Design of Hybrid Safety Relay system for Philips Instant fit LED Tubes (TLED)

By

Andapally Bharadwaj Reddy

Master of Science Thesis

Design of Hybrid Safety Relay System for Philips Instant fit LED Tubes (TLED)

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For the degree of Master of Science in Electrical Power

Engineering at Delft University of Technology

Andapally Bharadwaj Reddy

4324102

July 2, *2015*

Faculty of Electrical Engineering, Mathematics and Computer Science Delft University of Technology

The work for this thesis was conducted and carried out in collaboration with Philips Lighting-LED Platform Development in Eindhoven, Netherlands. Their cooperation is hereby gratefully acknowledged.

Acknowledgements:

The work for this thesis was conducted and carried out in collaboration with Philips Lighting-LED Platform Development in Eindhoven, Netherlands. This thesis could not have been finished without the help and support of many people. I would like to take this opportunity to express my gratitude to them.

First and foremost, I would like to thank Dr.Haimin Tao my daily supervisor at Philips, and Dr. Jelena Popovic, my daily supervisor at Delft University of Technology, for their assistance and patience during the writing of this thesis.

I would also like to thank Christiaan Van Dijk and Frits de Jongh at Philips for their technical support regarding the design and useful comments regarding this design project.

Delft University of Technology Department of Electrical Sustainable Energy - Electrical Power Processing

The undersigned hereby certify that they have read and recommend to the Faculty of Electrical Engineering, Mathematics and Computer Science for acceptance a thesis entitled

Design of Hybrid Safety Relay system for Philips instant fit LED Tubes (TLED)

By

Andapally Bharadwaj Reddy

in partial fulfillment of the requirements for the degree of

Master of Science Electrical Power Engineering

Supervisors	Dr. Haimin Tao
	Dr. Jelena Popovic
MSc Thesis Committee	Prof.Dr.ir. J. A. Ferreira
	Dr. Jelena Popovic
	Dr.ir.M.Popov
	Dr. Haimin Tao

Abstract

Fluorescent lamp has been a very successful source of light. Installed base of TL(Tube Linear) is huge; more than 60 percent of artificial light is being generated today by fluorescent tube. However in the past few years LED lighting technology has been rapidly developed. LED (Light emitting diode) is a new technology that has become more energy efficient compared to fluorescent tube giving more light-Lumens/watt. As LED technology is rapidly increasing, LED TL retrofit (TLED) is emerging as an attractive business to Philips from past years.

This master thesis project is based on LED replacement tube called TLED-instant fit retrofit tube.This TLED product developed is a fast and easy way of upgrading old fluorescent tubes to LED tubes -just plug and play type and no rewiring of fixture required. This new lamp, enables fastest and easiest way to upgrade HF (High Frequency) TL luminaires and instantly provides about 40% energy saving. Normal TL tube lamps are safe due to the fact that the gas inside the tube first has to be ignited (combination of starter and ballast or HF generated high voltage) before there is a conductive path between the two connections on the end of the tube. This safety is necessary when the tube is being installed into a fixture while the voltage is not disconnected from the mains. But in case of using this newly designed TLED based (retrofit) lamps there is a conductive path between the two ends (the electronics) of the tube and safety is not guaranteed. Electronics are not considered as a proper isolation for safety.

Hence the solution for solving this issue of safety is to use two electro mechanical relay combination in series with each other and HF ballast. Even though the two relay solution is solving present safety problems for customer, because of the internal built in architecture of these relays there is energy loss associated with them due to relay bouncing and arcing effect. The use of these two electromechanical relay solutions for TLED presently is a very costly solution for solving the pin safety issue .Hence the main motivation for writing this thesis is to evaluate the possibility of designing a new hybrid safety relay system, consisting of one electromechanical relay and other high voltage semiconductor switch to reduce the cost associated with use of two electro mechanical relay system and also to eliminate bouncing and arching effect involved by using just one electromechanical relay instead of two.

In this thesis, first a brief literature survey is made on different solid state relays and high voltage semiconductor switches to choose the optimum switch for this project. A Hybrid relay system with one electromechanical relay and semiconductor switch was designed in simulation and hardware prototype is built and analyzed for its intended functionality. Next, the designed hybrid relay system was integrated to present TLED relay board by analyzing the present TLED internal electronic architecture in simulation and later integrating hardware model to TLED. The implemented hybrid relay system was tested and analyzed for its functionality considering few design trades off.

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1 Chapter 1: Project introduction

1.1 The time line history of lighting

Human beings living on earth always try to learn from the nature and imitate the nature to build own creative things that exactly mimics the nature. An airplane, robot, solar cells, artificial lighting these are few of man's creation that is designed by learning how nature works. Today our daily lives are dependent on electrical energy to power your electronic gadget or any machine at home. Without electricity many of our works stand still and whole world cannot work efficiently. One of the main important functions of electricity is to power your artificial lighting devices at your home or office. Without light lamps whole world will be in dark and silence at night when sun goes down. The first milestone in using electric energy for practical use was using incandescent bulb to light up your house when Thomas Edison invented first incandescent bulb in the year 1879. The electric light bulb is seen as the most important invention since Stone Age where man used fire for lighting. Below in the Figure 1 shows the evolution of light bulbs. Figure 2 shows time line history of lighting in brief -starting from 18th century as discussed in [1] .Next paragraph gives the brief history of development of LED lighting which is present lighting market.

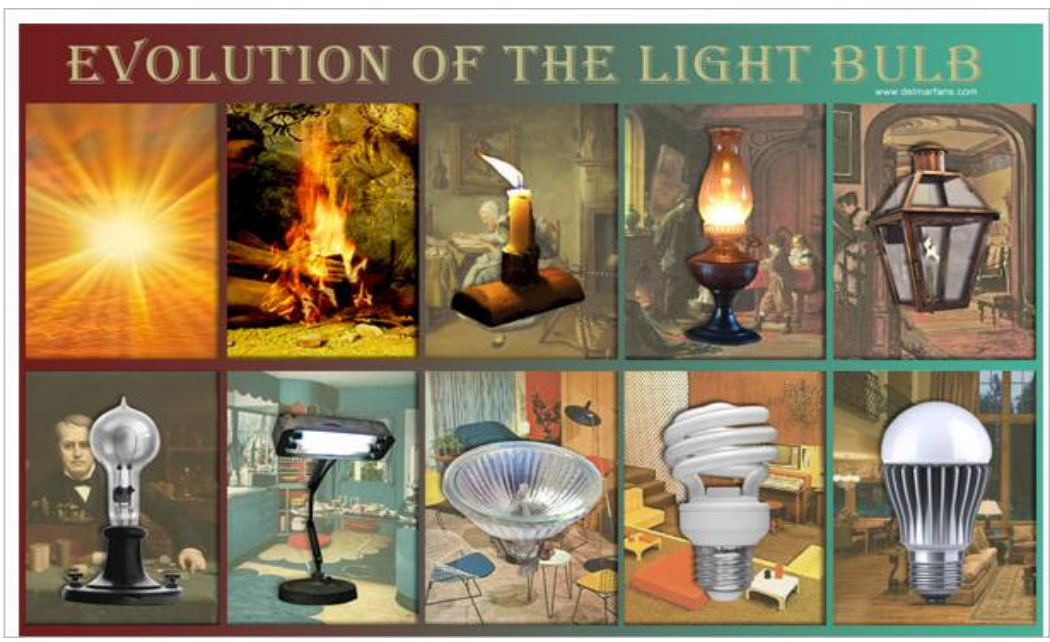


Figure 1: Evolution of light bulbs [1]

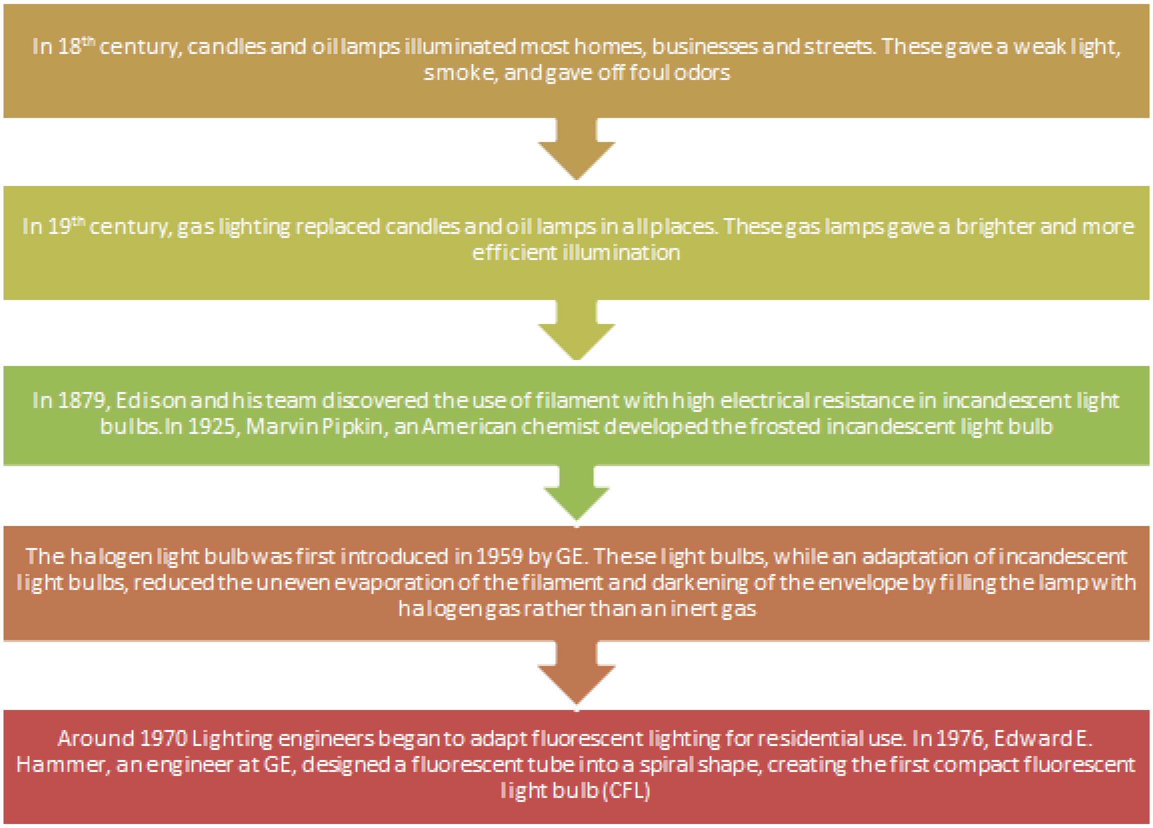


Figure 2: Time line history of lighting [1]

LEDs are a type of solid-state lighting that uses semiconductors to convert electricity into visible light. LEDs emit light in a specific direction (light exit window 180 degrees), which is the main important advantage compared to other light technology like fluorescent lamp (light exit window 360 degrees) [2].The brief history of LED lighting is shown in Figure 3.From past few years the price of LED bulbs has decreased more than 85 percent,making them an affordable choice for illuminating homes, businesses, and public spaces. LED bulbs are six to seven times more efficient than incandescent light bulbs, cut energy consumption by 80 percent, and last 25 times longer than incandescent bulbs.

This master thesis project is based on LED replacement tube called TLED-instant fit retrofit tube.This TLED product developed by Philips is a fast and easy way of upgrading old fluorescent tubes to LED tubes -just plug and play type. The figure of real instant fit LED tube (TLED) available in the market is shown below in Figure 4: TLED (Instant fit LED tube):

Figure 3: History of LED lighting [1]

Figure 4: TLED (Instant fit LED tube) [3]

1.2 The project and Research motivations

Fluorescent lamp is very energy efficient compared to incandescent bulbs giving more lumens per watt. Fluorescent lamp has been a very successful source of light. Installed base of TL(Tube Linear) is huge; more than 60 percent of artificial light is being generated today by fluorescent tube [2]. However in the past few years LED lighting technology has been rapidly developed. LED (Light emitting diode) is a new technology that has become more energy efficient compared to fluorescent tube giving more light-Lumens/watt. As LED technology is rapidly increasing LED TL retrofit is emerging as an attractive business to Philips from past years.

There are various LED replacement tubes being sold today in the market. In order to operate the LED lamp properly, most of them require rewiring of the TL fixture (bypassing the ballast).The easiest way to upgrade HF (high-frequency) TL luminaire is just by taking out the old TL tube and replacing it with a new LED tube. No rewiring or opening fixture shall be required. Here we refer to this kind of upgrade as "direct replacement". However, there is a lack of LED tube which allows this easy upgrade of the fixture. Hence Philips Lighting –LED Platform Development (LPD) team at Eindhoven, Netherlands came up with an innovative idea to design and develop HF compatible LED tube (TLED) for the EMEA (Europe, Middle East ,Africa) market. This new lamp, enables fastest and easiest way to upgrade HF TL luminaires and instantly provides about 40% energy saving.

