener diode (D5) and a capacitor (C2) can convert the already available $310V_{DC}$ *to* $15V_{DC}$.

6.2.5 Light Sensor

Generally LEDs are being used as a light sources. However due to its physical properties and its type of packaging, it is possible to be utilized as a light sensor [142]. In this design, the goal is to use one out of four LEDs in a double function of being both light source and light sensor. But first let's see how we can use this LED as a light sensor.

LED is a PN junction[7] and its reverse current is sensitive to the amount of

[7]A PN junction is a boundary or interface between two types of semiconductor material, p-type and n-type, inside a single crystal of semiconductor.

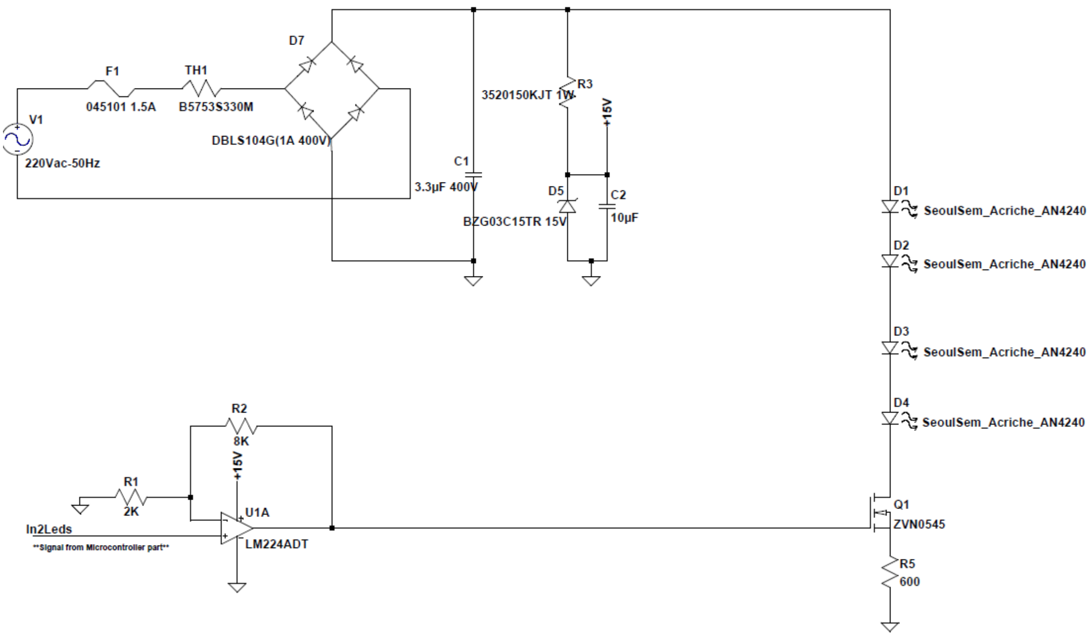


Figure 6.4: *Electrical schematics for driving the LEDs and dimming function*

light exposed to its junction. Studying the physics of semiconductors tells you that in PN junction the excess electrons and holes created in space charge region are separated very quickly by the electric filed so that a photo current is generated [143]. By looking at the results of tests on IV curve (current versus voltage) of the LEDs used in this design in Fig. 6.5, it is observed that the current in its reverse bias is sensitive to the exposed light to the LED. Thus it can work as a photo detector and convert optical signal to electrical signal.

The conclusion is that by forward biasing the LED, it works as a light source, and in reverse biasing it can operate as a light sensor by measuring the light exposed to the LED. In any moment of time, the LED can operate either as a light source or light sensor, functioning as both at the same time is not possible. Therefore for using the same LED in both functions, it should be switched between forward biasing and reverse biasing with the frequency which is not visible to the human eyes (above 50Hz). In the following sections, the electronic design for integrating the light sensor reader in our circuit and then the experiment results are explained.

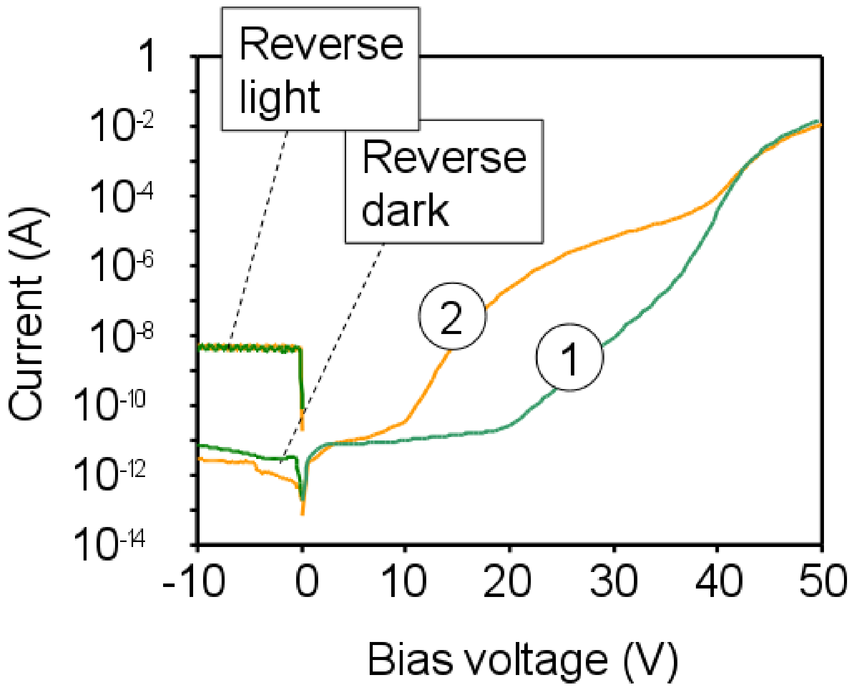


Figure 6.5: *IV curve of two LED samples (marked as (1) and (2)) from the Seoul Semiconductor (Acriche A4 series) in reverse bias and forward bias. The relationship between reverse current and ambient light are distinguished.*

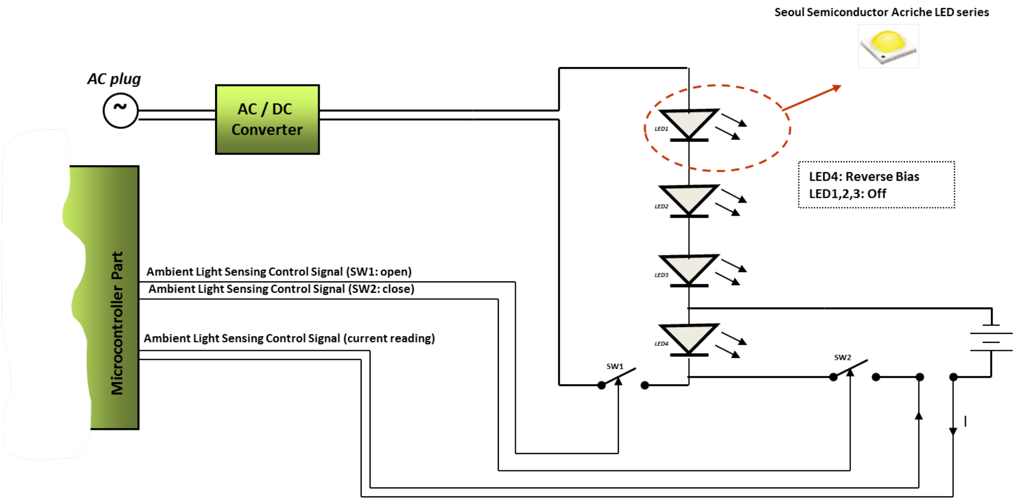


Figure 6.6: *The block diagram for light sensor readout for our SSL device.*

6.2.5.1 Designing the Light Sensor Readout

In the light engine of our SSL device, there are four HB LEDs in series which are powered by converted DC power from AC input power of 220V/50Hz. These LEDs can be dimmed from 0% *to* 100% by the signal from microcontroller. The concern now is how to use one of the LEDs as light sensor as well. The LEDs should be switched back and forth between light source mode and light sensor mode. In this design just one out of four LEDs will function as light sensor. It means either all four LEDS are forward bias (ON), or three of them are disconnected and one of them is performing as a light sensor (OFF or no light output from the device). If these switching ON and OFF happens fast enough, it is seen as a continuous light.

Measuring the light exposed to the LED is done by measuring the reverse current through it. Block diagram of the light sensor readout in the SSL device shown in Fig. 6.6 helps with understanding this design. Switch SW1 disconnects the chain of four LEDs and switch SW2 makes it possible to reverse bias one of the LEDS. Both switches are controlled by microcontroller. The current which passes through this LED is being read by the microcontroller. Indeed, in this mode, all LEDs are switched off. Therefore, it is important to keep this transient response as short as possible to prevent flickering the light.

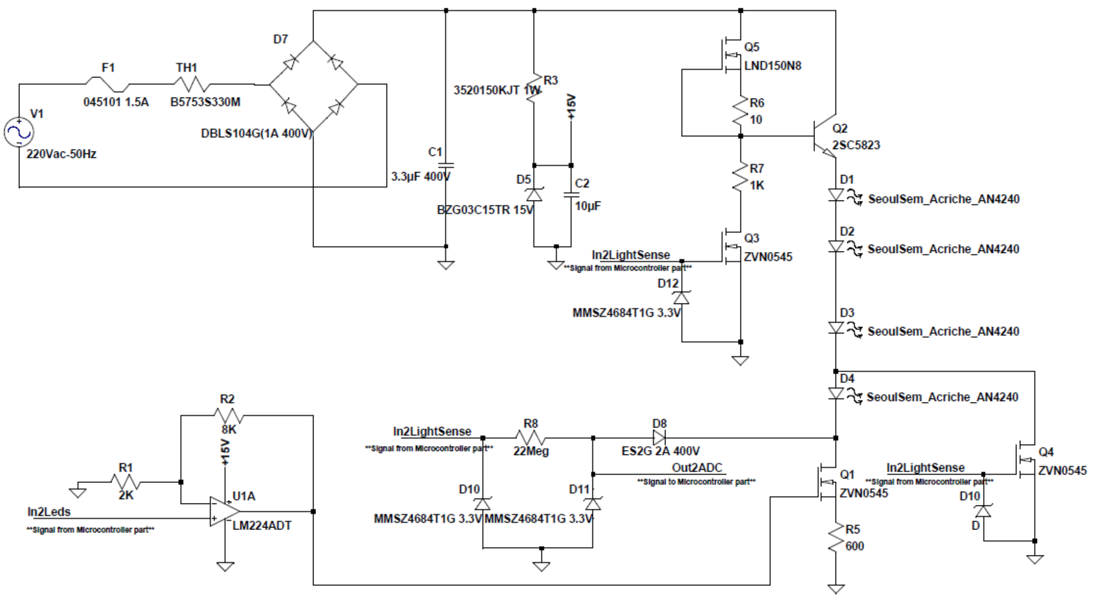


Figure 6.7: *Electrical schematics for driving the LEDs, dimming function, and using one of the LEDs as a light sensor.*

Fig. 6.7 shows the electronic schematics for the SSL device including the light sensor readout. Transistor Q1 and circuit with transistors Q2, Q3 and Q5 play the role of switch SW1 in block diagram in Fig. 6.6 and CMOS transistor Q4 plays the role of switch SW2. In order to measure the reverse current, first it is converted to voltage by means of a very big resistor (R8) and then it is read by 12-bit ADC (Analog to Digital converter) port of the microcontroller. The light intensity sensed by the LED which operates as light sensor is logged in the microcontroller memory, and is used later based on the defined application.