Normal TL tube lamps are safe due to the fact that the gas inside the tube first has to be ignited (combination of starter and ballast or HF generated high voltage) before there is a conductive path between the two connections on the end of the tube. This safety is necessary when the tube is being installed into a fixture while the voltage is not disconnected from the mains. In the situation when the lamp is not inserted correctly (one side inserted and the other not yet) the one side of the lamp is connected to live mains and the other side the electrical contacts are insulated by gas in the TL tube. Figure 5 shows this situation -where a fluorescent TL tube can be inserted into a 'live' mains fixture without any danger because the connection pins on either side are electrically insulated by the glass and gas of the lamp.

But in case of using this newly designed TLED based (retrofit) lamps there is a conductive path between the two ends (the electronics) of the tube and safety is not guaranteed. Electronics are not considered as a proper isolation for safety. Figure 6 shows this situation-where a typical LED TL retrofit module contains LED PCB's which offer little electrical insulation between connection pins when inserting the module

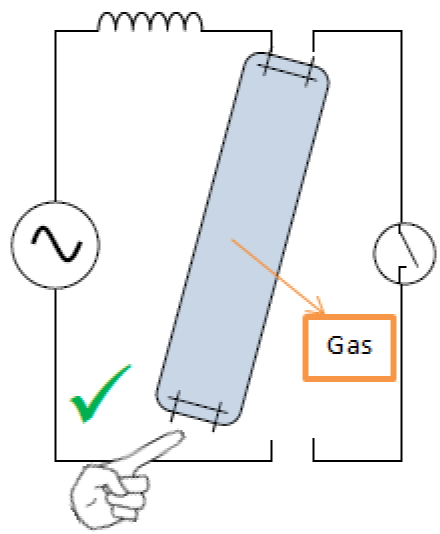


Figure 5: Normal fluorescent tube (TL tube) - where one end is connected to mains and other end is not yet connected to mains

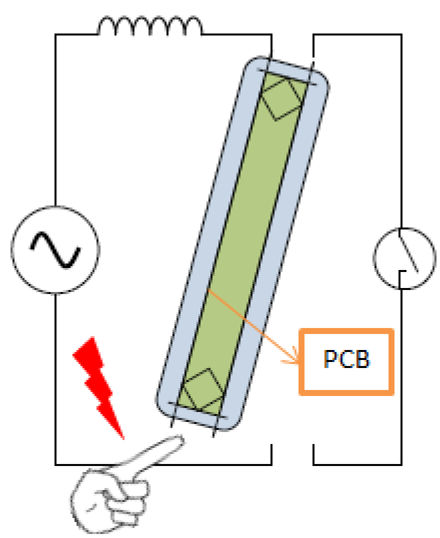


Figure 6: TLED (instant fit LED tubes)-where one end is connected to mains and other end is not yet connected to mains

Hence the solution for solving this issue of safety is to use two electro mechanical relay combination as shown in Figure 7, Figure 8 (shows the safety relay solution).

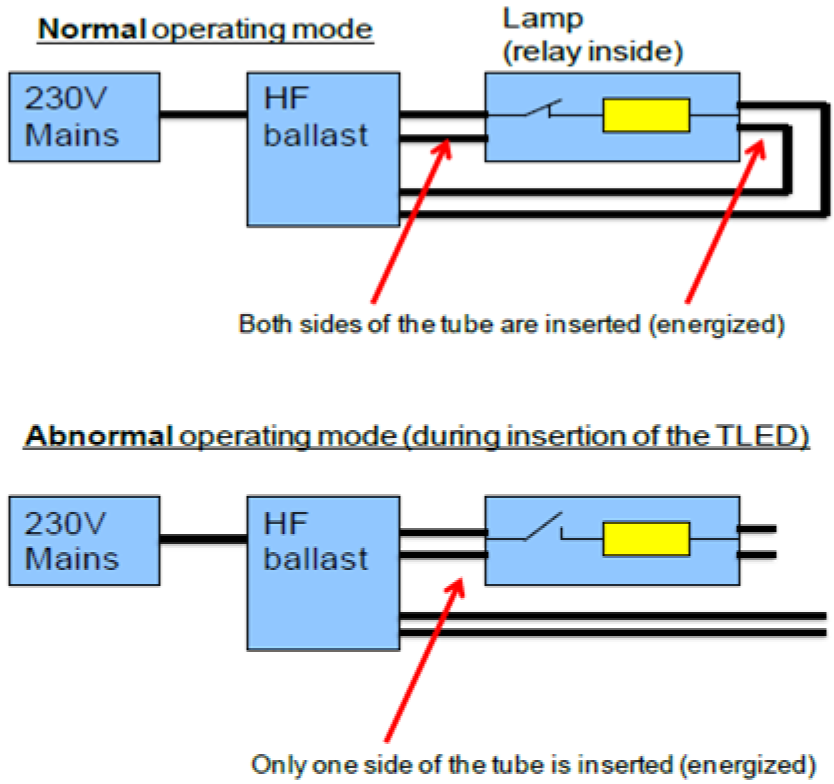


Figure 7: Safety solution developed by Philips LPD department

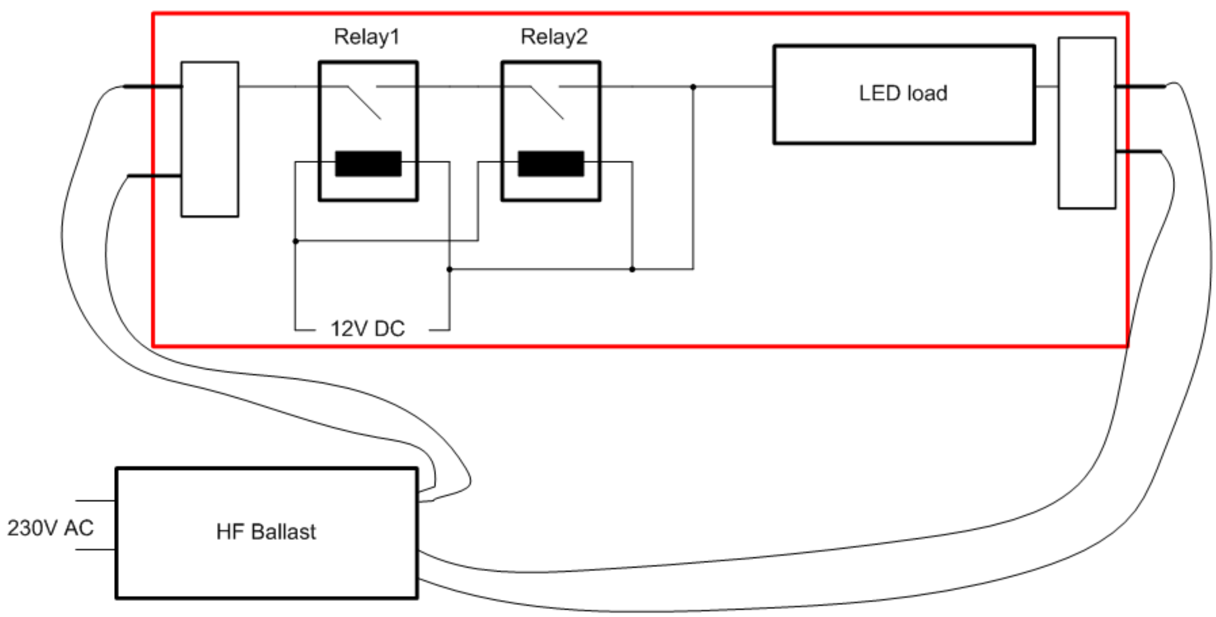


Figure 8: Overview of TLED safety solution consisting of two electromechanical relays in series

The main use of relay in LED tube is for pin safety: which consists of two relays (contacts) connected in series and their coils connected in parallel. The main important reason for using two relays instead of one is for ensuring fail proof i.e when one of the relay is failed after some operation cycles, still other relay will be in operating mode for ensuring safety. The other use of two relays in series with each other is to ensure that lamp can withstands >3kv test as shown below Figure 9, making it more safer and reliable according to IEC standards.

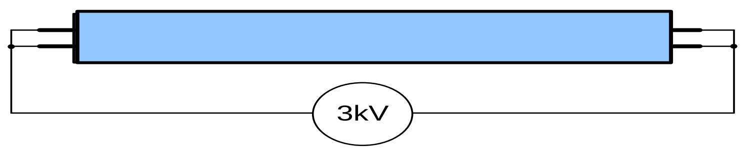


Figure 9: 3Kv test block diagram.

Even though the two relay solution is solving present safety problems for customer, because of the internal built in architecture of these relays there is energy loss associated with them due to relay bouncing and arcing effect [4].The use of these two electromechanical relay solutions for TLED presently is a very costly solution for solving the pin safety issue .Hence the main motivation for writing this thesis is to evaluate the possibility of designing a new hybrid safety relay system, consisting of one electromechanical relay and other high voltage semiconductor switch to reduce the cost associated with use of two electro mechanical relay system and also to eliminate bouncing and arching effect involved by using just one electromechanical relay instead of two. The proposed hybrid safety relay system is shown in Figure 10. Hence ultimately evaluating an alternative way of solving the pin safety solution with reference to the safety standards laid by IEC. The motivations can be summarized in to following reasons:

- The importance of TLED and its safety issues that has to be solved to make this product safer for the user, complying with the safety standards laid by IEC and others.

- The importance of using high voltage semiconductor switch with reference to disadvantages associated with present two electromechanical relay solutions (like bouncing and arching effects).

- The importance to reduce the cost of safety relays by developing and designing a new hybrid safety relay system for TLED.

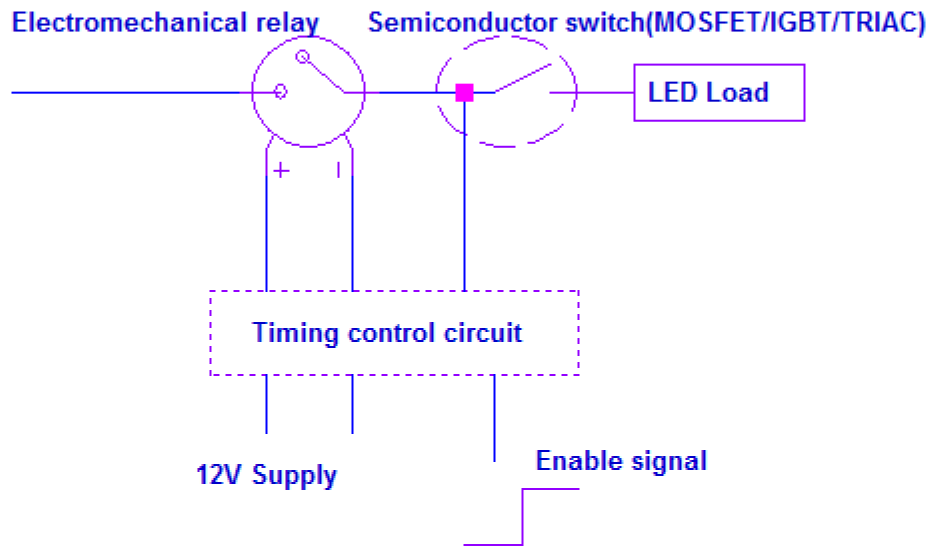


Figure 10: Proposed hybrid safety relay system

1.3 Research aims and objectives

1.3.1 Research goals

The main goal of this project is to design hybrid safety relay comprising of one electro mechanical and one semiconductor switch for reducing the bouncing and arcing effect [4], cost and also reducing the energy consumption of present relay system in steady state. The bouncing and arcing effect is shown in the Figure 11.

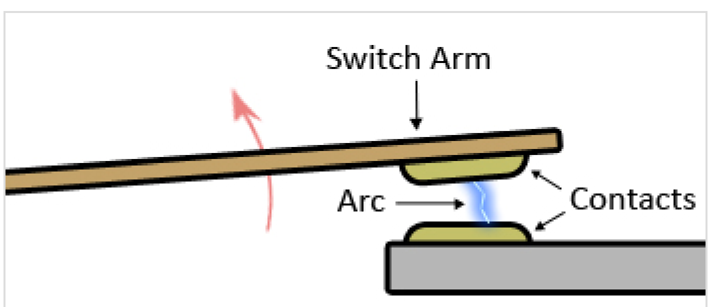


Figure 11: Bouncing and arcing effect in electromechanical relays [5]

In electromechanical relays, when two contacts close and make the circuit, there is a mechanical impact between them and as a result they rebound and bounce until all of its kinetic energy is dissipated [6]. When these relays opens or closes, for the moment that the arm of the switch is very close (but not connected) to the contact, the electric current can arc through the air between the contacts [5].The arcing effect causes contact erosion, degrade electrical properties and increase tendency for contact welding [4].

After analyzing and designing hybrid safety relay system for TLED the goal is to build and test the prototype. The present Philips TLED which is out in the market consists of two electromechanical relays that are costly and have some disadvantages in terms of bouncing effect, arcing and slow switching time. The main purpose of using two electromechanical relays is to increase the creepage and clearance requirement of reinforced insulation between the pins at one end and the other end so that it meets the safety regulations laid by IEC62776. The goals and steps of this thesis are as follows:

- The main goal of this thesis is to design and test the concept of replacing one of the two electromechanical relay in present TLED with one semiconductor relay such that it meets the safety regulations as well as cost effective.

I. In this goal first step is to evaluate different semiconductor switch available in the market which can block high voltage and current from HF (High Frequency) ballast during improper insertion of TLED i.e, one side if tube is connected to mains and other side is open. When a person tries to install this TLED, he may come in contact with this open end and hence he has a high level risk of getting electrical shock in this situation.
II. Next step is to work out the timing control circuit such that, the semiconductor switch should turn on after the relay has fully turned on. The relay operate time is about 5ms (average) from the data sheet values. Hence the semiconductor switch must be given a trigger signal for turn-on after (6-8) ms .The relay must be operated with dry switching (switch without a load).
III. Next step is to evaluate the best possible way to drive this semiconductor switch with optimum number of components, cost and energy consumption and also other relevant parameters that has to meet the requirements of safety of TLED.
IV. Next step is to integrate the newly designed relay system to the existing TLED design boards. Redesigning the internal electronics for making the newly designed hybrid relay system compatible with present TLED driver boards.
V. Final step is to study and analyze the newly designed hybrid safety relay system after integrating with, considering some trades off between essential requirements of TLED.

1.4 Research Questions

The following points represent the research questions for the thesis:

1) How to choose the optimum high voltage semiconductor switch for using as a safety switch in TLED(retrofit LED tube).

    - How to identify and analyze essential characteristics of high voltage switch that fulfills the requirements of TLED pin safety problem.

2) How to design a hybrid safety relay system using semiconductor switch and electro mechanical relay combination.

    - How to drive this hybrid relay system with minimum components and energy.

- How to drive both semiconductor switch and electromechanical relays with appropriate timing sequence to full fill the IEC safety standards.

3) How to integrate the hybrid relay system to present TLED driver boards.

- How to redesign the present TLED driver boards that can be compatible after integrating new relay system.

1.5 Methodological aspects

This section describes the methodology followed to answer the research questions and hence the goals of the thesis will be reached. The following list of steps describes that is going to be taken in overall thesis project.

- Review of different components of present TLED (retro fit tube) Philips product for understanding overall working of the product.
- Review of different kind of relays available in the market. Review the basics of solid state relays and also its pros and cons compared and analyzed with respective electro mechanical relays.
- Review of the different semiconductor switch like MOSFET/BJT/TRIAC for applications of these devices as a high voltage switch.
- Defining some basic essential criteria to evaluate and analyze these different semiconductor switches for choosing the optimum switch for present application as a relay in TLED. Review the basics of chosen optimal semiconductor switch.
- Exploring the ways to implement this switch as a relay considering the ease of driving of this switch and respective cost of implementing technology.
- Studying the effects of this newly designed hybrid safety switch solution on other components of TLED by integrating this design board in to TLED product.
- Proposing ideas for further research in this safety switch for TLED Philips product for optimum design.

1.6 Thesis Organization

1.6.1 Main contributions

The following points describe the main contributions of the thesis:

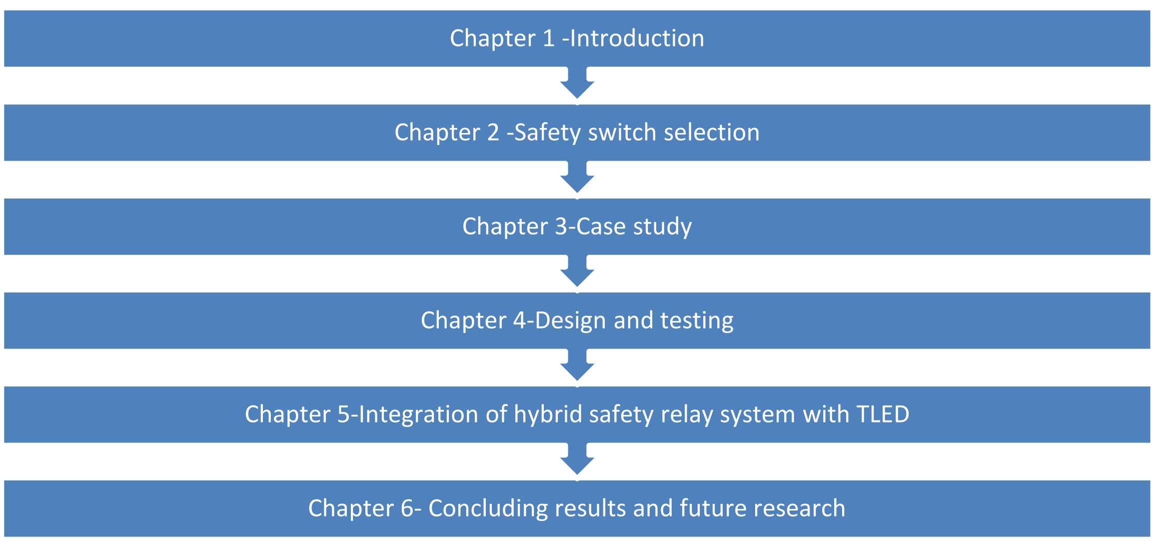
1. Summarize the pros and cons of electromechanical relays.
2. Summarize the need of solid state relays in application to TLED (retrofit LED tube).
3. Explore the ways of implementing semiconductor safety switch using high voltage MOSFET/IGBT/TRIAC.

4. Explore the ways of driving this semiconductor switch with minimum components and reduce the energy consumption from the power supply board.
5. Explore the ways to integrate the newly designed hybrid relay system to present TLED driver boards and to see the effect of designed hybrid safety relay on other components of TLED system, considering safety standards laid on the product by IEC etc.

1.6.2 Thesis outlines description

The thesis consists of six chapters. The first chapter will introduce the project outline, objectives, deliverables, research motives and methodology that is followed in overall project. Second chapter will cover the basics of relays. Third chapter will cover more in detail literature survey of the semiconductor switch that is chosen for this project. Fourth chapter will cover the design principles of the hybrid safety switch for TLED. Fifth chapter deals with integration of this designed system to present TLED driver boards and discuss about the results and its working demonstrator. Sixth chapter will conclude the project and discuss about recommendations and future research.

The contents of each chapter are as follows:



Chapter 2: Covers the basic description of relays and classification of different types of relays available in the market based on the applications. This chapter introduces the basic concepts of relays and its types followed by solid a state relay which is the main topic of project. Since solid state relays have advantages and disadvantages compared to other relay types, a comparison is made between electro mechanical and solid state relays. Next, the focus will be on the different ways of realizing the safety relay switch for TLED using MOSFET/BJT/TRIAC/IGBT.A brief discussion on implementation of solid state relays using different semiconductor switch based on type of and design requirements for TLED (instant fit LED tube) application is made .Based on different parameters for selection of suitable semiconductor switch, a comparison is made between MOSFET/BJT/TRIAC/IGBT. After this a brief analysis is made in this chapter focusing on choosing the best Switch for safety relay solution for TLED.

Chapter 3: After analyzing on few parameters to choose the best switch for TLED application which is discussed in previous chapter, A suitable semiconductor high voltage switch is considered to be best fit for TLED application considering cost and energy efficiency and other relevant parameters .This chapter introduces the case study of the project, an overview of TLED architecture is first discussed. Next, a literature survey on basics of this semiconductor switch is made. After that, different ways of implementing this switch as a relay is discussed. A detailed analysis is made on these switch characteristics such as dV/dt that satisfies the basic requirement for TLED relay application. This chapter is then concluded with a brief comparative analysis on different switches rated for different voltages, current, and dV/dt. From this comparison a particular switch based on its characteristics that is best suited for TLED application is chosen.

Chapter 4: This chapter covers the design of novel hybrid safety relay for TLED. First the basics of design principles of relay for this application are discussed. Next detailed discussion on experimental set up and results are made. Experimental set up design in Philips lighting lab discussed along with the simulation design. The differences in simulation and experimental results are discussed in detail and analyzed respectively.

Chapter 5: This chapter first analyzes the TLED architecture for integrating the newly designed hybrid relay system with the present TLED driver boards. Next the effect of semiconductor relay on other parts of retrofit tube is discussed. Finally a brief discussion on design trades off of novel safety switch for TLED is made.

Chapter 6: This chapter will narrow down the discussion of the main experimental results of designed safety relay and provides an overview of the work performed at Philips in this project. Finally recommendations for future work are discussed for designing an optimum safety relay solution for TLED

Chapter 2: Safety switch selection and TLED architecture

2 Chapter 2: Safety switch selection and TLED architecture

This chapter first gives a brief introduction of relays and gives an overview on solid state relays. Next a brief study of TLED architecture and its associated components is made. After that a brief analysis is made to select a high voltage switch that is suitable for using as TLED safety switch. In this chapter basics are reviewed from [7] [8] [9] [10] [11] [12] [13].

2.1 Relays

Relays are basically electrical switches that are under the control of another circuit. Relays are in general made of electromagnets, but also some application use relay made up of semiconductor switches called solid state relays .Relays are mainly classified in to two types:

1. Electromechanical relays(EMR)
2. Solid state relay(SSR)

The main difference between electromechanical relays and solid state relays is that EMR have moving parts, whereas SSR do not. A relay can control electrical output that is higher than the electrical input it receives [13]. An example of electromagnetic relay is shown in Figure 12.There are various types of electromecahnical relays-Automotive Relays,Power Relays, Signal Relays,Reed Relays. In present TLED, Signal relays are used –which have typical coil voltage of (12-24)VDC and maximum switch current of (1-2)A and switch volatges upto 250VAC.In this signal relays there are again classified according to differrent contact configuration like SPST(single Pole single throw),SPDT(single pole double throw),DPST,DPDT etc. In TLED as disccued in first chapter two of the signal relays are placed in series with each other to function as a safety relays .

Solid state relays are relays which have no movable contacts. SSRs are designed and constructed employing semiconductor switching components such as SCR,TRIAC, DIODE, MOSFET,IGBT BJT.And also , SSRs are designed using optical semiconductors called photocouplers to isolate input and output signals [8]. An example of SSR is shown in Figure 13.

The advantages and disadvantage of SSRs compared to EMR are in numerous and few of them are discussed in next section.

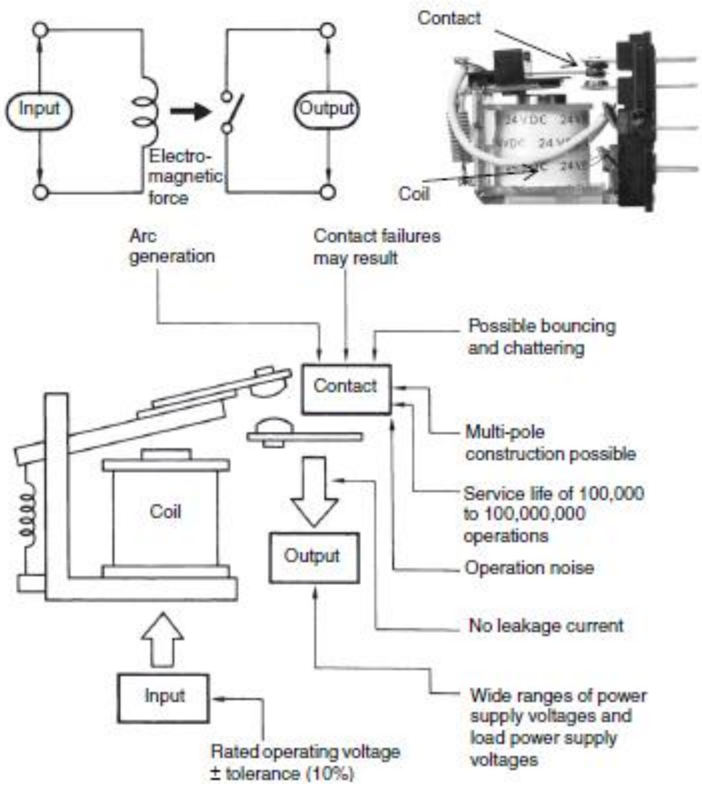


Figure 12: Electromagnetic relay (EMR) [8]