6.2.5.2 Testing LED as a Light Sensor

In this section, first the experimental setup is explained. Then the tests results are shown. The goals of the tests are proving the reproducibility of the light sensing function in each device and consistency of the results between devices. The sensitivity of this light sensor (LED including its readout) is calculated. Last part of this section discusses the potential applications of using LED as a light sensor regarding health management.

Experimental Setup

Ten devices are manufactured and serve as specimen in these experiments. As it is shown in Fig. 6.8(a) The specimens can exchange data with a computer via wireless connection. The setup for reading the light sensing output is shown in Fig. 6.8(b). The specimen are exposed to an external light source with controllable light output intensity. The intensity of light output of the external light source is measured by a light spectrometer. AvaSpec-ULS2048 spectrometer from Avantes which can measure wavelengths from 200nm to 1100nm is used [144]. The experiments are performed in a dark room in order to have full control over the amount of the exposed light to the devices. Devices are tested at room temperature of around $25°C$.

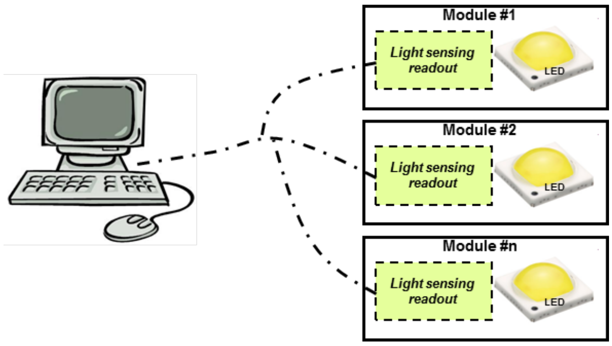
Test Results

There are three major questions to be answered in these experiments; the first two are regarding the reproducibility and consistency of the results for each individual SSL device and then in comparison to the other SSL devices. Last question is how much the sensitivity of this system is to light variation.

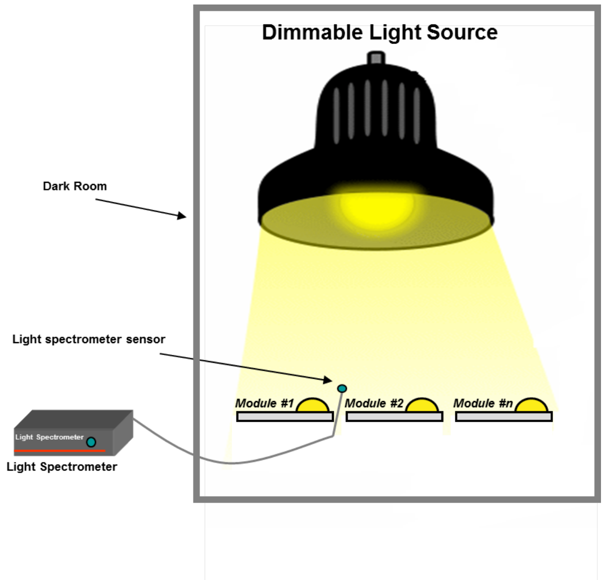
For answering the questions about the consistency and reproducibility of the results for each individual SSL device and comparison between different SSL devices, the tests are performed on 10 modules. All 10 modules are exposed to three different light intensities. In each case, the reverse current of LED in the first module is sampled for 10 times. Then the procedure is repeated for the second module and so on till the tenth module. This routine was repeated for 14 iterations. This helps removing the effect of possible faults in the software and in the wireless communication links which is the media to transfer the light sensing readout value to the computer. Table 6.1 shows the mean value and standard deviation of the 10 modules under tests.

In order to answer the first question, we should look at the standard deviation of each module in different light intensities. The mean values are in range of 64nA to 86nA, the standard deviations of the modules are less than 2.7nA. It shows that the results are reproducible.

In order to answer the second question, the different modules behavior with respect to each other are studied. Looking at the standard deviations between mean values from different modules in the same light status is the way to achieve



(a) Focusing on light sensing, each module includes LED which works as a light sensor and light sensor readout which has the capability of being connected through wireless communication to the computer for the purpose of data acquisition.



(b) Light sensing experimental setup. Light spectrometer is used to have information about the intensity of light exposed by a dimmabale light source to the modules. Tests are performed inside a dark room in order to be isolated from outside light. The tests are performed at room temperature.

Figure 6.8: *Experimental setup for testing SSL devices light sensing functionaly.*

Table 6.1: *LED reverse current mean value and standard deviation for 10 modules in three different light intensity of 0, 42, 140 [$\mu W/cm^2$]. The values are the results of 140 measurements.*

Light intensity	Dark Status (LED reverse current[A])		$42\mu W/cm^2$ (LED reverse current[A])		$140\mu W/cm^2$ (LED reverse current[A])	
	Mean 1×10^{-7}	Std 1×10^{-8}	Mean 1×10^{-7}	Std 1×10^{-8}	Mean 1×10^{-7}	Std 1×10^{-8}
Module1	0.67	0.03	0.72	0.01	0.86	0.02
Module2	0.68	0.01	0.69	0.02	0.82	0.02
Module3	0.65	0.01	0.66	0.12	0.80	0.08
Module4	0.68	0.16	0.72	0.17	0.85	0.02
Module5	0.66	0.01	0.70	0.02	0.80	0.05
Module6	0.65	0.03	0.71	0.03	0.78	0.01
Module7	0.68	0.04	0.72	0.02	0.85	0.05
Module8	0.67	0.02	0.73	0.02	0.83	0.02
Module9	0.68	0.03	0.72	0.03	0.85	0.02
Module10	0.69	0.27	0.72	0.02	0.85	0.03
Min	0.65		0.66		0.78	
Max	0.70		0.73		0.86	
Max-Min	0.05		0.08		0.09	
Mean	0.67		0.71		0.83	
Std (1×10^{-8})	0.16		0.22		0.2861	

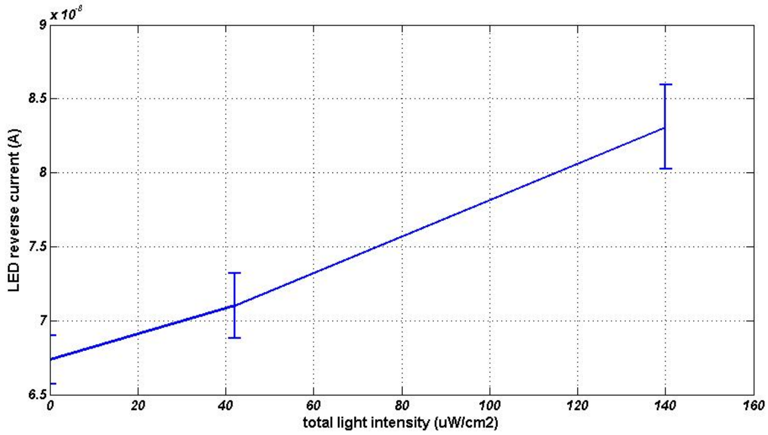


Figure 6.9: *Mean value of LED reverse current for 10 modules with respect to the total light intensity exposed to them. This graph shows the standard deviation of the values in each reading point. The total light intensity is in the range of 400nm to 900nm of the light spectrum.*

the answer. With the same range of mean values for each module the standard deviations are less than 2.9nA. Fig. 6.9 is the illustration of the mean value and standard deviation for all 10 modules.

In order to answer the third question, the sensitivity of the modules to the exposed light are calculated. To reach this goal, a new set of measurements with more variation of light intensities are performed. The number of modules under test is 3 modules. Data reading procedure is the same as previously mentioned. In each light intensity, the reverse current of LED in the first module, the second module, and the third module are read for 10 times. The whole routine is repeated for 14 iterations. In total 140 times the reverse current of the LED in each module is measured. Fig. 6.10 is the illustration of the mean value of the three modules. The calculated standard deviation of the data is less than 0.1nA. In this figure the data points are fitted to a linear curve:

$$\begin{aligned} y &= p_1.x + p_2 \\ p_1 &= 2.374 \times 10^{-11} \\ p_2 &= 7.3816 \times 10^{-8} \end{aligned} \tag{6.1}$$

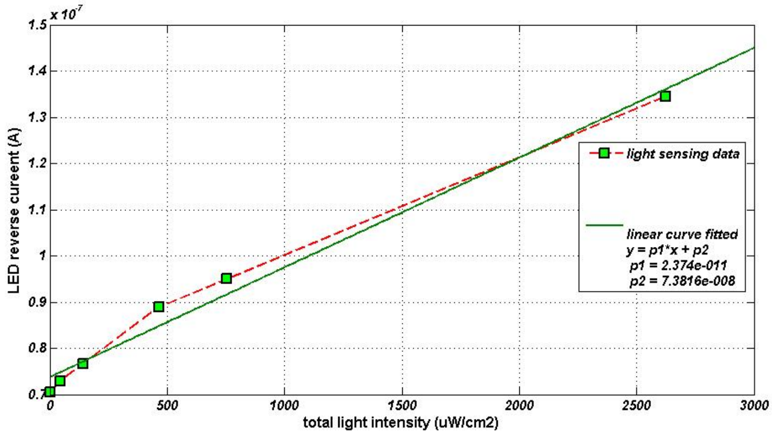


Figure 6.10: *Mean value of LED reverse current of 3 modules with respect to the total light intensity exposed to them. The total light intensity is in the range of 400nm to 900nm of the light spectrum. The solid line shows the linear fitted curve.*

Discussions

In any photo-detector device, one of the important parameters is the quantum efficiency of the device. It is defined as the number of carriers produced per photon. The other similar metric is responsivity which uses optical power as a reference [145]. Equation 6.2 explains the calculation of the responsivity which is proportional to quantum efficiency.

$$\begin{aligned}
&\Re = \frac{I_{ph}}{P_{op}} = \frac{\eta q}{h\nu} \\
&\Re : Responsivity \\
&I_{ph} : Photocurrent \\
&P_{op} : Optical\ power \\
&\eta : Quantum\ efficiency \\
&q : Unit\ electron\ charge \\
&h\nu : Photon\ energy
\end{aligned} \tag{6.2}$$

In our case the photo-detector is a photodiode which the diode is in the reverse bias. In a photo diode we can calculate the quantum efficiency as follows [145]:

$$
\begin{aligned}
&\eta = (1-R)[1-\frac{exp(-\alpha W_D}{1+\alpha L_P}]\\
&R : Reflection\ coefficient\\
&\alpha : Optical\ absorption\ coefficient\\
&L_P : Diffusion\ length\ of\ holes\\
&W_D : Depletion\ layer\ width
\end{aligned}
\tag{6.3}
$$

The quantum efficiency of a photodiode is constant, and is dependent to the device's design, readout design, and material. Therefore it can be concluded that photo current of our LED in its reverse bias is proportional to the optical power. In Equation 6.1, p_1 is the responsivity in our modules to the optical power, and p_2 is the dark current in the reverse bias.