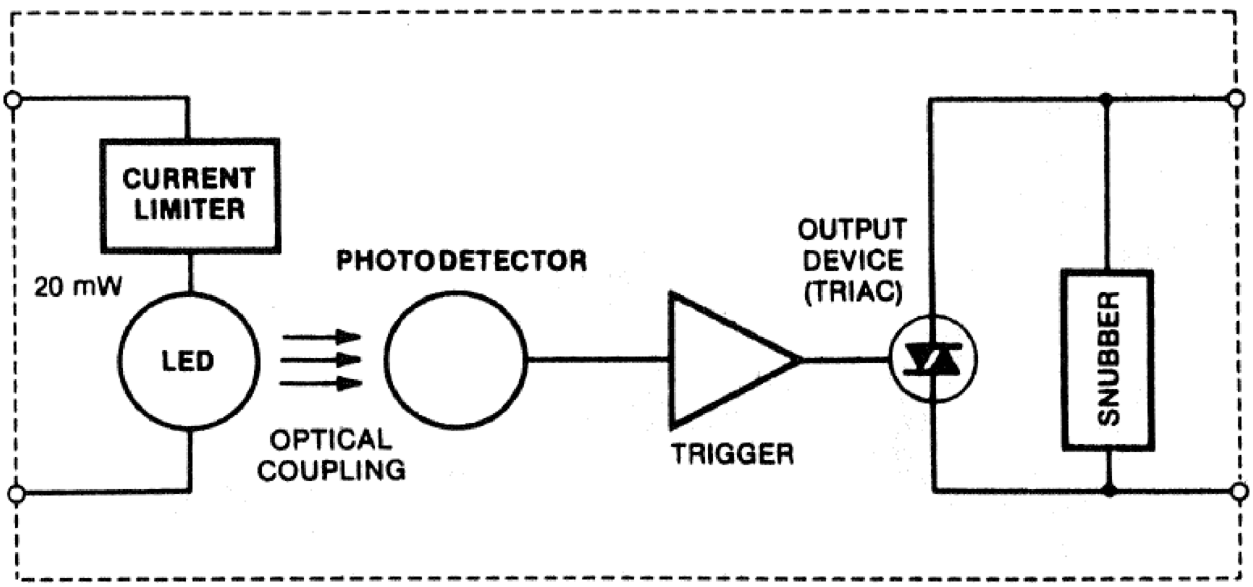


Figure 13: An example of Solid State Relay [7]

2.1.1 Pros and cons of SSRs compared to EMR

Some of the advantages of using SSR/Semiconductor switch based relays compared to electromechanical relays (EMR) are [7] [8] [12] :

- Higher reliability
- Smaller size
- Faster switching times
- No switch bounce(bouncing effect) [4]
- No arcing [4]
- Lower triggering currents
- Robust packaging
- No mechanical moving parts
- No contact failures
- No operation noise
- Long operating life
- High input-output isolation
- Wide input range possible
- No EMI(electromagnetic interference)from contact commutation

Hence the advantages of SSR are numerous and it goes on. However there are bad sides of SSRs compared to EMR:

- Higher relative on state resistances
- Low load current capacity
- Higher cost
- Ease of design

However with rapid development of quantum technology, now SSRs also designed with low on state resistances, and also higher load current capacity.

2.2 TLED Architecture

To understand how we can use safety switch in this design project, working of present TLED internal architecture has to be understood. Hence this section of this chapter deals with understanding of preset TLED system and its architecture, next section deals with basics of HF ballasts.

Figure 14 shows the basic TLED architecture. In this schematic it is seen that total electronic components are designed in two PCBs-A and B. PCB-A is called relay mother board and placed at one end of the tube, and this is the main important board studied in detailed to carry out this thesis.

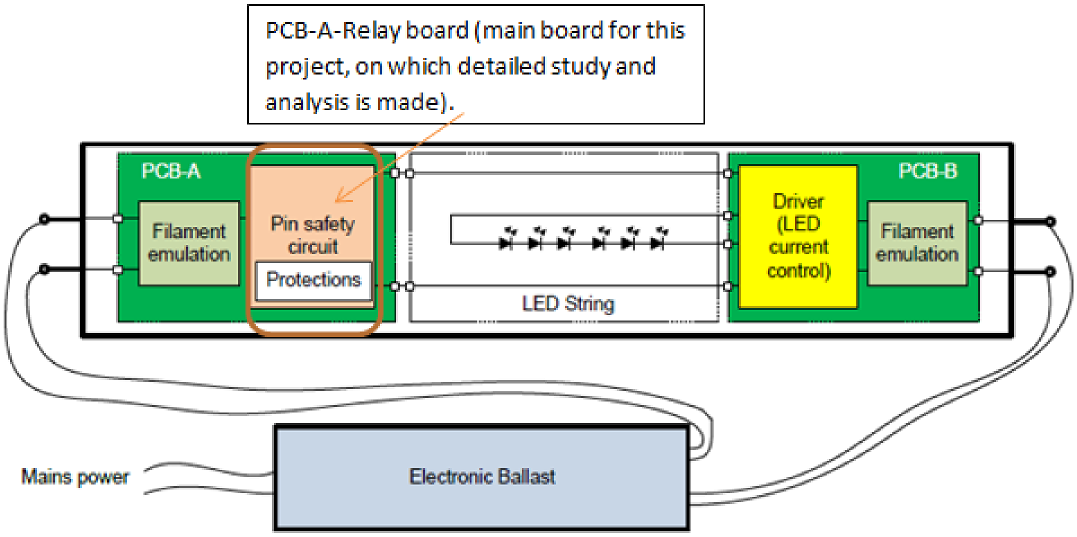


Figure 14: TLED basic architecture

PCB-A consists of filament emulation network (explained later in this section) and pin safety circuit and other necessary protections. This PCB-A is designed in such a way that it also consists of another small PCB attached to it called the daughter board. Daughter board consists of two electromechanical relays and associated passive elements. PCB-B consists of LED driver and associated control circuits and placed at the other end of TLED.

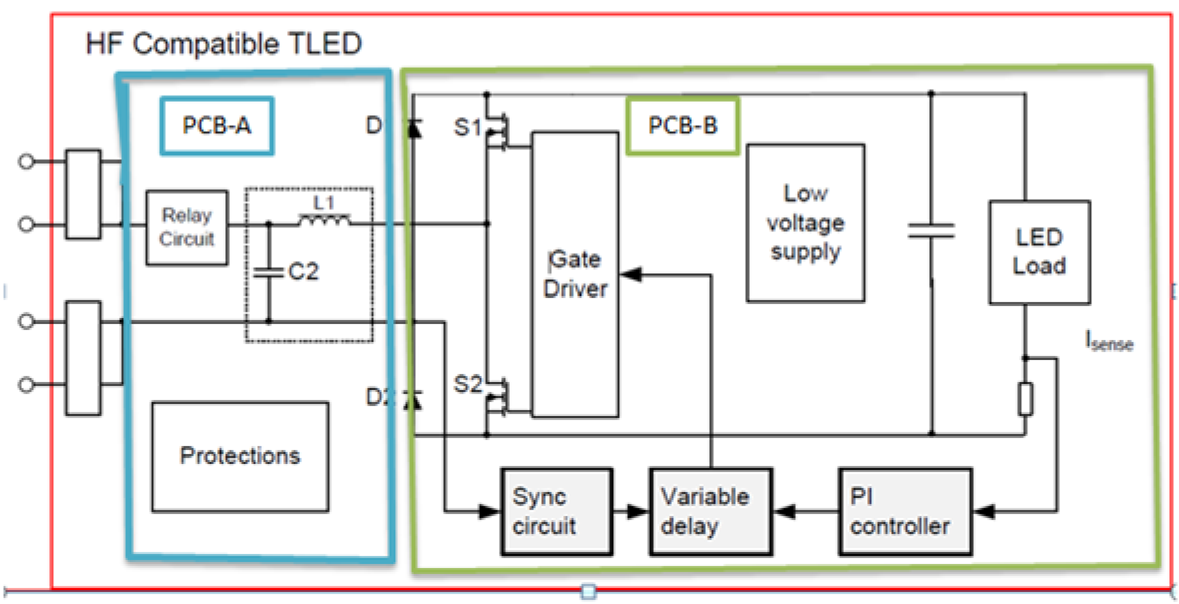


Figure 15: TLED internal functional block diagram

Figure 15 shows the full functional block diagram of TLED. Next we shall discuss about functionality of each network shown in the above figures.

1. Filament emulation circuit: Filament circuit is the interface between the lamp and the ballast. It greatly impacts the compatibility, safety and reliability of the ballast. Furthermore filament is directly related to misuse safety since it is connected right at the pins. In normal TL fluorescent tubes, filaments are used to preheat the lamp before ignition, such that lamp can start quickly and with lower voltage applied between end of tube (cathode and anode).Hence in order for TLED tube to emulate the TL filament in a correct way in order to guarantee safe and reliable operation of ballast, filament emulation network has been designed.

Figure 16 shows the typical electronic ballast TL fixture, showing the filaments at both ends of tube for preheating.

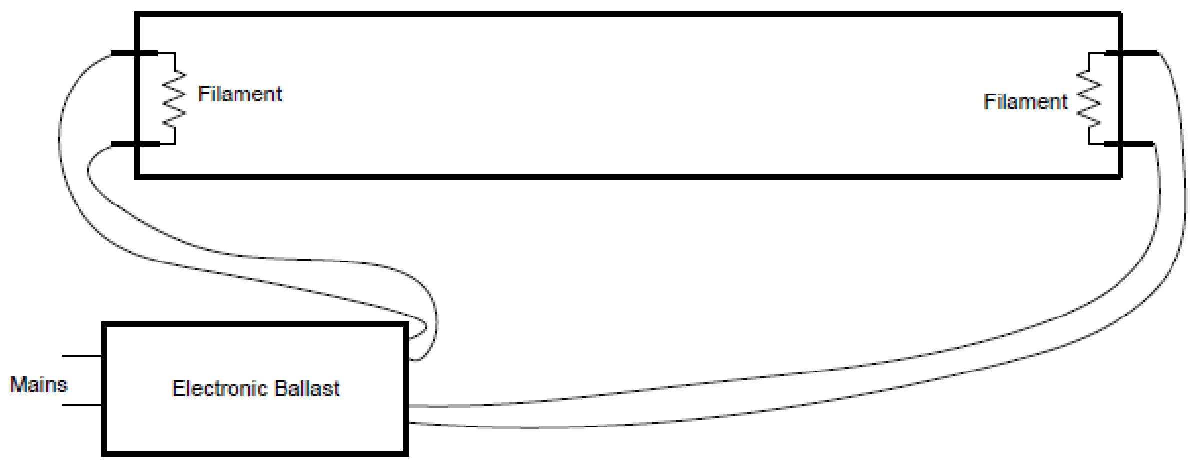


Figure 16: Typical electronic ballast TL fixture.

Figure 17 shows an example of TLED filament emulation circuit consists of number of series connected resistors, current limiting elements, voltage limiting element to ensure safe and reliable operation of the ballast.

2. HF ballast: In short, HF ballast is used to provide filament heating, ignition voltage, and stabilize the lamp current in steady state, when used with fluorescent TL tubes. However to replace fluorescent tube with new LED tube, bypassing the HF ballast is required, which is only done by rewiring the fixture. Hence HF ballast stays in the same position as it is in old TL tubes while replacing with retrofit LED tubes (TLED).Hence to make TLED compatible with old HF ballasts, whole internal electronics are redesigned in TLED. More detailed discussion on working of HF ballasts is discussed in next section.

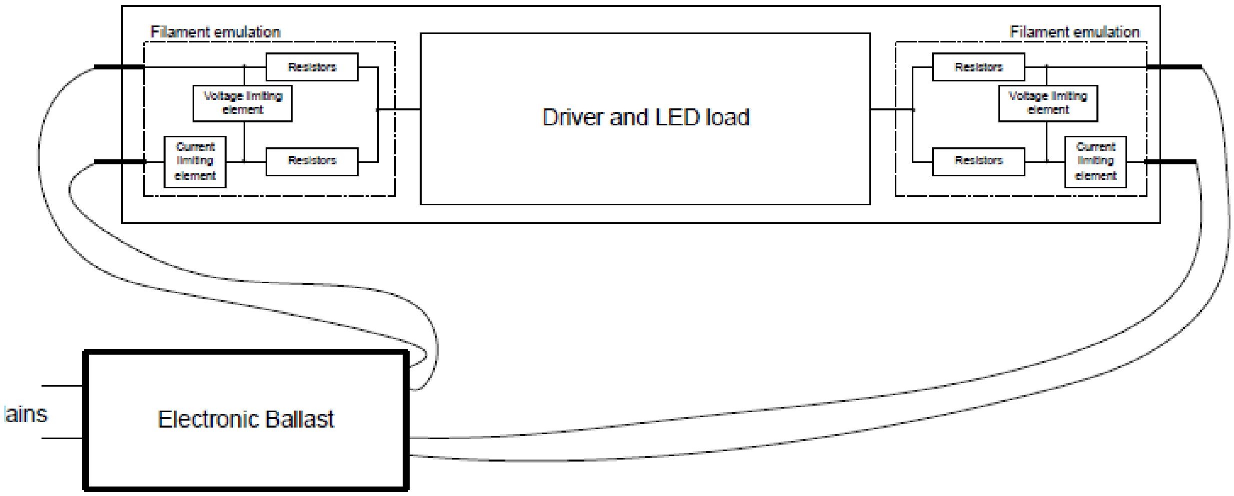


Figure 17: TLED filament emulation circuit.