In order to define the sensitivity of this module with respect to light power, we make use of Equation 6.1 and the maximum value of the standard deviations. Assume that there are two points on the linear curve of the LED reverse current with respect to light intensity ($[x_a, y_a]$ and $[x_b, y_b]$) which this module is capable to properly distinguish. The following inequalities equation should be true:

$$
\begin{aligned}
&y_b - std_{max} > y_a - std_{max}\\
&x_b - x_a > \frac{2std_{max}}{p_1}
\end{aligned}
\tag{6.4}
$$

If we use the maximum value of the standard deviation which applies to all 10 modules which is 2.8nA then the minimum difference between two light power which is readable by this module is $235\mu W/cm^2$.

6.3 System in Operation

In this section it is explained how such a system can use its capabilities regarding prognostics and health management. In a lighting system with this design, the modules can be programmed to do the following tasks:

- All modules are functioning as light sources.
- All modules are functioning as light sensors, thus they measure the ambient light in the environment.
- One module is functioning as light source and the rest of the modules in the environment are functioning as light sensors. The adjacent modules can measure the light output of the light source module plus the ambient light.

By exchanging the information with the other modules, each module has the information about ambient light intensity, and light intensity produced by each of the modules including itself. Now the discussion is what can be done with this information:

- The case of "no light output" of any of the modules can be reported to the maintenance department.
- The case of any module having "lower light output than the minimum light defined in the module specification"[8] can be reported to the maintenance department.
- All modules can be programmed to be dimmed to lower than 100% (for example 80%). In case of one of the modules failure the rest can provide more light to compensate for the failed module.
- Light degradation of each module during time is monitored. In case of the existence of a model based on virtual assessment or experiments (refer to work in Chapter 4 and Chapter 5) the remainder of the module's lifetime can be predicted.
- In case of being able to predict the lifetime of each module, the remainder of the lifetime of the device can be continuously reported to the maintenance department. In addition to that, when it is close to the end of its

[8]One example of this specification is the "ASSIST recommendation" [36] which says the light output should be at least 70% of the initial light output of the device.

lifetime the module can be dimmed down and make the degradation process slower. It can keep the module functional till the time for replacement. This is a method for self-maintenance of the device (refer to Chapter 3 for explanation about self-maintenance) .

In the ideal case with no degradation, the light measured by the module through time should be the same. But in reality this is not the case, LED degradation changes its capability as a light sensor as well. Therefore while using the LED as light sensor, we should keep in mind that each module degradation also affects the value which is measured by each LED in light sensing mode. This is a topic for a new research, and can be used as a method to define the degradation level in the LED itself. By exposing the module in light sensing function to a fixed and controlled amount of light through time this degradation can be known. This idea is registered as an intellectual property in Philips "Replacement indicator of LED systems by using the light emitting diode as a light sensor" [146]. This method can be used for testing LEDs after manufacturing as well. It means instead of measuring light output of LEDs in a sphere, LED reverse current can be measured while it is exposed to a fix and controlled amount of light. This idea needs more research.

6.4 Conclusions

An SSL system is designed which has the requirements of a system with prognostics and health management capability. This system includes SSL modules which besides being able to act as an ordinary lamp, are constructed with three more major blocks: the processing, monitoring, and communication parts. The processing part is a microcontroller board which perform the processing function. The microcontroller board has the capability of communicating through USB connection and wireless connection with the other modules and a server computer. This part covers the communication part. The monitoring part is a light sensor. The light sensor in these modules is one of the LEDs, which operates as both functions of light source and light sensor. The LED reverse current represent the amount of light exposed to the LED.

The microcontroller puts the LED in forward and reverse bias in a cyclic way with a frequency high enough that the light flicker is not visible to our eyes. The experiments in this work show the reproducibility of LED operating as a light sensor. By means of experimental test results, the LED sensitivity to the light is calculated. The sensed light by each module is being gathered and sent to the other modules and server computer. This data contains information about ambient light and light output of each module at each moment. We have demonstrated that the prognostics and health management procedure is possible by making use of this data over time. Nevertheless, it requires acquiring the knowledge about effect of aging on the LED as both light source and light sensor.

Chapter 7

Conclusions and Recommendations

In this chapter, the research objectives of the thesis are revisited. The primary findings of the presented research toward the goal of addressing the reliability of solid state lighting drivers with a systematic approach are summarized. Finally, recommendations are given for future research.

7.1 Conclusions

Solid state lighting (SSL) is a recent lighting technology which uses the light emitting diodes as the light source. This technology due to several outstanding characteristics has become very attractive to both manufacturers and consumers. Examples of these characteristics are lower power consumption, longer lifetime, and design flexibility with respect to the conventional lighting. Two major parts in any SSL devices are the optical part which includes light engine, and the SSL driver. SSL devices and more specifically SSL drivers as one of the major part of the SSL devices require special attention regarding to their reliability due to the following reasons:

- SSL is a new technology with very little existing field information.
- SSL has a long lifetime (over 20,000 hours) which makes its testing till the end of lifetime before releasing the product into the market very difficult.
- SSL is a more complex system with far more different failure modes than conventional lighting devices.
- SSL driver reliability study has received much less attention than the light engine part. Therefore there is a concern that SSL driver can be the bottle neck for the performance and lifetime expectations of the SSL devices.

The most suitable reliability assessment method for SSL drivers

There are four common reliability assessment methods which are based on field data, test data, handbooks, and stress and damage model. Reliability prediction based on handbooks have been criticized due to their lack of accuracy. Reliability prediction based on field data is not applicable yet because of long lifetime of the SSL and it being a relatively new technology. Reliability prediction methods based on stress and damage model and based on test data are the most suitable ones for the case of SSL drivers. A method based on stress and damage model can not only give an estimation about lifetime of the driver but also valuable information for designers to improve the design regarding reliability issues. The disadvantage of this method is that it is not a fast solution, and it takes time to understand and to develop a proper model.

Implementing a system-level reliability assessment methodology

A new partitioning method for SSL driver for reliability purpose is introduced. This method distinguishes the device's functional elements and packaging elements. There are advantages and disadvantages for this new partitioning method. The disadvantage of this method is that much traditional reliability information of the components will be hard to use. The reason is that they mostly refer to failure rate for the whole component, functional and packing elements together. As advantages of this method, we can mention the following; different parts which share different functions share the same failure modes and thus makes the reliability study easier. Also finding the dominant failure mode becomes easier. Finally, due to categorizing different parts by their functions, the design can be assigned to different professionals to examine its reliability performance. Based on the introduced partitioning method, the reliability study is divided in four categories which exchange information with each other. They are electrical, electromagnetic, thermal, and mechanical reliability analysis. It is a more structured reliability procedure and therefore makes it more possible to be applied in computer programs.

Multi-physics reliability assessment methodology

The multi-physics reliability simulation method introduced in this thesis helps understanding electrical / thermal status of an SSL driver during its lifetime. This method can be a good complementary tool for experimental tests such as lifetime test. This method uses the component behavior in different time and temperature in a system-level simulation method, in SPICE and MATLAB. The results show that our proposed method is able to forecast the lifetime of the driver. Sensitivity analysis indicates the most important parameters on component level that determines the lifetime estimate. Our iterative multi-physics reliability simulation method can be a strong technique to support the design of SSL drivers.

Two limitations can be mentioned for our method. First, like every repetitive simulation method, it can be time consuming. Second, this simulation is strongly dependent on the information from components; the components non-ideal models and their value dependency to temperature and time which should be provided by manufacturers. For complex components such as the controller part, it can be complicated to provide such information. Also for very cheap components such as passive components, manufacturers usually are not eager to spend time and money to provide this information. But the bright side for the later problem is that recently more and more attention is attracted to the physics of failure method as the preferred method for reliability study of the devices. Therefore, more and more research is being done on components physics of failure. Therefore a bright future for such system reliability simulation based on physics of failure of the components can be predicted.

Experiments on thermal / electrical performance of SSL devices with aging

Thermal and electrical experiments are performed on the driver of an SSL halogen replacement lamp in order to monitor the changes during the aging of the device. There are two groups of samples: the first group samples are 0-hour old and the second group samples are 6000-hours old. The second group has been working under controlled conditions for continuous 6000 hours. Extra experiments to monitor the effect of ambient temperature on 0-hours are performed. The experiments show the following results:

- Effect of ambient temperature:
  - There is linear dependency of the device temperature with the ambient temperature.
  - Application for these tests: these sets of measurements can define the range of ambient temperature which device can work properly.
- Effect of aging:
  - The steady state operational temperature of SSL driver increases with aging. This is an irreversible change.

- The electrical power dissipation in the SSL drivers of the aged samples is higher, and respectively the electrical efficiency of the aged samples is lower. This is an irreversible change.
- Application for these tests: by having enough samples in different ages, the dependency of the temperature and efficiency of the samples and their components to the aging can be modeled. Devices' lifetime can be predicted by means of such models.

Design for reliability

An SSL device is designed with system prognostics and health management capability. It has wireless communication and light sensing capability which can monitor the light in the environment. When there is a network of these devices in an environment by cyclic switching ON and OFF the devices, each device can have the information about ambient light and light output of each of the devices including itself. The speed of switching ON and OFF the devices is fast enough which is not detectable by human eyes. With this information the health state of each device is known to all devices. The LED of the device plays both roles of light source and light sensor in the device. It is concluded that using the LED in this way is well possible and can be used in application to sense the deterioration of the system. Nevertheless indeed it requires acquiring the knowledge about effect of aging on the LED as both light source and light sensor.

7.2 Recommendations for Future Research

In the light of the research objective sought in this thesis, the following suggestions are given for future research:

♦ Further development of multi-physics reliability simulation methodology:

- Integration of SPICE with thermal analysis FEM (Finite Elements Method) simulation programs such as COMSOL Multi-physics or ANSYS is one of the steps. In the future work instead of a simplified thermal model, details of the enclosure, PCB board(s), and components are to be considered in the thermal analysis simulation programs.

– Integration of electromagnetic analysis by using simulation programs such as COMSOL Multi-physics or ANSYS.

– Integration of mechanical analysis by using commercial available software like ANSYS, Abaqus or Marc/Mentat.

– Integration of optical analysis by using programs such as Lighttools in order to conduct real-time reliability simulations and/or lifetime predictions.

– Make a library for physics of failure information of the components which are used in different types of SSL drivers: This library can be extended every time new investigations are done on components behavior in different stress conditions and with aging.

– In the current work physics of failure models for discrete components have been taken into account. The developed method can be extended to integrated circuits as well.

♦ More case studies in order to determine the confidence level of the simulations:

– Monitor (in-situ) the electrical and thermal behavior of different case studies during their lifetime (or at least during a period of the lifetime) and compare the results with the outcome of the multi-physics reliability simulation.

– Taking variations in ambient temperature into account is preferred, since keeping it constant is a very rough estimation and only applies for in-door applications. For out-door applications a model that can cope with the variation of ambient temperature should be developed.

♦ Correlations with actual field return data to verify the predictions / simulations:

– In order to verify the reliability simulation method with confident and more accuracy, data from the actual field returns should be compared with the results of the simulation.

♦ Extend the multi-physics reliability simulations to be used in other applications:

- This method which has been used for reliability assessment of SSL drivers can be applied for any other electronic device. Clearly, The developed simulation method can be applied on different levels on a system in packages (SiP), first on the component level and then the results can be used in the higher levels.

Appendix A

SSL Driver Related Standards

Communication	ANSI/IESNA RP-16-05 Addendum a ANSI/IESNA RP-16-10 IEC/TS 62504
Measurement	ANSI C82.XX
Performance	IEC 62384 ANSI C82-SSL1-200X
Safety	ANSI/UL 1012 ANSI/UL 1310 IEEE project P1789 IEC 61347-2-13 ed1.0 UL 8750
Electromagnetic Compatibility	ANSI C82-SSL1-200X NEMA ANSI C82.77:2002 CISPR 15 IEC 61547 ed2.0 IEC 61000-3-2 ed3.2 (EMC)
Technology Development	IEC 62386-207 ed1.0 NEMA LSD-49 NEMA SSL-1

ANSI/IESNA RP-16-05 Addendum a

Nomenclature and Definitions for Illuminating Engineering

Power source - A transformer, power supply, battery, or other device capable of providing current, voltage, or power within its design limits. This device contains no additional control capabilities.

Power supply - An electronic device capable of controlling current, voltage, or power within design limits.

LED control circuitry - Electronic components located between the power source and the LED array designed to limit voltage and current, to dim, to switch,or otherwise control the electrical energy to the LED array. The circuitry does not include a power source.

LED driver - A power source with integral LED control circuitry designed to meet the specific requirements of a LED lamp or a LED array.

LED driver, Class II - An LED driver that operates within Class II limits as defined by the latest version of the National Electrical Code (NEC) and the Canadian Electrical Code (CEC).

ANSI/IESNA RP-16-10

Nomenclature and Definitions for Illuminating Engineering

Better measurement techniques have led to more international agreement in fundamental units and constants used in basic laws of physics. There is greater use of SI units today in illuminating engineering. This standard reflects the above with several new terms and definitions and revisions in existing definitions submitted through the continuous maintenance process.

IEC/TS 62504

General lighting - LEDs and LED modules - Terms and definitions

presents terms and definitions relevant for lighting with LED light sources. It provides both descriptive terms (such as "built-in LED module") and measurable terms (such as ”luminance”).

IEC 62384

DC or AC supplied electronic control gear for LED modules - Performance requirements

This international standard specifies performance requirements for electronic control gear for use on d.c. supplies up to 250 V and a.c. supplies up to 1000 V at 50 Hz or 60 Hz with an output frequency which can deviate from the supply frequency, associated with LED modules according to IEC 62031. Control gear for LED modules specified in this standard are designed to provide constant voltage or current. Deviations from the pure voltage and current types do not exclude the gear from this standard.

ANSI/UL 1012

Power units other than class 2

- These requirements cover portable, stationary, and fixed power units having an input rating of 600 volts or less, direct- and alternating- current, with at least one output not marked Class 2, and that are intended to be employed in ordinary locations in accordance with the National Electrical Code, ANSI/NFPA 70.

- These requirements cover general purpose power supplies and power supplies for uses such as to supply some household appliances, school laboratories, cathodic protection equipment; power supply-battery charger combinations; and industrial equipment, including inverters, divided into two classes - those rated 10 kilovolt-amperes or less and those rated more than 10 kilovolt-amperes.

ANSI/UL 1310

Power units class 2

- These requirements cover indoor and outdoor use Class 2 power supplies and battery chargers. These units utilize an isolating transformer and may incorporate components to provide an alternating- or direct-current output. Each output provides Class 2 power levels in accordance with the National Electrical Code, ANSI/NFPA 70. Maximum output voltage does not exceed 42.4 V peak for alternating current, 60 V for continuous direct current. These products are intended primarily to provide power to low voltage, electrically operated devices. These requirements apply to:

- Portable and semi-permanent mounted direct plug-in units provided with 15 A blade configurations for use on nominal 120 or 240 V alternating current branch circuits with a maximum potential of 150 V to ground;
- Cord- and plug-connected units provided with a 15 or 20 A attachment plug configuration for use on nominal 120 or 240 V alternating current branch circuits with a maximum potential of 150 V to ground;
- Units permanently connected to the input supply for use on nominal 600 V or less alternating or direct current branch circuit.

IEEE project P1789

Recommended Practices of Modulating Current in High Brightness LEDs for Mitigating Health Risks to Viewers

The scope of this standard is to: 1) Define the concept of modulation frequencies for LEDs and give discussion on their applications to LED lighting, 2) Describe LED lighting applications in which modulation frequencies pose possible health risks to users, 3) Discuss the concept of dimming of LEDs by modulating the frequency of driving currents/voltage 4) Present recommendations for modulation frequencies for LED lighting and dimming applications to protect against known adverse health effects

IEC 61347-2-13 ed1.0

Lamp controlgear - Part 2-13: Particular requirements for d.c. or a.c. supplied electronic controlgear for LED modules

This part of IEC 61347 specifies particular safety requirements for electronic controlgear for use on d.c. supplies up to 250 V and a.c. supplies up to 1000 V at 50 Hz or 60 Hz and at an output frequency which can deviate from the supply frequency, associated with LED modules.

UL 8750

The Standard for Safety of Light Emitting Diode (LED) Equipment for Use In Lighting Products

- These requirements cover LED equipment that is an integral part of a luminaire or other lighting equipment and which operates in the visible light spectrum between 400 - 700 nm. These requirements also cover the component parts of light emitting diode (LED) equipment, including LED drivers, controllers, arrays, modules, and packages as defined within this standard.

- These lighting products are intended for installation on branch circuits of 600 V nominal or less in accordance with the National Electrical Code (NEC), ANSI/NFPA 70, and for connection to isolated (non-utility connected) power sources such as generators, batteries, fuel cells, solar cells, and the like.

- LED equipment is utilized in lighting products that comply with the end-product standards listed below. The requirements in this standard are intended to supplement those in other end-product standards.

NEMA ANSI C82.77:2002

Harmonic emission limits - related power quality requirements for lighting equipment

Specifies harmonic limits and methods of measurement for lighting equipment.

CISPR 15

Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment

This standard applies to the emission (radiated and conducted) of radio frequency disturbances from different lighting equipments.

IEC 61547 ed2.0

Equipment for general lighting purposes - EMC immunity requirements

For electromagnetic immunity requirements applies to lighting equipment which is within the scope of IEC Technical Committee 34, such as lamps, auxiliaries and luminaires, intended either for connecting to a low voltage electricity supply or for battery operation. Excluded from the scope of this standard is equipment for which the immunity requirements are formulated in other IEC or

CISPR standards.

IEC 61000-3-2 ed3.2 (EMC)

Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current 16 A per phase)

This standard deals with the limitation of harmonic currents injected into the public supply system. Specifies limits of harmonic components of the input current which may be produced by equipment tested under specified conditions.

IEC 62386-207 ed1.0

Digital addressable lighting interface - Part 207: Particular requirements for control gear - LED modules (device type 6)

This standard specifies a protocol and test procedures for the control by digital signals of electronic control gear for use on a.c. or d.c. supplies, associated with LED modules. This Part 207 is intended to be used in conjunction with IEC 62386-101 and IEC 62386-102, which contain general requirements for the relevant product type (control gear or control devices).

NEMA LSD-49

Solid State Lighting for Incandescent ReplacementBest Practices for Dimming

The main objective for this paper is to encourage coordination among control, power supply, and LED module manufacturers to achieve desired performance. This effort may end up divided into (1) power supplies and integrated light sources designed for retrofit to existing incandescent dimmer sockets, and (2) power supplies and controls for new installations. The latter may achieve a simpler solution for the power supply if more intelligence is put into the control (dimmer). This must be coordinated within the industry; otherwise, there may be as many incompatible solutions as there are manufacturers, which will slow marketplace acceptance.

NEMA SSL-1

Electronic Drivers for LED Devices, Arrays, or Systems

This standard provides specifications for and operating characteristics of nonintegral electronic drivers (power supplies) for LED devices, arrays, or systems intended for general lighting applications. Electronic drivers are devices that use semiconductors to control and supply dc power for LED starting and operation. The drivers operate from multiple supply sources of 600 V maximum at a frequency of 50 or 60 hertz.

Appendix B

Applying Handbook Method on a Case Study

Although reliability prediction based on handbook has been criticized for different reasons [57], but it is still very popular due to its ease of use and providing the results in a very short time. The case study here is an SSL driver which has been designed for the car headlamp. Handbook used for this case study is Telcordia-SR332 standard [63]. SSL driver in this case study is a buck-boost power converter which converts the power from car battery to power up 'Luxeon Altilon' high power LED [147] for generating 1000lumen. This SSL driver consists of over 100 components (Table B.1 and Table B.2) to function as a power converter besides all filters and over-current, over-voltage protection circuits. The following is the steps to follow based on Telcordia SR332 reliability prediction standard.

First Step: The black box steady state failure rate (λ_{BB}). This parameter is calculated for every single component in the SSL driver. An example of look up tables of this handbook is shown in Fig. B.3, Failures in 10^9 hours (FIT rate).

By means of this look-up table λ_G of capacitors in the circuit can be found.

$$\begin{aligned}
&\lambda_{BB} = \lambda_G.\lambda_Q.\lambda_S.\lambda_T \\
&\lambda_G : Generic\ steady\ state\ failure\ rate \\
&\lambda_Q : Quality\ factor \\
&\lambda_S : Stress\ factor \\
&\lambda_T : Temperature\ factor
\end{aligned} \tag{B.1}$$

Second Step: The steady state failure rate (λ_{SS}) for one device when there is no lab or field data available:

$$\lambda_{SS} = \lambda_{BB} \tag{B.2}$$

Third Step: First year multiplier (π_{FY}) for device with limited or no burn-In:

$$\begin{aligned}
&if(1.14 \geq \pi_T.\pi_S) : \pi_{FY} = \frac{4}{(\pi_T.\pi_S)^{0.75}} \\
&otherwise : \pi_{FY} = 1 + \frac{3}{\pi_T.\pi_S}
\end{aligned} \tag{B.3}$$

Fourth Step: First year multiplier for device with extensive burn-In (t_{e_i}).