3. Detuning network: Inductor L1 and capacitor C2 are used as detuning network for impedance matching between HF ballast and LED driver. This LC network also used to improves EMI results.

4. Relay circuit and associated protection circuits: The relay circuit provides power supply to two electromechanical relays during startup and in steady state. The detailed relay circuit was discussed in chapter 5.

5. HF compatible LED driver: The primary function of an HF compatible driver is to reduce the lamp power intake while keeping the ballast operating properly. HF ballast can be classified as [14] [15] [16]

    - Constant power source
    - Constant current source

Majority of the ballasts in the market is a constant current source. The ballast delivers constant current to the load (refer Figure 18).

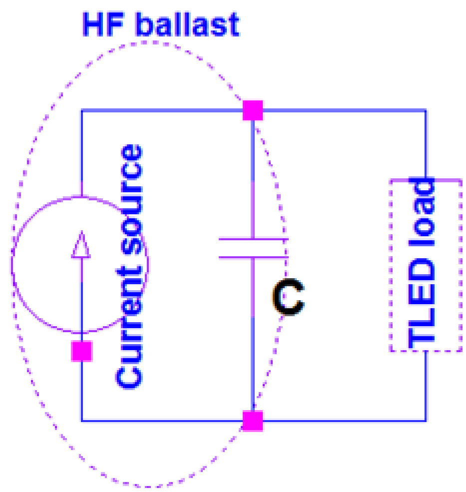


Figure 18: Simple model of constant current type HF ballast

The lamp input voltage can be controlled to influence the lamp power intake, either by modulating the amplitude or modulating the duty cycle. In fact both methods reduce the amplitude of the first harmonic. Since the power transfer is mainly takes place at the first harmonic, both methods can control the lamp power. Amplitude modulation is best to be implemented with a switching mode driver, like a buck boost converter; whereas the duty cycle modulation can be implemented with a shunt switch as in case of TLED. For shunt switch configuration refer to Figure 15.

2.3 HF (High frequency) Ballasts

For designing the hybrid safety relay system for TLED, working principle of HF ballasts is very important and hence this section discuss briefly about HF ballasts.

Fluorescent lamps with higher luminous efficiency have been used since last few decades, for commercial and household lighting applications, displacing almost all incandescent lamps .Fluorescent lamps are a kind of gas –discharging lamps, exhibiting negative incremental resistance and requires ballast for stable operation. At first, electromagnetic (EM) ballasts are used for fluorescent lighting, which has major drawbacks like producing flickering and audible noise and being large in size (ballast). To eliminate these problems, High frequency (HF) electronic ballast was developed. High frequency (HF) ballast is being widely used from last few decades (since 1970s) in fluorescent lighting, since it has higher luminous efficiency and very compact compared to EM ballasts [15].

The main purposes of electronic HF ballasts are [16]:

- Provide a start-up voltage across the end of electrodes
- Maintain a constant current when the lamp is operating in the steady state.

- Assuring the circuit stability even in fault conditions.
- Comply with international and local safety standards.
- Conversion of main power into a current suitable for operating a TL (Tube Linear) lamp.

Fluorescent lamps are classified in to three types according to their starting methods [15]:

1. Rapid starting
2. Preheat starting
3. Instant starting

Preheat starting is the first developed starting method, in which cathode terminals are preheated before ignition. Instant starting is the next method developed; in which lamp starts with relatively high voltage between the cathodes without preheat. Rapid starting method is most common and matured technology, where cathode terminals are preheated before ignition and also provides filament heating after lamp has been started up.

Ballast topologies:

The present HF ballasts consists of different blocks, they are [14]:

1. Electromagnetic interference (EMI) filtering network: this prevents ballast generated noise from entering the mains power supply.
2. Rectification block: to convert AC current to DC.
3. Power Factor Correction (PFC) block: for making input current wave form look like a pure sine wave.
4. Under voltage lockout(UVLO) and fault protection:
5. Half-bridge switches along with the driver and timing circuit: for high frequency operation of lamp.
6. Output stage: to power the lamp.

A simplified block diagram for typical HF ballast is shown in Figure 19.

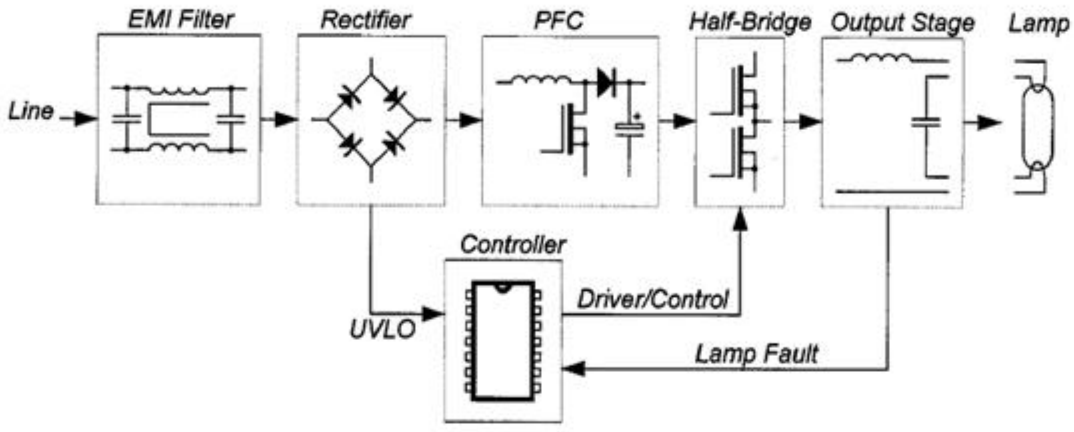


Figure 19: Ballast functional diagram [14]

Depending up on the different topologies used in input stage, output stage, control, output, and starting methods, there are various HF ballasts available in the market.

In general for all lamps, a current for a specified time to preheat the filaments, a high ignition voltage, and also running power is required. These above mentioned requirements are satisfied by changing the frequency of the input voltage and properly selecting parameters like V_{in}(Input Voltage),L(Inductance) and C(Capacitance) [14].The simplified model for ballast is shown in Figure 20.

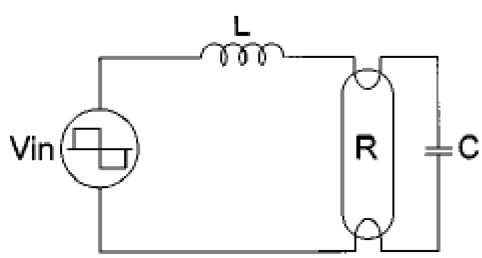


Figure 20: Simplified model of ballast output stage [14]

During preheat and ignition phase, the lamp is not yet conducting and hence the circuit shown in above figure acts as a series L-C network. But during running phase, lamp is conducting and the circuit is in an L in series with a parallel R-C network.

Variety of the HF ballast circuit designs are based on from following aspects:

1. Different values of L and C in the tank, different combinations;
2. Different operating frequencies;
3. Fixed vs. variable operating frequency (in steady state);
4. Fixed output vs. dimming;

5. Different preheat time and method;
6. Different filament heating circuits;
7. Different implementation of protections;
8. Different control strategy of the PFC stage;
9. Different implementations of the startup circuit;
10. Different shutdown / automatic restart feature.

Below Figure 21, shows the typical half bridge topology of ballast:

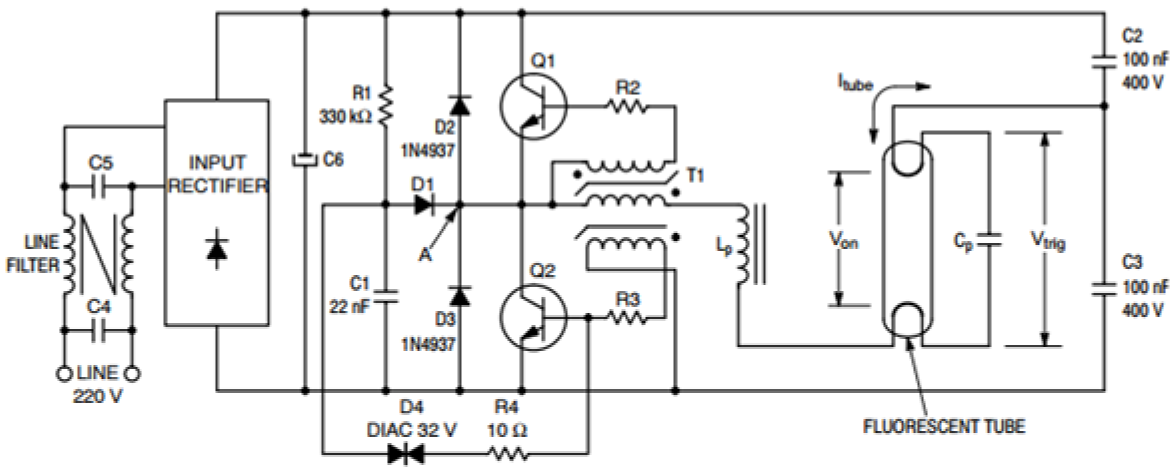


Figure 21: Typical half bridge topology [16]

Ballast operating principle:

Typical resonant tank of HF ballast is a parallel loaded LC tank. Figure 22 below plots the lamp voltage as a function of the operating frequency. Lamp voltage is low at high frequency and increases dramatically at frequencies near the resonance. The lamp can therefore be ignited with the high voltage. After the lamp is ignited, it enters steady sate, and the lamp current is stabilized by the inductor of the LC tank.

In steady state, there are several control strategies possible that varies between different company design brands. Some ballasts operate the lamp at a fixed frequency, while others ballasts regulate the lamp power by controlling the operating frequency. Fixed frequency is sometime beneficial because of very predictable operating frequency and lower cost.

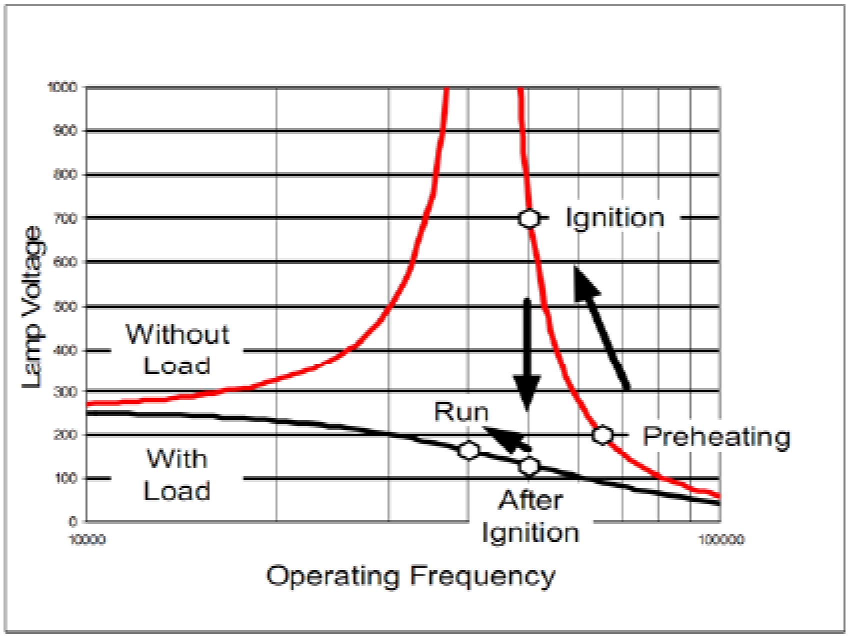


Figure 22: LC tank characteristics showing the lamp voltage vs frequency

Warm start ballast is typically controlled by an IC. The IC controls the operating frequency of the half-bridge. Normally the controller does a frequency sweep during the startup phase, as shown in Figure 23. The resulting HF voltage is illustrated in Figure 24.