But first the equivalent operating time for burn-in should be calculated.

$$t_{e_i} = \frac{A_{b,d}t_{b,d} + A_{b,u}t_{b,u} + A_{b,s}t_{b,s}}{A_{op}\pi_{S_i}}$$
$$A_{b,d} : Arrhenius\ acceleration\ factor\ corresponding\ to\ the\ device\ burn-in\ temperature$$
$$t_{b,d} : device\ burn-in\ time\ (hours)$$
$$A_{b,u} : Arrhenius\ acceleration\ factor\ corresponding\ to\ the\ unit\ burn-in\ temperature$$
$$t_{b,u} : unit\ burn-in\ time\ (hours)$$
$$A_{b,s} : Arrhenius\ acceleration\ factor\ corresponding\ to\ the\ system\ burn-in\ temperature$$
$$t_{b,s} : system\ burn-in\ time\ (hours)$$
$$A_{op} : temperature\ acceleration\ factor\ corresponding\ to\ normal\ operating\ temperature.$$
$$If\ the\ temperature\ is\ unknown,\ use\ 1,\ which\ assumes 40°C. \quad (B.4)$$

$$\begin{aligned} &X = t_{e_i}.\pi_{T_i}.\pi_{S_i} and Y = X + 8760 \times \pi_{T_i}.\pi_{S_i} \\ &if(X \geq 10000) : \pi_{FY} = 1 \\ &if(Y \leq 10000) : \pi_{FY} = \frac{0.46 \times [y^{0.25} - X^{0.25}]}{\pi_T.\pi_S} \\ &otherwise : \pi_{FY} = \frac{1.14}{\pi_T.\pi_S}.[\frac{X}{10000} - 4.[\frac{X}{10000}]^{0.25} + 3] + 1 \end{aligned} \quad (B.5)$$

Fifth Step: Parts count steady state failure prediction for a unit (λ_{PC}):

$$\begin{aligned} &\lambda_{PC} = \pi_E.\sum_{i=1}^{n} N_i.\lambda_{SS_i} \\ &n : Number\ of\ different\ devices\ in\ the\ unit \\ &N_i : Quantity\ of\ ith\ device\ type \\ &\pi_E : Unit\ environmental\ factor \end{aligned} \quad (B.6)$$

Sixth Step: Unit steady state failure rate ($lambda_{SS}$) when there is no lab or field data available:

$$\lambda_{SS} = \lambda_{PC} \tag{B.7}$$

Seventh Step: Unit first year multiplier (π_{FY}):

$$\pi_{FY} = \frac{\sum_{i=1}^{n} N_i.\lambda_{SS_i}.\pi_{FY_i}}{\sum_{i=1}^{n} N_i.\lambda_{SS_i}} \tag{B.8}$$

Eighth Step: Serial System Reliability (λ_{SYS}):

$$\lambda_{SYS} = \sum_{j=1}^{M} \lambda_{SS_j} \tag{B.9}$$

	Description	Value	Type	Production Code	Manufacturer
1	CON V 3P M 1.27 SM 284696 R		284696	284696	ERNI
2	CON H 3P M 1.27 SM 234450 R		234450	234450	ERNI
3	CER2 0805 X7R 50V 100N PM10 R	100nF	GCM21BR7	GCM21BR71H104KA37L	MURATA MFG. CO. LTD
4	CER1 0603 NP0 50V 56P PM5 R	56pF	GCM1885C	GCM1885C1H560JA16D	MURATA MFG. CO. LTD
5	CER2 1206 X7R 50V 1U PM10 R	1u0	GCM31MR7	GCM31MR71H105KA55L	MURATA MFG. CO. LTD
6	CER1 0603 NP0 100V 100P PM5 R	100pF	GCM1885C	GCM1885C2A101JA16D	MURATA MFG. CO. LTD
7	CER1 0603 NP0 100V 100P PM5 R	100pF	GCM1885C	GCM1885C2A101JA16D	MURATA MFG. CO. LTD
8	CER1 0603 NP0 100V 100P PM5 R	100pF	GCM1885C	GCM1885C2A101JA16D	MURATA MFG. CO. LTD
9	CER1 0805 NP0 50V 100P COL R	100pF	31980160	319801601010	PHILIPS CONSUMER ELECTRONICS B.V.
10	CER1 0603 NP0 100V 100P PM5 R	100pF	GCM1885C	GCM1885C2A101JA16D	MURATA MFG. CO. LTD
11	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
12	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
13	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
14	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
15	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
16	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
17	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
18	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
19	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
20	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
21	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
22	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
23	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
24	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
25	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
26	CER2 1210 X7R 50V 4U7 PM10 R	4u7	GCM32ER7	GCM32ER71H475KA55L	MURATA MFG. CO. LTD
27	CER1 0603 NP0 100V 270P PM5 R	270p	GCM1885C	GCM1885C2A271JA16D	MURATA MFG. CO. LTD
28	CER1 0603 NP0 100V 330P PM5 R	330p	GCM1885C	GCM1885C2A331JA16D	MURATA MFG. CO. LTD
29	CER2 0805 X7R 50V 1N PM10 R	1n0	GCM216R7	GCM216R71H102KA37D	MURATA MFG. CO. LTD
30	CER2 1206 X7R 50V 1U PM10 R	1u0	GCM31MR7	GCM31MR71H105KA55L	MURATA MFG. CO. LTD
31	CER2 0805 X7R 25V 2U2 PM10 R	2u2	GCM21BR7	GCM21BR71E225KA73L	MURATA MFG. CO. LTD
32	CER2 1210 X7R 25V 10U PM10 R	10u	GCM32ER7	GCM32ER71E106KA57L	MURATA MFG. CO. LTD
33	CER2 1210 X7R 25V 10U PM10 R	10u	GCM32ER7	GCM32ER71E106KA57L	MURATA MFG. CO. LTD
34	RST SM 0805 1M PM5 COL R	1M0	31980215	319802151050	PHILIPS CONSUMER ELECTRONICS B.V.
35	RST SM 0805 RC12H 51K1 PM1 R	51K1	RC12H	RC0805FR-0751K1L	YAGEO CORPORATION
36	RST SM 0805 47K PM5 COL R	47K	31980215	319802154730	PHILIPS CONSUMER ELECTRONICS B.V.
37	RST SM 0805 47K PM5 COL R	47K	31980215	319802154730	PHILIPS CONSUMER ELECTRONICS B.V.
38	RST SM 0805 RC12H 18K PM1 R	18K	RC12H	RC0805FR-0718K	YAGEO CORPORATION
39	RST SM 0805 RC05 33K PM5 R	33K	RC0805	RC0805JR-0733KL	YAGEO CORPORATION
40	RST SM 0805 RC11 4K7 PM5 R	4K7	RC11	232273061472	YAGEO CORPORATION
41	RST SM 0805 RC12H 100K PM1 R	100K	RC12H	232273461004	YAGEO CORPORATION
42	RST SM 0805 RC12H 100K PM1 R	100K	RC12H	232273461004	YAGEO CORPORATION
43	RST SM 0805 RC12H 5K6 PM1 R	5K6	RC12H	232273465602L	YAGEO CORPORATION
44	RST SM 0805 RC12H 1K PM1 R	1K0	RC12H	232273461002	YAGEO CORPORATION
45	RST SM 0805 RC12H 1K PM1 R	1K0	RC12H	232273461002	YAGEO CORPORATION
46	RST SM 0805 RC11 10R PM5 R	10R	RC11	232273061109L	YAGEO CORPORATION
47	RST SM 2010 WSL 0R05 PM1 R	0R05	WSL	WSL2010R0500FEA18	VISHAY INTERTECHNOLOGY INC.
48	RST SM 0805 RC12H 68K PM1 R	68K	RC12H	RC0805FR-0768KL	YAGEO CORPORATION
49	RST SM 0805 RC12H 100K PM1 R	100K	RC12H	232273461004	YAGEO CORPORATION
50	RST SM 0805 100R PM5 COL R	100R	31980215	319802151010	PHILIPS CONSUMER ELECTRONICS B.V.
51	RST SM 2010 WSL 0R1 PM1 R	0R1	WSL	WSL2010R1000FEA	VISHAY INTERTECHNOLOGY INC.
52	RST SM 2010 WSL 0R068 PM1 R	0R068	WSL	WSL2010R0680FEA	VISHAY INTERTECHNOLOGY INC.
53	RST SM 0805 RC12H 82K PM1 R	82K	RC0805	RC0805FR-0782KL	YAGEO CORPORATION
54	RST SM 2816 WSL 0R033 PM1 R	0R033	WSL	WSL2816R0330FEA	VISHAY INTERTECHNOLOGY INC.
55	RST SM 0805 RC05 16K PM5 R	16K	RC0805	RC0805JR-0716KL	YAGEO CORPORATION
56	RST SM 0805 10R PM5 COL R	10R	31980215	319802151090	PHILIPS CONSUMER ELECTRONICS B.V.
57	RST SM 0805 470K PM5 COL R	470K	31980215	319802154740	PHILIPS CONSUMER ELECTRONICS B.V.
58	RST SM 0805 RC11 0R05 JUMPER	0R	RC11	0805 0R	YAGEO CORPORATION
59	RST SM 0805 10R PM5 COL R	10R	31980215	319802151090	PHILIPS CONSUMER ELECTRONICS B.V.
60	RST SM 0805 33K 1% PM5	33K	RC12H	232273463303	PHILIPS CONSUMER ELECTRONICS B.V.
61	RST SM 0805 33K 1% PM5	33K	RC12H	232273463303	PHILIPS CONSUMER ELECTRONICS B.V.
62	RST SM 0805 RC11 0R05 JUMPER	0R	RC11	0805 0R	YAGEO CORPORATION
63	RST SM 0805 10K PM5 COL R	10K	31980215	319802151030	PHILIPS CONSUMER ELECTRONICS B.V.
64	RST SM 0805 RC12H 12K4 PM1 R	12K4	RC0805	RC0805FR-0712K4L	YAGEO CORPORATION
65	RST SM 0805 RC12H 5K6 PM1 R	5K6	RC21H	232273465602L	YAGEO CORPORATION
66	RST SM 0805 RC12H 22K PM1 R	22K	RC12H	232273462203	YAGEO CORPORATION
67	RST SM 0805 RC12H 22K PM1 R	22K	RC12H	232273462203	YAGEO CORPORATION
68	RST SM 0805 220K PM5 COL R	220K	31980215	319802152240	PHILIPS CONSUMER ELECTRONICS B.V.
69	RST SM 0805 330K PM5 COL R	330K	31980215	319802153340	PHILIPS CONSUMER ELECTRONICS B.V.
70	RST SM 0805 RC12H 12K PM1 R	12K	RC12H	RC0805FR-0712KL	YAGEO CORPORATION
71	RST SM 2010 WSL 0R2 PM1 R	0R2	WSL	WSL2010R2000FEA	VISHAY INTERTECHNOLOGY INC.
72	RST SM 2010 WSL 0R27 PM1 R	0R27	WSL	WSL2010R2700FEA	VISHAY INTERTECHNOLOGY INC.
73	RST SM 2010 WSL 0R27 PM1 R	0R27	WSL	WSL2010R2700FEA	VISHAY INTERTECHNOLOGY INC.