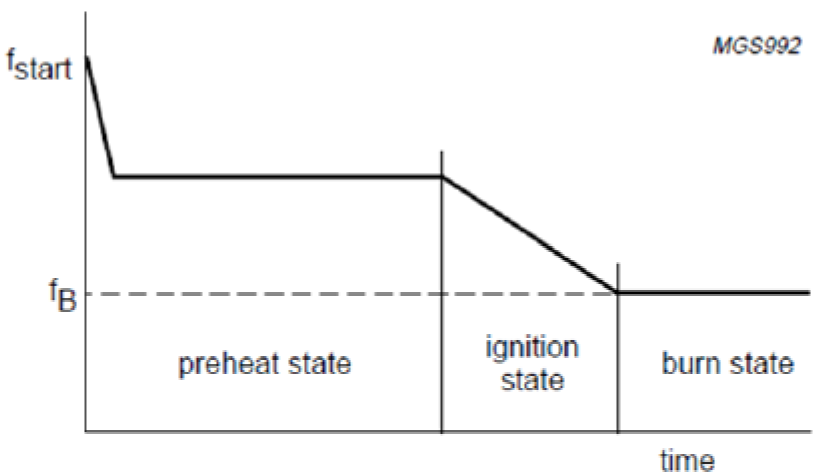


Figure 23: Ballast frequency during operation phases [14]

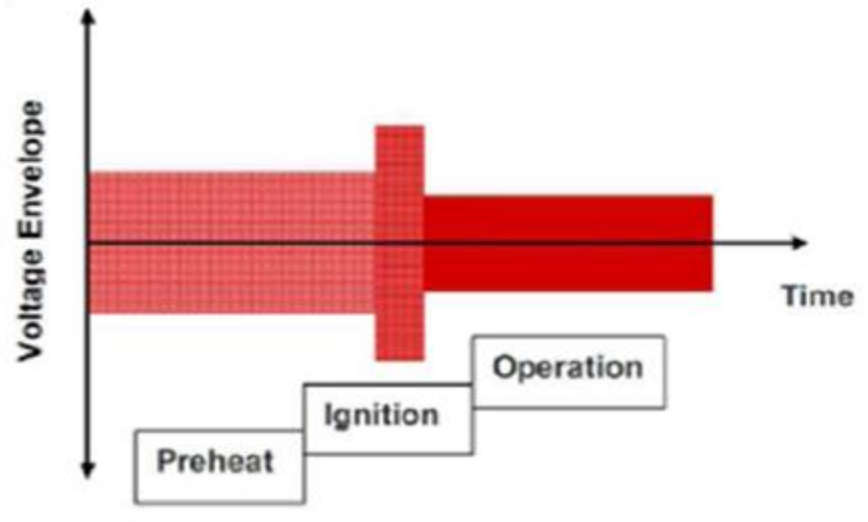


Figure 24 : Fluorescent lamp voltage during operation phases

HF ballast basic governing equations [14]:

The basic equations describing the behavior characteristics are discussed in this section. The operating frequencies of ballast at different times depend up on, circuit elements L, C, Input voltage, filament preheat current, ignition voltage, lamp running voltage and also power.

During preheat, the resistance of the lamp is assumed to be infinite and the filament resistance is negligible, and the circuit behaves as an L-C series circuit as discussed previously. Taking the impedance across the capacitor in to consideration: The preheat frequency is:

$$f_{ph} = \frac{I_{ph}}{2\pi C V_{ph}} [HZ] \qquad [1]$$

Where, f_{ph} is preheat frequency[HZ]; V_{ph} is lamp preheat voltage amplitude[volts];I_{ph}=filament preheat current amplitude(amperes);C is output stage capacitor(farads).

During ignition, the frequency for a given ignition voltage can be found using equation 2.

$$f_{ign} = \frac{1}{2\pi} \sqrt{\frac{1+\frac{4V_{in}}{\pi V_{ign}}}{LC}} \text{ [HZ]} \qquad [2]$$

Where V_{ign} is the lamp ignition voltage (volts); L is output stage inductor (henrys);V_{in} is input square wave voltage(volts);

Ignition current is then,

$$I_{ign} = f_{ign} C V_{ign} 2\pi \qquad \text{[amperes)} \qquad [3]$$

Where I_{ign} is ignition current flowing in the circuit.

After the lamp has ignited, the resistance of the lamp comes in to play and the system becomes RCL series parallel circuit with transfer function given on equation 4.

$$\frac{V_{run}}{\frac{4V_{in}}{\pi}} = \sqrt{\frac{1}{(1 - LCw^2)^2 + \frac{L^2}{R^2}w^2}} \qquad [4]$$

2.4 Design requirements for TLED hybrid safety relay system

In this design project the main task is to evaluate the concept of replacing one electromechanical relay with one solid state switch. Here only one electromechanical relay is to be replaced and other relay is still be used as fail proof (safety) and provides necessary high voltage isolation of 1.5kV between input and output. It is generally very costly to opt for using a commercially available SSR to replace one electromechanical relay. But even we go for designing a SSR in lab, the cost is very high. Apart from the cost the most important design requirement for designing TLED hybrid safety relay system is that, the desired semiconductor switch system should block high voltage and high frequency from HF ballast in both directions and also conduct current in both directions (bidirectional). All most all the commercially available SSR are designed to switch with mains frequency (60Hz) and not for high frequency such as (40-120 kHz) with which HF ballast operates. Hence for this design project we cannot use SSRs available in the market for following reasons:

- Higher Cost
- Requirement of blocking high frequency and voltage (switching with high frequency) with bidirectional current flow and blocking capability.
- Commonly SSRs are designed with optocoupler for high isolation between switching side and control side. But for this project we need high galvanic isolation (1.5 KV) and also need to transfer more amount of(few 100mw) power from control side to main switch to trigger high voltage switch, which is not possible with optocoupler triggering methods which can maximum handle only few mw(0-20)mw [7] .

2.5 Choosing the appropriate high voltage switch that is capable of blocking high voltage and frequency bidirectionally

From previous section it is clear that SSR are not the best choice for this project. Hence opting for various semiconductor switches is the best choice.

The basic requirements of a high voltage semiconductor switch that can be used in TLED in designing hybrid safety relay system are:

- Bidirectional blocking ability
- High voltage rating
- High dV/dt capability
- Low cost
- Bidirectional conduction
- Low energy requirement for driving the switch

Now this section further discusses on how to choose the appropriate semiconductor switch that suits this requirement of the project.

There are many ways to implement a bidirectional blocking (and conducting) capable devices using semiconductor switches like TRIAC/MOSFET/BJT/IGBT. Some of the possible ways of implementing bidirectional switch configuration is studied from [9] [10] [11] [12] [17] [18].

2.5.1 BJT

BJT (Bipolar junction transistor) is a basic power switch that can be used in this project. Since a single BJT switch is unidirectional, we need to use at least two BJTS connected in series along with two power diodes for making it to conduct bidirectionally as shown in Figure 25.This kind of configuration is designed for AC mains, however can be used for high frequencies with some extra components.

From the figure and discussions from [17], it is very clear that using two BJTs and two diodes for bidirectional conduction is not efficient as it involves 4 components and in each conducting interval it involves two components which leads to high conduction loss can be high. The most important drawback of this design is that, driving two BJTS in series is not easy and requires two drivers for that, which involves complexity as these drivers have to be synchronized with the frequency of HF ballast and cost to the final design. Hence using BJT is not appropriate for this project.

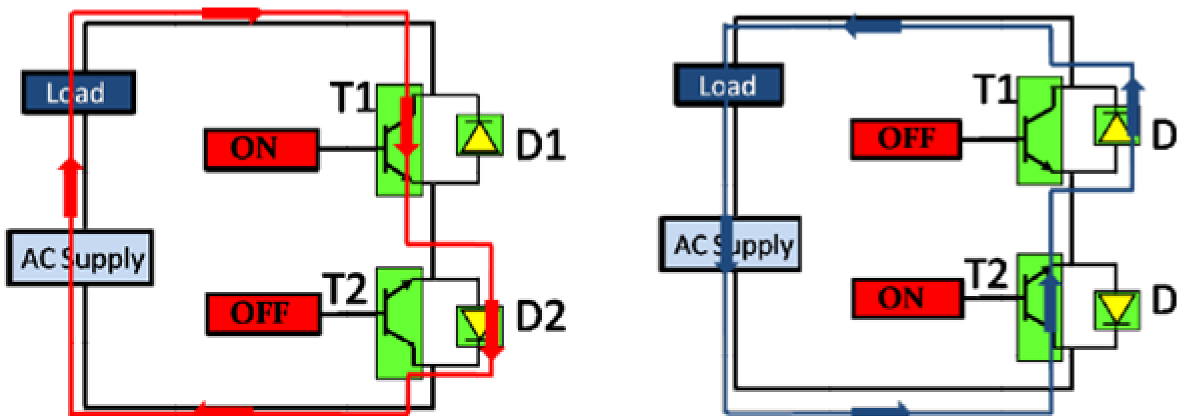


Figure 25: Bidirectional current conduction using BJT [17]

2.5.2 IGBT

In similar lines, IGBT which is unidirectional switch can be used to switch bidirectional current as shown in Figure 26.

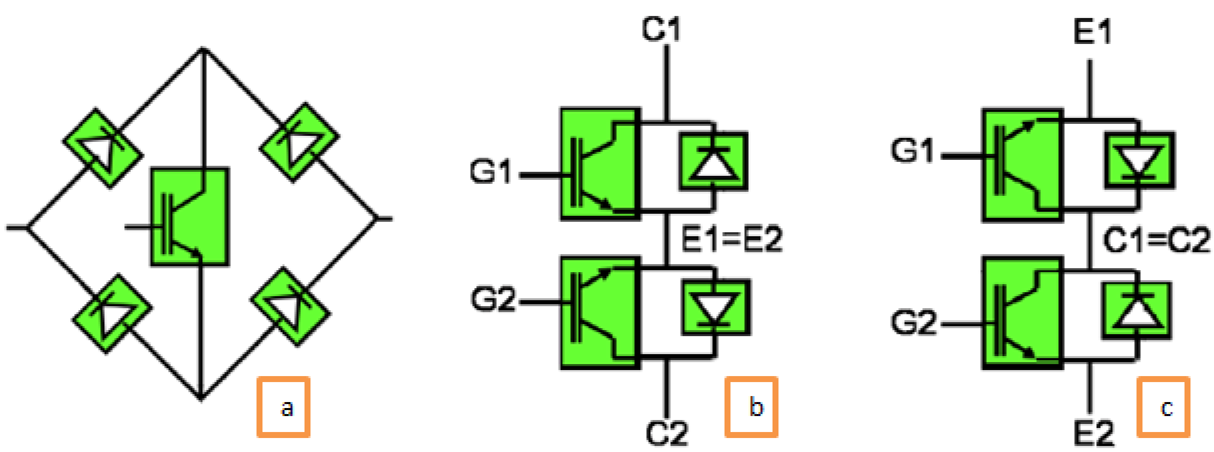


Figure 26: Bidirectional switch topologies using IGBT [17] (a) Diode embedded switch (b) common-Emitter switch (c) Common-Collector switch [17]

From above figure, first configuration (a) involves 2 diodes and IGBT for each conducting interval, second (b) and third(c) configuration involves only one diode and one IGBT hence conduction losses are lower compared to first (a). However single IGBT switch is costly and this kind of switch configuration requires two IGBTs for lower conduction losses and hence driving these two switches is complex, since the two IGBTS gate drivers have to be synchronized with switching frequency of HF ballast in our project. Hence using IGBTs are not good choice for this project.

2.5.3 MOSFET

For exploring the ways to make a MOSFET switch suitable for bidirectional voltage blocking and conducting current, references [9] [10] [11] [12] [18] were studied in detail.

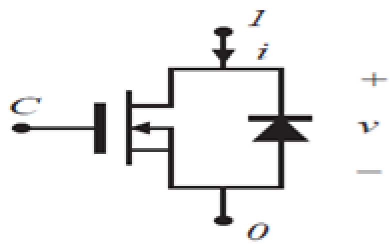


Figure 27: A typical N-Channel MOSFET switch with its integral body diode. [9]

Figure 27 shows a typical N-channel MOSFET switch with its internal body diode. In general a MOSFET is device which can block voltage only in one direction when it is in OFF state and conduct current in both directions when it is in ON state. However to make it block voltages in both directions, an external diode should be connected to MOSFET as shown in Figure 28. However this kind of connection allows only unidirectional current flow when switch is ON. Hence to ensure bidirectional conduction during ON state and bidirectional voltage blocking capability during OFF state, two MOSFETs have to be connected such that two source terminals of MOSFETs are connected to same point as shown in Figure 29.

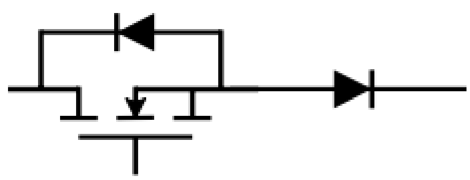


Figure 28: Connection diagram for MOSFET to block voltages in both directions [18]

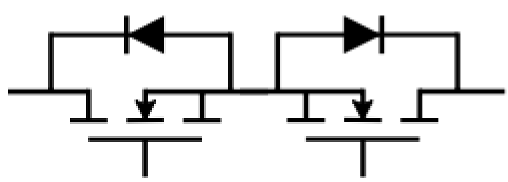


Figure 29: Connection diagram for MOSFETs to conduct bidirectional (ON) and block Voltages bidirectional (OFF) [18]

Hence by above discussion it is clear that we can operate two MOSFETs connected in series with each other with common source terminal, bidirectional power flow is possible. However using two MOSFETS for this design project will add up components and associated conduction loss and also two MOSFETs gate drives have to be synchronized. In general MOSFETs are preferred over BJT due to ease of drive since MOSFETs are voltage controlled, whereas BJTs are current controlled but MOSFETs have higher ON state loss. However to reduce the power loss in MOSFETs during ON state, it is very essential to select low ON state(R_{DsON}) resistance MOSFET switch which can be a costly solution and also needs to test the thermal behavior of these switches under TLED average load current.

2.5.4 TRIAC

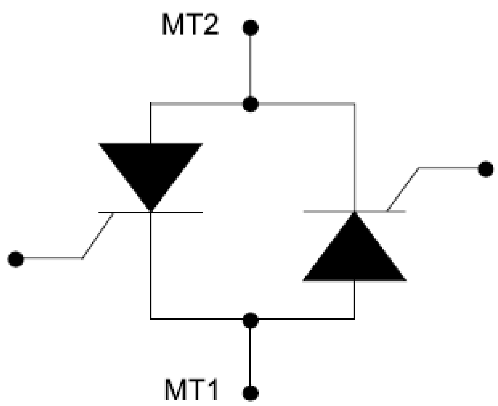


Figure 30: TRIAC basic structure [19]

From [7] [19] [20] [21] we can say that TRIAC is a device that can block voltages in both directions and conduct current in both direction and thus operation of TRIAC is possible in all quadrants of operation. Hence TRIAC can be a best suitable high voltage switch that can be used in TLED hybrid safety relay system design. The basic structure is shown in Figure 30, which shows a TRIAC as combination of two thyrsistors/SCRs connected antiparallel to each other thus allowing bidirectional current flow and voltage blocking capability.

Hence TRIAC does not need any extra component to make it bidirectional conducting and blocking and it is also cheaper. The main advantage of the TRIAC is that once switch is triggered in to ON state and when its anode current reaches latching current level (I_L), there is no need of any triggering pulse to keep it in ON state and this is a typical characteristic of any SCR/TRIAC. Hence to drive TRIAC in steady state no triggering energy is required in steady state and hence low energy consumption from board and thus these characteristics is very essential for this project to design hybrid safety relay system for TLED.

However the important characteristic of TRIAC that need to be checked for using as a safety switch in TLED is its static dV/dt capability, which is the a measure of the ability of a thyristor to retain a blocking state under the influence of a voltage transient. More in detailed explanation on this dV/dt is dealt in section 3.1.2. Another important characteristic that has to be checked before deciding on using TRIAC as a safety switch is its thermal behavior when current is flowing through it for long time when it is switched ON.

Hence by above discussions its section -2.5.3 and 2.5.4, it is clear that either MOSFETs or TRIACS can be used for this project. But to decide the appropriate device, understanding thermal behavior of each device (TRIAC and MOSET) is essential to choose the best system with lower losses. Next section deals with thermal tests on TRIAC and MOSFET.

2.5.5 Thermal tests on TRIAC and MOSFET for choosing the best switch among them with lower temperature rise.

To test for temperature change in the component (TRIAC/ MOSFET) when a continuous current is flowing through them (300-600) mA, a test circuit was designed as shown in Figure 31 and Figure 32.

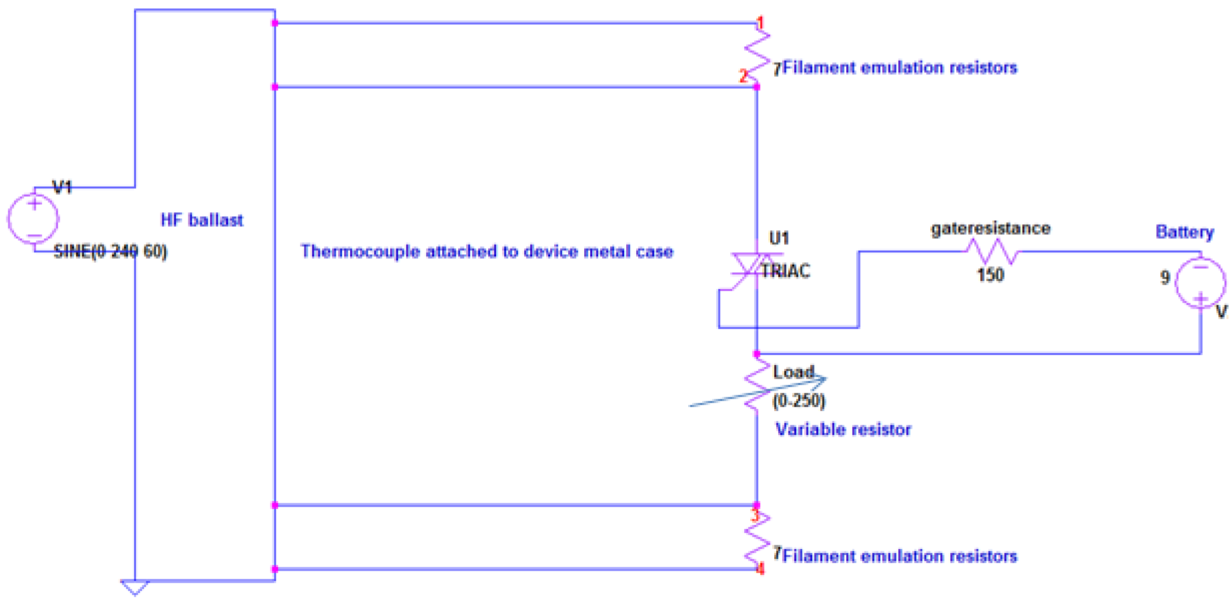


Figure 31: Thermal test setup for testing TRIAC thermal behavior

In this test design circuit, 9V battery supply is used as gate power supply to TRIAC and MOSFET. The variable resistance is used to increase or decrease the current flowing through switch from (300-600) mA so as to emulate different type of ballast output current. Filament emulation resistors are used in this circuit so as to emulate the TL fixture filament network in TLED. A thermocouple is attached to device metal case to measure the temperature rise of device from its initial condition-room temperature (23^{o}C) when a current magnitude of (300-600) mA flows through the switch for ten minutes. To test the MOSFETS for its thermal behavior, MOSFETS with low On-State resistance R_{DSon} are selected from a bunch of commercially available switch samples which are cost effective. Similarly TRIACs are selected on the basis of cost and high voltage, high dV/dt capability and also current handling capacity.

The results of the test are shown in Table 1:

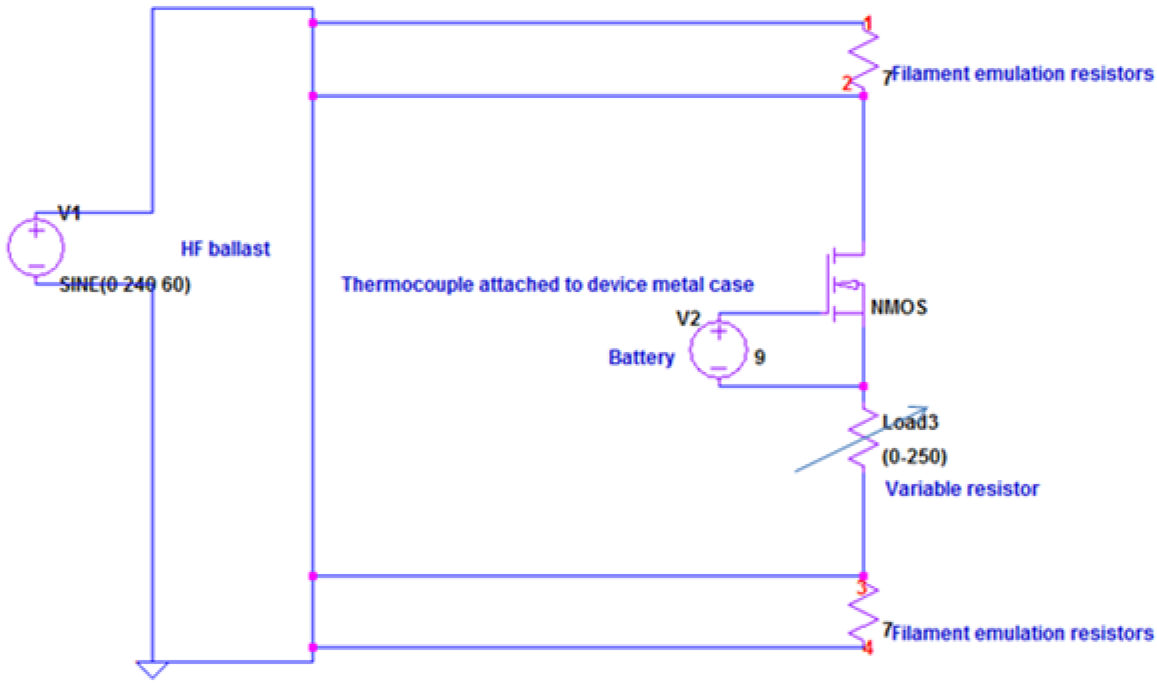


Figure 32: Thermal test setup for testing MOSFET thermal behavior

Table 1: Thermal tests on TRIAC and MOSFET

Switch type	Temperature (C)after 10min of conduction-300mA	Temperature (C)after 10min of conduction-600mA
MOSFET-800V - 1.9Ω - 4.3A *STP5NK80Z*	41	80
TRIAC-800V,8A,IGT=30mA ACST830-8FP	36	49
TRIAC-800V,4A, IGT=35mA. BTA 204-800CT	38	51
TRIAC-800V,2A,IGT=10mA ACTT2X 800E	42	58

2.5.5.1 Conclusion of the thermal tests

Initial temp=room temp=23(^{o}C)

- TRIAC switches ACST800-8FP,BTA204800C,ACTT2X800E shows the best thermal results ,which shows very less change in temperature .i.e. initial switch temp =23^{o}c and final stabilized temp of switch after ballast is switched on for ten min is (36,38,42) ^{o}C respectively at 300mA current level flowing through them .whereas at 600mA current flowing through each switch, the final temperature is 49,51, 58 respectively. Hence a TRIAC switch shows a very less increase in temperature for a typical ballast current level of (300-600) mA, so TRIAC switches has a better thermal performance than MOSFET as discussed next.

- MOSFET switches- (*STP5NK80Z,* 3AFQP3N80C) in similar lines show a large increase in temperature from its initial temperature for ten minutes conduction.

Hence after analyzing the thermal results for TRIAC and MOSFET, it can be clearly said that TRIAC is best suitable switch for proposed TLED hybrid safety relay system .This conclusion is based on its thermal behavior, ease of driving and most importantly it blocks voltages bidirectional and conduct current bidirectional without any need of any extra components, whereas MOSFETS/IGBT/BJT that need extra components for its bidirectional blocking capability.

Chapter 3: The TRIAC and testing of its characteristics

3 Chapter 3: The TRIAC and testing of its characteristics

3.1 Overview of TRIAC and its Characteristics

This section gives an overview of TRIAC structure and its characteristics from the references [19] [22] [23] [24] [25].

The TRIAC is a bidirectional thyristor device, that can be used to pass or block current in both directions (Positive and negative).The structure of TRIAC is equivalent to two thyrsitors connected in anti-parallel direction with a common gate electrode as shown in Figure 33.The triac has mainly three terminals, MT1 and MT2 are main terminals which are connected to load, and a gate terminal G. Main terminals are connected to both p and n regions ,in order to conduct current in both directions depending upon the polarity of applied voltage. In the same way gate terminal is also connected to both regions (p and n) such that it can be triggered by both positive and negative pulses. Commonly the triac polarity is defined with reference to (MT1), where the term (MT2+) implies that terminal MT2 is more positive compared to terminal MT1.