Figure B.1: *The component's list of the case study for SSL driver of an automotive headlamp (1/2).*

	Description	Value	Type	Production Code	Manufacturer
74	IND FXD SM DRA127 22U PM20 R	21u47	DRA127	DRA127-220-R	COOPER
75	IND FXD SM DRA127 10U PM20 R	9u63	DRA127	DRA127-100-R	COOPER
76	IND FXD 2220 EMI 100MHZ 400R R	400R	HF50ACC	HF50ACC575032-T	TDK CORPORATION LTD.
77	IND FXD SM DRA74 47U PM20 R	46u56	DRA74	DRA74-470-R	COOPER
78	IND FXD SM DRA74 33U PM20 R	33u21	DRA74	DRA74-330-R	COOPER
79	IND FXD SM DRA74 22U PM20 R	22u25	DRA74	DRA74-220-R	COOPER
80	IND FXD SM DRA74 15U PM20 R	15u14	DRA74	DRA74-150-R	COOPER
81	IND FXD SM DRA74 3U3 PM20 R	3u3	DRA74	DRA74-3R3-R	COOPER
82	IND FXD SM DRA74 3U3 PM20 R	3u3	DRA74	DRA74-3R3-R	COOPER
83	IND FXD SM DRA74 10U PM20 R	9u62	DRA74	DRA74-100-R	COOPER
84	DIO SIG SM BAT54LG (ONSE) R		BAT54	BAT54LT1G	SEMICONDUCTOR COMPONENTS INDUSTRIES
85	DIO SIG SM BAT54CW (COMC00) R		BAT54CW		COMC00
86	DIO SIG SM BAT54LG (ONSE) R		BAT54	BAT54LT1G	SEMICONDUCTOR COMPONENTS INDUSTRIES
87	DIO SIG SM BAT54LG (ONSE) R		BAT54	BAT54LT1G	SEMICONDUCTOR COMPONENTS INDUSTRIES
88	DIO REG SM BZX84-C12-V (VISH)R		BZX84-C12	BZX84C12-V-GS08	VISHAY INTERTECHNOLOGY INC.
89	DIO REG SM BZX84-C10-V (VISH)R		BZX84-C10	BZX84C10-V-GS08	VISHAY INTERTECHNOLOGY INC.
90	DIO REC SM 12CWQ06FNPBF (VISH) R		12CWQ06FNPBF	12CWQ06FNTRPBF	VISHAY INTERTECHNOLOGY INC.
91	DIO REC SM 12CWQ06FNPBF (VISH) R		12CWQ06FNPBF	12CWQ06FNTRPBF	VISHAY INTERTECHNOLOGY INC.
92	TRA SIG SM BC847BS (COL) R		BC847BS(COL)	319801042330	PHILIPS CONSUMER ELECTRONICS B.V.
93	TRA SIG SM BC847C (KEC0) R		BC847C	BC847C-RTK	KEC CORPORATION
94	TRA SIG SM BC857 (PHSE) R		BC857	933589740215	NXP Semiconductors
95	FET POW SM FDD4141-F085 (FSC0) R		FDD4141	FDD4141-F085	FAIRCHILD SEMICONDUCTORS CORP.
96	FET POW SM IPD30N06S4L-23 (INFI) R		IPD30N06S4L-23	IPD30N06S4L-23	INFINEON TECHNOLOGIES AG
97	IC SM TL431AQDBZR (NXP0) R		TL431AQDBZR	TL431AQDBZR	NXP Semiconductors
98	IC SM TLV3502AQDCNQ1 (TI00) R		TLV3502AQDCNRQ	TLV3502AQDCNRQ1	TEXAS INSTRUMENTS INCORPORATED
99	FET POW SM IPD30N06S4L-23 (INFI) R |		IPD30N06S4L-23	IPD30N06S4L-23	INFINEON TECHNOLOGIES AG
100	IC SM LM3421Q0MH (NSC0) L		LM3421Q0	LM3421Q0MH	NATIONAL SEMICONDUCTOR CORP.

Figure B.2: *The component's list of the case study for SSL driver of an automotive headlamp (2/2).*

DEVICE TYPE	FAILURE RATE[b]	TEMP STRESS (Tbl 7-7)	ELEC STRESS (Tbl 7-6)	NOTES
CAPACITORS, DISCRETE				
FIXED				
Paper	10	2	J	
Paper/Plastic	10	2	J	
Plastic	1	3	J	
Mica	1	7	G	
Glass	1	7	G	
Ceramic[c]	1	1	H	
Tantalum, Solid, Hermetic[c]	1	3	J	
Tantalum, Solid, Non-Hermetic	5	3	J	
Tantalum, Nonsolid	7	3	G	
Aluminum, Axial Lead				
< 400 µf	15	7	E	
400 µf-12000 µf	25	7	E	
> 12000 µf	40	7	E	
Aluminum, Chassis Mounted				
< 400 µf	40	7	E	
400-12000 µf	75	7	E	
> 12000 µf	105	7	E	
VARIABLE				
Air, Trimmer	10	5	H	
Ceramic	8	3	J	
Piston, Glass	3	5	H	
Vacuum	25	2	I	
CAPACITOR NETWORK				Sum Individual Capacitor Failure Rate

Figure B.3: *Device Failure Rates in Telcordia SR332, Similar tables exists for the other types of components.*

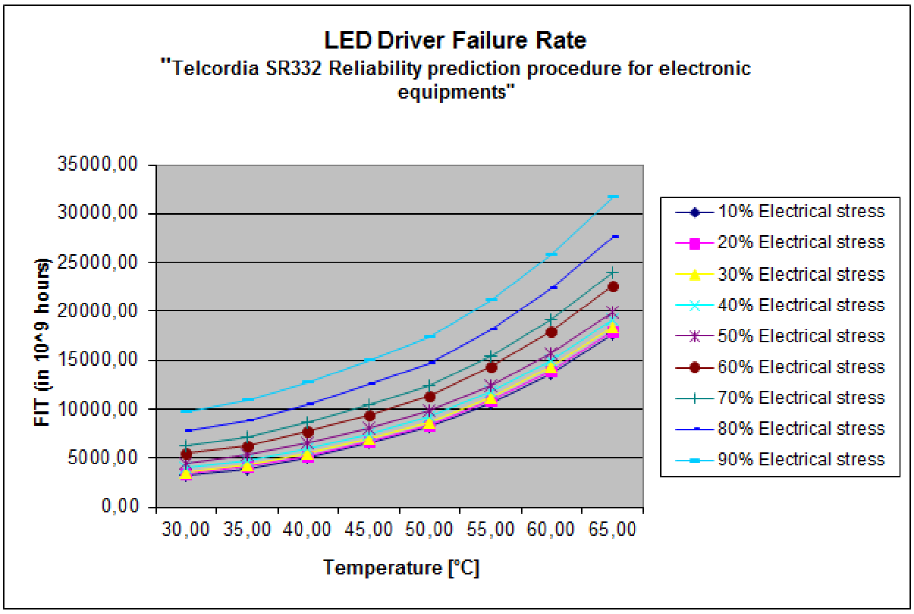


Figure B.4: *Applying Handbook method on the case study SSL driver design for automotive headlamp*

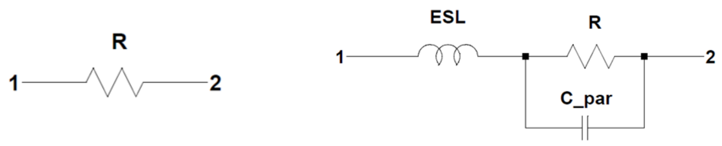
Appendix C

Non-ideal Model of Passive Components

Non-ideal model is mostly available for the discrete components. In case of integrated circuits, sometimes the SPICE model representative of the non-ideal model is provided by the manufacturer.

C.1 Resistors

Resistors restrict the flow of electric current, passing current is proportion to its voltage. They are three categories of resistors used in power electronics circuits: Carbon composition, film ,and wirewound resistors. They are in commercial SMD (Surface Mounted Device) and through hole packages. Each of these three categories due to their construction have their own special characteristics and can be more suitable for specific applications. The ideal resistor follows Ohms law (Equation C.1) where the voltage over it as well as the current through it can



(a) Symbol of an ideal resistor.

(b) Equivalent circuit of a non-ideal resistor using lumped element model.

Figure C.1: *Electronic symbol for resistors*

change infinitely fast.

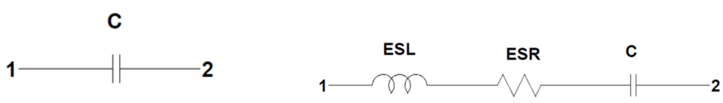
$$\begin{aligned} &V = R \times I \\ &V: \ Voltage \\ &R: \ Resistance \\ &I: \ Current \end{aligned} \tag{C.1}$$

But in practice the electrical model of a resistor, in addition to ohmic part it has inductive and capacitive part as well. Fig. C.1(a) shows the symbol of an ideal resistor and Fig. C.1(b) shows equivalent circuit for a non-ideal resistor using lumped element model[1]. It includes equivalent series inductor (ESL) and parallel capacitor (C-par). Type of resistor and type of its packaging are two factors which define this non-ideality in its electrical model. For example the leads in through-hole package creates a much bigger inductive elements in comparison to SMD packaging.

C.2 Capacitors

The capacitors are made from two electrodes isolated with a dielectric medium, serving to store electrical charge. Capacitors carrying out the same function with so much variety from the constitutive material point of view. There are three

[1]The lumped element model simplifies the description of the behavior of spatially distributed physical systems into a topology consisting of discrete entities that approximate the behavior of the distributed system under certain assumptions.



(a) Symbol of an ideal capacitor.

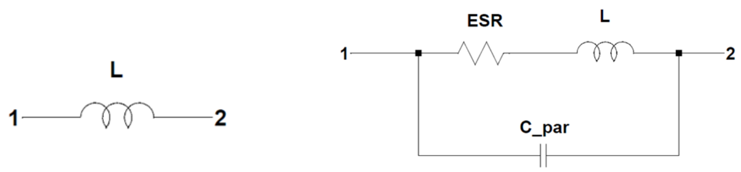
(b) Simplified equivalent circuit of a capacitor using lumped element model.

Figure C.2: *Electronic symbol for capacitors*

major types of capacitors which are being used in power electronic circuits; metal oxide dielectric capacitors, Plastic film dielectric capacitors, and Ceramic dielectric capacitor. Due to their technology, they are available in certain capacitance and voltage range. They are in commercial SMD (Surface Mounted Device) and through hole packages. The capacitor is a voltage stiff component. The voltage applied over an ideal component follows the Equation C.2.

$$\begin{aligned} &V = \frac{1}{C}\int i(t)d(t) \\ &V:\ Voltage \\ &C:\ Capacitancee \\ &I:\ Current \end{aligned} \tag{C.2}$$

In practice the electrical model of a capacitor, in addition to capacitive storage has inductive and resistive part as well [148]. Fig. C.2(a) shows the symbol of an ideal capacitor and Fig. C.2(b) shows a simplified equivalent circuit for a capacitor using lumped element parameter. It includes a series inductor(ESL) and a series resistor (ESR). Type of capacitor and type of its packaging are two factors which define this non-ideality. Although the simplified model is sufficient in most of the analysis, but much more complicated model of a single capacitor have been introduced. Specially in high frequency applications the simple model is not sufficient.



(a) Symbol of an ideal inductor. (b) Simplified equivalent circuit of an inductor using lumped element model.

Figure C.3: *Electronic symbol for inductors*

C.3 Inductors

There are many types of wound components, and within each type there are numerous construction and package types. They include various types of inductors and transformers. Inductors usually have single windings, while transformers have multiple windings. Wound components may be packaged in variety of ways (through hole and SMD packages), including no package at all. Inductor is a current stiff component, in which the voltage is determined by Equation C.3.

$$\begin{aligned} &V = L\frac{di(t)}{dt} \\ &V: \ Voltage \\ &L: \ Inductance \\ &I: \ Current \end{aligned} \tag{C.3}$$

A non-ideal inductor will have a resistance due to the resistivity of the material on the windings. As for the resistor, there will be a voltage difference due to the resistance between each neighboring winding. This will lead to capacitive couplings between the windings. These capacitive couplings are distributed along the entire inductor, but like the resistor and the capacitor, they can be modeled as a lumped parameter, see Fig. C.3. Although the simplified model is sufficient in most of the analysis, but much more complicated model of a single inductor have been introduced. Specially in high frequency applications the simple model is not sufficient.

Appendix D

Using LED as its Own Junction Temperature Sensor

In Section 6.2 of this thesis an SSL device is designed with health monitoring capability. One other monitoring capability which it is designed in this work but not fully tested due to the shortage of time, is using LED as its own junction temperature sensor. The details of this design are explained in this appendix.

This idea has a great potential for online reliability monitoring of SSL device light engine. One of the major causes for LED failures in SSL devices is LED'S high junction temperature [38, 149]. LED junction temperature cannot be measured directly, but must be calculated. Thus it is strongly dependent to the material information from the LED itself which is not always available to the customers [150]. The method introduced here is capable of calculating LED junction temperature from its forward voltage and current.

In I-V characteristics curve of the LEDs shown in Fig. 6.5 illustrate this fact that after the operating voltage which is around 40volt the behavior of the specimen match each other. A wide deviation of the I-V characteristics is shown for voltages lower than the operating voltage. However, this deviation does not influence the objective of this work. This dependency is observable in the I-V diode characteristics reported in the Equation D.1 [145]. By means of this equation and knowing the voltage across an LED and current which flows through, the junction temperature can be calculated. The goal is to design a circuit which can measure current and voltage of one of the LEDs in the design of the SSL device in Section 6.2.

$$
\begin{aligned}
&I = I_0.(e^{\frac{V}{nV_T}} - 1)\\
&I : diode\ current\\
&I_0 : reverse\ bias\ saturation\ current\\
&V : voltage\ across\ the\ diode\\
&V_T : thermal\ voltage\\
&n : ideality\ factor\ which\ varies\ from\ 1\ to\ 2
\end{aligned}
\tag{D.1}
$$

Fig. D.1 shows the schematics for the SSL device including the hardware for LED operating as its own junction temperature sensor. Based on this dependency, one of the LEDs in the LED chain is used as the temperature sensor. That LED is forward biased for three or four different currents values, Then its voltage and current values are monitored by a voltage-current monitoring circuit (Fig. D.1(b)). The more LED voltage and current points are monitored, the higher is the precision of junction temperature calculation. In the following paragraphs more details of this design are explained.

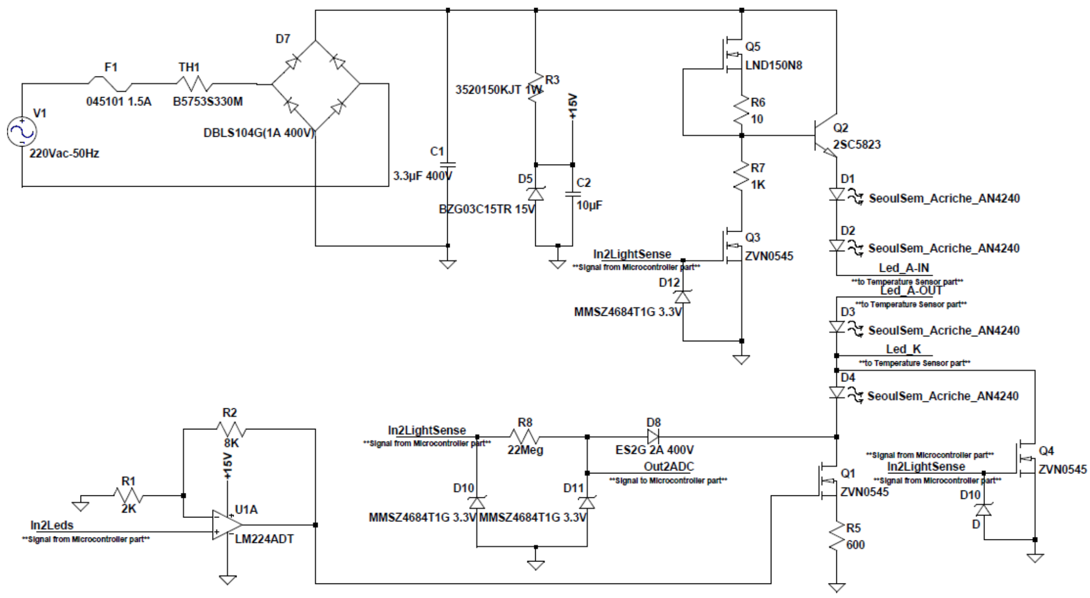
To be able to measure and calculate the LED junction temperature, one of the LEDs (D3 in Fig. D.1(a)) is connected to a voltage-current monitoring chip[1] (U1 in Fig. D.1(b)). This chip reads the voltage value across the LED and the current value which flows through LED. The data from this chip is passed to the microcontroller board by means of I^2C serial link[2]. Two opto-coupler chips[3] (U3 and U4) are used to isolate the connection to microcontroller from the voltage-current monitoring chip. These opto-coupler chips are powered by a different voltage, a voltage regulator[4] is providing this power to them (U2).

[1]LTC4151 is a high voltage I^2C current and voltage monitor from Linear Technology

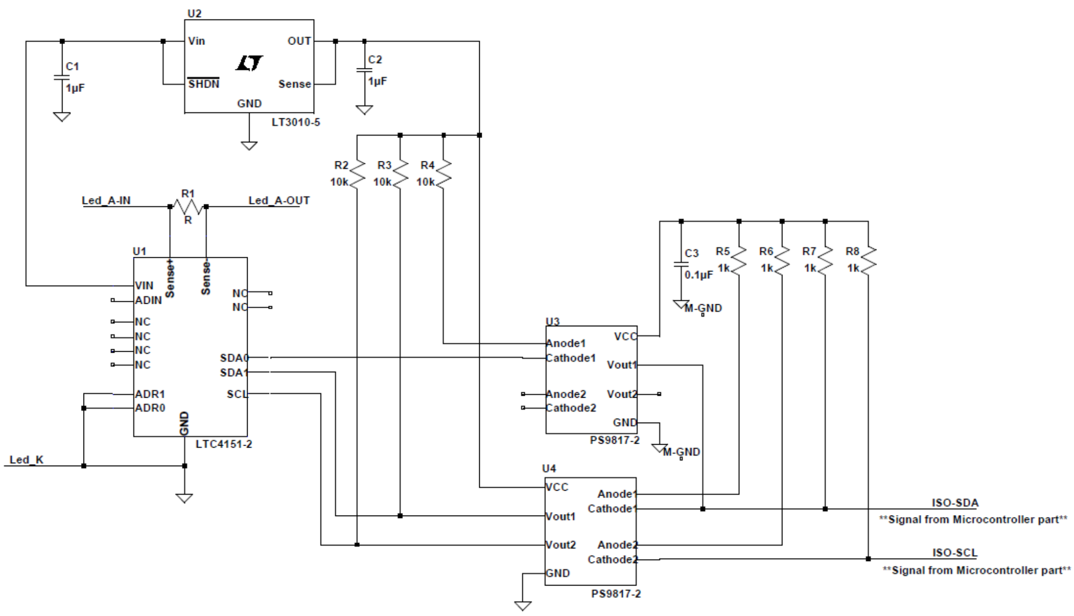
[2]Inter-Integrated Circuit, referred to as I^2C is a multimaster serial single-ended computer bus invented by Philips used for attaching low-speed peripherals to a motherboard, embedded system, cellphone, or other electronic device.

[3]In electronics, an opto-coupler is a component that transfers electrical signals between two isolated circuits by using light.

[4]A voltage regulator is designed to automatically maintain a constant voltage level.



(a) Schematic page1



(b) Schematic page2

Figure D.1: *Electrical schematics for SSL device with capability of LED as its own temperature sensor.*

In order to conduct the procedure to calculate the LED junction temperature, the following steps are performed:

- Put LEDs in forward bias at three or more different current values.
- In each of driving points, the voltage and current of the LED by means of the voltage-current monitoring chip are measured and transferred to the microcontroller.
- Calculate the LED junction temperature by means of data from measurements and Equation. D.1.

Although during the measurements in junction temperature calculation, the intensity of light by changing the voltage-current of LEDs are changed three or four times, this transient time is not very critical. The reason is that LED remains in ON state and also human being eyes can not distinguish a short time changing of the light intensity.

As it was mentioned before as well, LED's high junction temperature is one of the important causes of SSL devices' failure. By using the same LED in light source as the junction temperature sensor, we can monitor the junction temperature and thus assess the reliability status of the system frequently. This design can be used for reliability assessment and lifetime prediction of the LED lighting. Based on the reliability assessment information some innovative solutions can be applied in order to elongate the system lifetime.

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Summary

"Systematic Approach to Address the Reliability of Solid State Lighting Drivers"

Sima Tarashioon

Solid State Lighting (SSL) technology is a new technology based on light emitting diodes as light sources. This technology due to its several outstanding characteristics such as lower energy consumption, longer lifetime, and higher design flexibility with respect to the conventional lighting technology has become very attractive to both manufacturers and consumers. It is applied in variety of applications such as in-door, out-door, automotive, and agriculture lighting. Like any other new and fast evolving technology, SSL technology reliability requires special attention, and its long lifetime brings extra challenges to this study. Reliability assessment results for any device is the product of the results from the device's different parts. The optical parts of SSL devices have received far more attention regarding reliability assessment than the SSL devices electrical driver (SSL driver). Therefore, it is a necessity to perform researches toward understanding the reliability of SSL drivers.

In this thesis, a systematic approach to address the reliability of SSL drivers is introduced. There are many design variations for SSL drivers due to the application field criteria. It means SSL driver as one term refers to a wide range of devices. The systematic approach tries to provide guidelines suitable to be applied to different types of SSL drivers. The primary step toward this systematic approach is to find out the suitable reliability assessment methods to address the reliability of SSL drivers. Based on the selected method a system-level reliability assessment methodology integrated in the design phase is implemented. In order

to predict the SSL driver's thermal / electrical behavior and consequently to define its lifetime, a multi-physics reliability assessment methodology is introduced. In order to examine the thermal / electrical behavior of an SSL driver in real life, experiments are performed on a commercially available product type. An example design to show how the concept of "design for reliability" can effect the driver of an SSL device is the last topic discussed in this thesis.

In seeking for the most suitable reliability assessment method, the four main category of assessment methods which are based on field data, handbooks, test data, and stress and damage model are investigated. The most common methods practiced by industry and research centers for SSL drivers reliability assessment are handbooks and test data. Occasionally reliability assessment based on stress and damage model are performed to get more insight about the components which show more frequent failures in the results of reliability assessment method based on test data. Reliability prediction based on field data is not applicable yet because of long lifetime of the SSL devices and being a relatively new technology. Reliability prediction based on handbooks have been criticized many times due to their lack of accuracy. Reliability prediction methods based on stress and damage model and based on test data are the most suitable ones for the case of SSL drivers. This work focus is on a system-level reliability assessment method based on stress and damage model which uses the component level information. This method not only is capable of estimation of the SSL driver's lifetime but also includes valuable information for the designers for design improvement. The results of reliability prediction method based on test data can be used to validate the findings from reliability prediction method based on stress and damage model.

The primary step to define a system-level reliability assessment methodology for a complex device is distinguishing its least complex elements. A new partitioning method for reliability purpose is introduced which distinguishes the device's functional elements and packaging elements. Categorizing the SSL driver parts based on the function they perform, makes it feasible for people from different functional groups and different skills to cooperate toward the goal of reliability assessment. Based on the introduced partitioning method, the reliability study is divided to four categories which exchange information with each other: electrical, thermal, electromagnetic, mechanical reliability analysis.

The multi-physics reliability simulation method introduced in this thesis helps understanding thermal / electrical status of an SSL driver during its lifetime. This method uses the component behavior in different time and temperature in a system-level simulation method, built in SPICE and MATLAB programs. By monitoring the thermal / electrical conditions which makes the device incapable of providing the required function, the end of lifetime of the device is defined. Sensitivity analysis as a complementary tool indicates variation of which components value have the most contribution to the failure cause.

Thermal and electrical experiments are performed on the driver of an SSL halogen replacement lamp in order to monitor the changes during its aging. The results of experiments on new samples and aged samples shows an irreversible increase of operational temperature in the aged SSL drivers with respect to the new samples. The results demonstrate an irreversible increase in electrical power dissipation in the aged SSL drivers, and respectively decrease in electrical efficiency of the aged samples.

An SSL device is designed with system prognostics and health management capability which is an approach to cover design for reliability. This device has wireless communication and light sensing capability which can monitor the light in the environment. Each device in a large system including many of these devices, can have the information about ambient light and light output of all devices including itself. By means of this information the health state of each device is known to all devices. One of the light emitting diode of the device plays both roles of light source and light sensor in the device. It is concluded that using the LED in this way is well possible and can be used in application to sense the deterioration of the system. Nevertheless indeed it requires acquiring the knowledge about effect of aging on the LED as both light source and light sensor.

Samenvatting

"Een Systematische method om de betrouwbaarheid van Solid State Lighting besturingen te adresseren"
Sima Tarashioon

Solid State Lighting (SSL) technologie is een nieuwe technologie gebaseerd op licht emitterende diodes als licht bron. Deze technologie heeft uitstekende eigenschappen zoals lager energie verbruik, langere levensduur en een grotere flexibiliteit ten opzichte van conventionele verlichting technologie.Daarom is deze technologie zeer interessant voor zowel professionele als consumenten toepassingen. Het word toegepast in verschillende toepassingen zoals binnenshuis, buitenshuis, de auto-industrie en agrarische verlichting. Zoals elke andere nieuwe en snel evoluerende technologie, heeft de SSL betrouwbaarheid extra aandacht nodig, en de lange levensduur vormt hierbij een extra uitdaging. Betrouwbaarheidsanalyse isafhankelijk van de verschillende onderdelen van het apparaat. De optische onderdelen van SSL apparaten hebben veel meer aandacht gekregen met betrekking tot betrouwbaarheidsanalyses dan de elektrische besturing (SSL besturing). Daarom is het nodig om onderzoek te doen naar het begrijpen van de betrouwbaarheid van dezeelectronica.

In deze thesis, word een systematische methode gentroduceerd om de betrouwbaarheid van SSL besturingen te onderzoeken.Door de verschillende criteria zijn er vele ontwerp variaties voor SSL besturingen. Dit betekend dat een SSL besturing als n termverwijst naar een breed gebied van apparaten en toepassingen. De systematische benadering probeert richtlijnen geschikt te maken om toegepast te worden voor verschillende vormen van SSL besturingen. De primaire stap naar deze systematische benadering is het uitzoeken van een geschikte betrouwbaarheidskwalificatie methoden voor het adresseren van de betrouwbaarheid van SSL besturingen. Op de geselecteerde methoden word een systeemniveau betrouwbaarheidskwalificatie methodologie gentegreerd in de ontwerp fase. Om het thermische en elektrische gedrag van de SSL besturing te karakteriserenen om uiteindelijk de levensduur te definiren, word een multi-fysische methodologie gentroduceerd. Om het thermische en elektrische gedrag van een SSL besturing in real-life te bekijken zijn experimenten uitgevoerd op een product. Een voorbeeld ontwerp laat zien hoe het concept Ontwerpen voor betrouwbaarheid een invloed kan hebben op de besturing van een SSL apparaat, dit is het laatste onderwerp dat word besproken in deze thesis.

In de zoektocht naar de meest geschikte betrouwbaarheidskwalificatie methode, worden de vier hoofd kwalificatie methoden onderzocht welke gebaseerd zijn op veld-data, handboeken, test-data, en spanning-schade modellen. De meest gebruikte methoden toegepast door industrie en onderzoekscentra voor SSL besturingen betrouwbaarheidskwalificaties, zijn handboeken en test-data. Soms worden betrouwbaarheidskwalificaties uitgevoerd welke gebaseerd zijn op spanning en schade modellen om zo meer inzicht te krijgen in de componenten welke frequenter falen in de betrouwbaarheidskwalificatie methode gebaseerd op test-data. Dit is de zogenaamde Physics of Failure methode. Betrouwbaarheidsvoorspellingen gebaseerd op veld-data zijn nog niet toepasbaar door de lange levensduur van SSL apparaten voornamelijk omdat het een nieuwe technologie is. Betrouwbaarheidsvoorspellingen gebaseerd op handboeken worden vaak bekritiseerd door hun gebrek aan nauwkeurigheid. Betrouwbaarheidsvoorspelling methoden gebaseerd op spanning en schade modellen en gebaseerd op test-data zijn het meest geschikt voor SSL apparaten. Dit werk focusseert op een systeemniveau betrouwbaarheidskwalificatie methode gebaseerd op spanning en schade modellen welke componentniveau informatie gebruiken. Deze methode is niet alleen geschikt voor schatting van de SSL besturingslevensduur maar bevat ook waardevolle informatie voor ontwerpers voor ontwerp verbeteringen. De resultaten van betrouwbaarheidsvoorspellingen methoden gebaseerd op test-data, kunnen worden gebruikt voor validatie van de vindingen van de betrouwbaarheid voorspellingsmethoden welke gebaseerd zijn op spanning en schade modellen.

De primaire stap voor het definiren van systeemniveau betrouwbaarheidskwalificatie methodologie voor een complex apparaat, is het onderscheiden van de minst complexe elementen. Een nieuwepartitionering methode voor betrouwbaarheid gericht onderzoek is gentroduceerd welke onderscheid maakt tussen de functionele en verpakkingselementen van het apparaat. Categoriseren van de SSL aansturingsonderdelen gebaseerd op de functie die ze vervullen, maakt uitvoering van betrouwbaarheidskwalificatie door mensen uit verschillende functies en met verschillende skills mogelijk. Het betrouwbaarheidskwalificatie onderzoek is verdeeld in 4 categorien welke informatie met elkaar verdelen: elektrisch, thermisch, elektromagnetisch en mechanische betrouwbaarheidskwalificatie en welke gebaseerd zijn op de gentroduceerde partitionering methode.

De, in deze thesis, geintroduceerde multi-fysische methodologie maakt het mogelijk om de thermische en electrische status van een SSL besturing gedurende zijn levensduur te begrijpen. De methode gaat uit van de componenten en hun gedrag gedurende de tijd. Dit is ingebouwd in een simulatie op systeem nivo daarbij gebruik makend van de software SPICE en MATLAB. Door de thermische en electrische status van elk component te monitoren is het mogelijk om te berekenen wanneer de SSL besturing buiten zijn eigen specificatie valt en dus het einde van zijn levensduur is bereikt. Door gebruik te maken van sensitiviteits analyses, is het mogelijk uit te zoeken welk component de grootste bijdrage heeft op het falen van de SSL besturing.

Thermische en electrische experimenten zijn uitgevoerd op de electronica van een SSL product dat uiteindelijk de conventionele verlichting zal vervangen (in dit geval een spaarlamp). De resultaten van een nieuw en een verouderd product laten een onomkeerbare verhoging van de temperatuur in het verouderde product zien. De resultaten tonen ook een onomkeerbare verhoging van het wattage zien en daarmee een verlaging van de efficiency van het product.

Een SSL product is ontworpen met daarin de mogelijkheid om de gezondheid van het systeem te monitoren. Dit is wat men noemt: design for reliability, ofwel ontworpen voor levensduur. Het ontworpen product bezit de mogelijkheid tot draadloze communicatie en licht metingen om dit te bewerkstelligen. Een light systeem bestaande uit meerdere van deze producten deelt dan de informatie over licht en ieders status met elkaar. En zo weet elk onderdeel dan de gezondheid van de ander. In elk SSL product is een licht emitterende diode zo opgesteld dat hij buiten het geven van licht eneneens het nivo van licht kan meten, hij dient dan als de sensor. Er is aangetoond dat dit mogelijk is en in applicaties kan worden gebruikt om de veroudering van het systeem te monitoren. Al is dan zowel kennis over de veroudering van de lichtbron als de lichtsensor nodig.

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Sima Tarashioon received her BSc. degree in Electronic Engineering from Shahid Beheshti University of Tehran, Iran in 1999. She worked for seven years as an electronic test engineer, electronic board designer, system designer, and team leader in telecommunication and process controller industries in Tehran, Iran. She got her MSc. degree in microelectronics from Delft University of Technology in July 2009. She was accepted for working on her master thesis in NXP semiconductor in Eindhoven on the topic of "designing a MEMS accelerometer for microphone body noise cancellation". The results of this research was submitted as European and US patents. She started her PhD in August 2009 in ECTM department in EWI faculty of Delft University of Technology. She was the first PhD researcher in Micro/Nano system integration and reliability group under supervision of Prof. G.Q. Zhang. Her PhD is funded by Materials innovation institute (M2i), and it is a part of SE2A project from ENIAC European projects. Her main research interests are reliability in electrical devices and system engineering. Since September 2013, Sima has been working as an R&D engineer in Allseas Engineering B.V. in Delft.