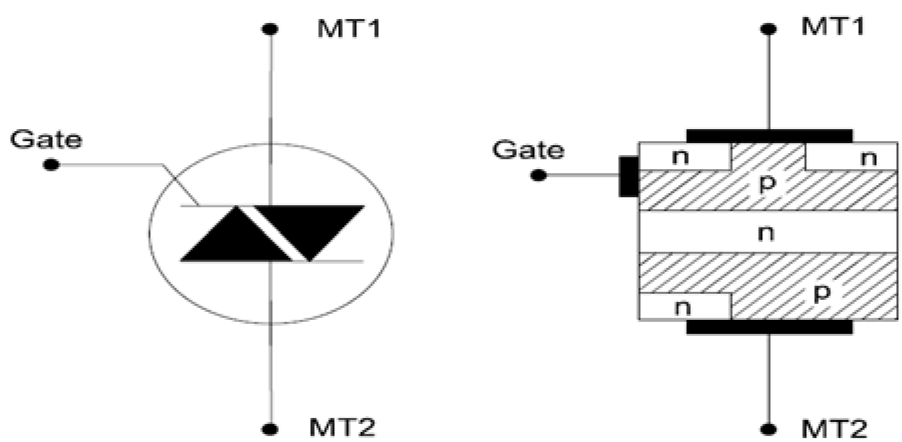


Figure 33: TRIAC circuit symbol and basic structure [19]

Figure 34 shows the triac static characteristics. Since triac is a bidirectional device, it can block voltages in either direction compared to thyristor which can block voltages only in one direction.one of the interesting property of triacs is that, due to physical layout of the semiconductor layers in it, the values of latching current (I_L), Holding current (I_H) and gate trigger current (I_{GT}) are not same for different operating quadrants.

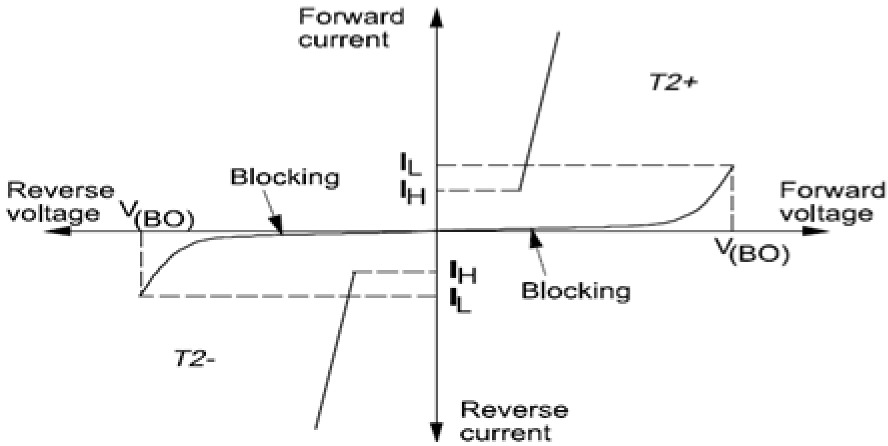


Figure 34: TRIAC static characteristics [19]

Table 2 shows the operating quadrants for the triacs and Figure 35 shows the triac triggering quadrants. From [19] [23] it is clear that for triggering triacs efficiently(less energy consumption), quadrant 2 and 3 is mostly preferred for all standard triacs. The reason for this is that for triggering triac in 4th quadrant, the gate trigger current is higher compared to all other quadrants. The latching current is slightly higher in 2nd quadrants compared to other quadrants. When gate sensitivity of triac is critical factor and also when the triac needs to be triggered effectively for bidirectional applied voltage (AC) like in case of TLED, negative gate current triggering circuit is preferred for reducing the power consumption from the board.

Table 2: Operating quadrants for TRIACS [19]

Quadrant	Polarity of MT2 wrt MT1	Gate polarity
1 (1+)	MT2+	G+
2 (1-)	MT2+	G-
3 (3-)	MT2-	G-
4 (3+)	MT2-	G+

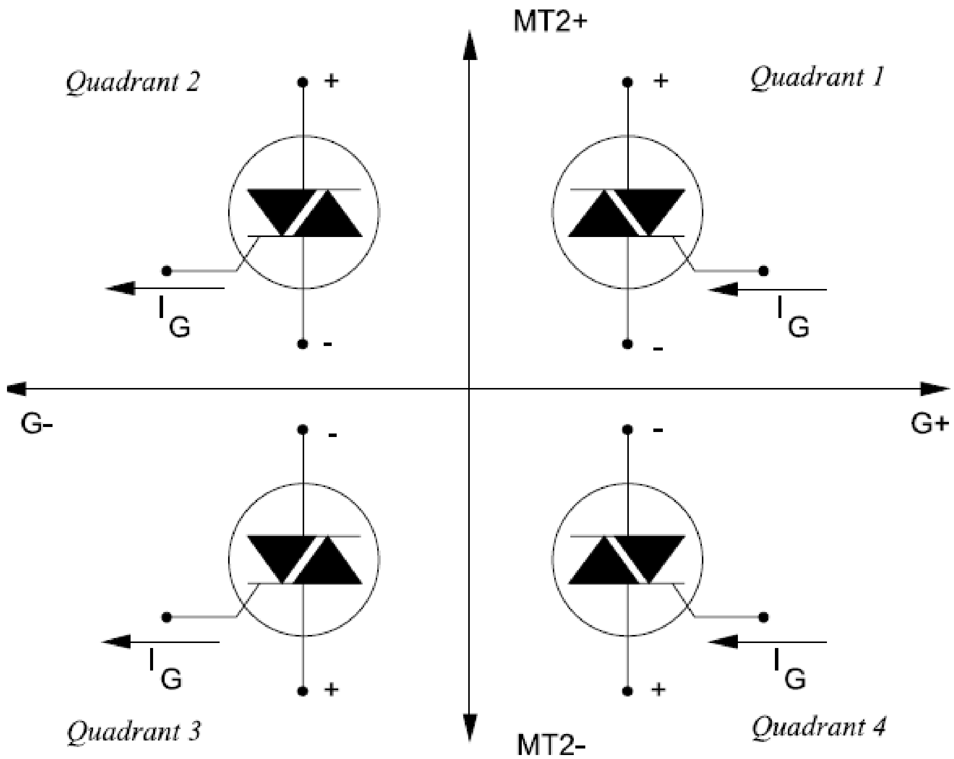


Figure 35: TRIAC triggering quadrants [19]

3.1.1 TRIAC triggering methods

From the literature [19] [23], various thyristor/triac turn on methods are discussed:

1. Turn on by exceeding the break over voltage: When the breakover voltage, VBO, across a thyristor is exceeded, the thyristor turns on. Break over voltage triggering method is not a commonly used triggering method.

2. Turn on by gate triggering: Gate triggering is the common method of turning a thyristor on. In general a single pulse or pulse trains are used to trigger the triac and to ensure full bidirectional conduction.

3. Turn on by dV/dt(false turn-on): Since thyristor/triac is made up of p and n regions forming p-n junction. This p-n junction has capacitance - the larger the junction area the larger the capacitance. If a voltage ramp is applied across the anode-to-cathode of a p-n-p-n device, a current will flow in the device to charge the device capacitance according to the relation shown in equation 5 below. If the charging current becomes large enough, the density of moving current carriers in the device induces switch-on. However, this kind of triggering method is very uncommon and should be avoided at all costs. Detailed explanation on this false turn-on due to dV/dt is discussed in next section 3.1.2.

$$I_C = C * \frac{dV}{dt} \tag{5}$$

Where I_C is the p-n junction capacitance current injected in to the gate of triac/thyristor.

There are many ways of triggering triac by gate pulses and most of the methods are found in many design circuit literature circuits. Based on the typical requirements of the safety standards of the product, there are two basic gate control circuits:

- Non isolated SCR/TRIAC gate control circuits
- Isolated SCR/TRIAC gate control circuits.

When there is no requirement of isolation between gate circuit and high voltage switching circuit, then non isolated gate control circuits are used. In this control, to supply gate current to triac, two kind of power supply bias are used:

- Positive power supply(Figure 36)
- Negative power supply (Figure 37).

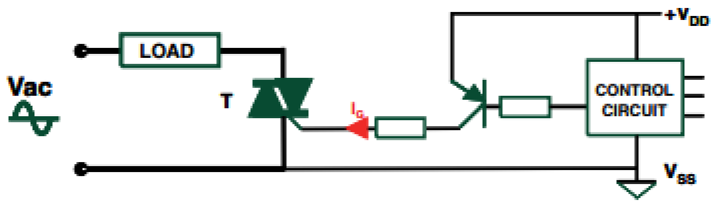


Figure 36: Triggering triac with positive power supply [23]

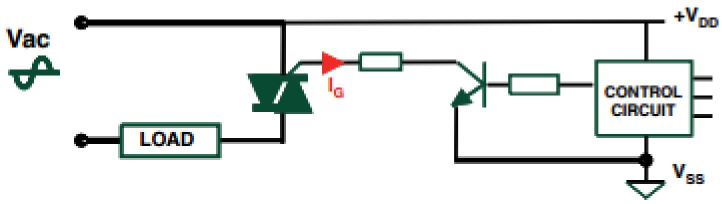


Figure 37: Triggering triac with negative power supply [23]

When there is a requirement of galvanic isolation between gate control circuits and high voltage switching network, then isolated gate control circuits are used (Figure 38).

Since the main requirement for designing TLED hybrid safety relay system is to isolate gate drive circuit from the high voltage and high frequency ballast signals, isolated gate drive control circuits are used , which is discussed in detailed in section 4.4.1.2.2.

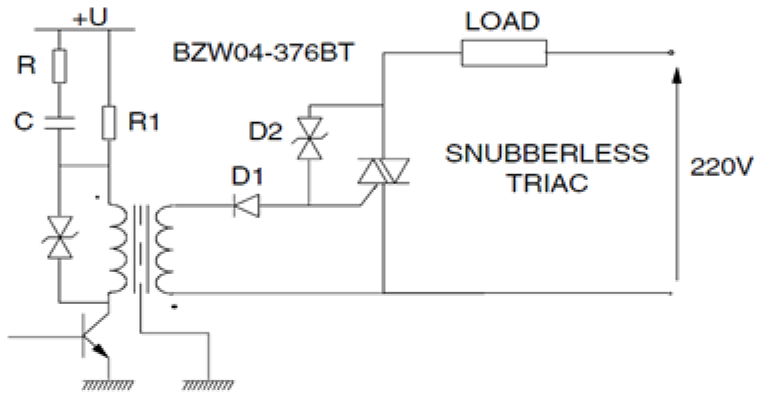


Figure 38: Example of isolated triac control circuit [26]

3.1.2 Static dV/dt

Static dV/dt is a measure of the ability of a thyristor to retain a blocking state under the influence of a voltage transient. Static dV/dt turn-on (unwanted triggering) is a consequence of the Miller effect and regeneration. A change in voltage across the junction capacitance induces a current through it. This current is proportional to the rate of voltage change dV/dt. It triggers the device on when it becomes large enough to raise the sum of the NPN and PNP transistor alphas to unity [22].Figure 39 shows the typical behavior of triac static dV/dt with respective applied peak voltage. Thus in all circumstances this kind of dV/dt false turn on of triac should be avoided. To improve static$(\frac{dV}{dt})_S$, an external resistor should be connected between gate and MT1.This resistor provides a path for leakage and dV/dt induced currents due to miller effect. Figure 40 shows the effect of adding this resistor on dV/dt improvement. Generally different range of resistor values is preferred for sensitive and non-sensitive gate triacs. From [22], it states that maximum $(\frac{dV}{dt})_S$ only occurs with a short between gate and cathode without an external resistor.

For this design project, testing for static dV/dt of triacs is very essential to avoid false turn-on, since in this design triac is used as a safety switch that has to block high voltage and frequency signals from HF ballast. Hence the first task of this project is to test for static (dV/dt) capability of 5 samples, commercially available triac switches, which is discussed in section 3.1.4.

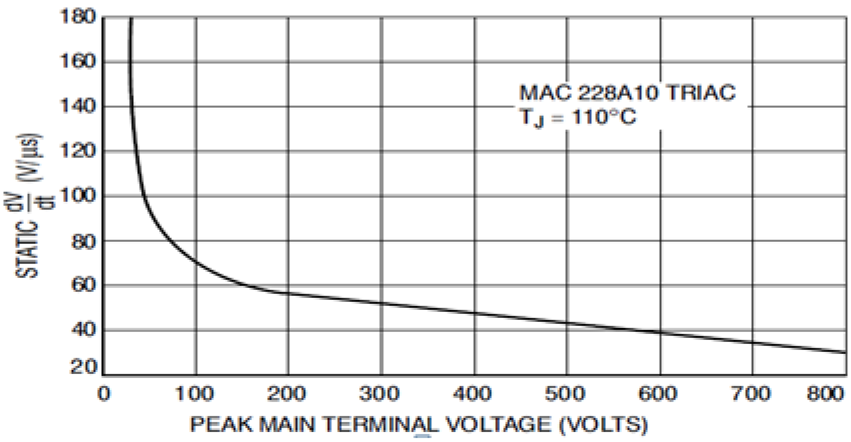


Figure 39: Static (dV/dt) versus peak voltage [22]

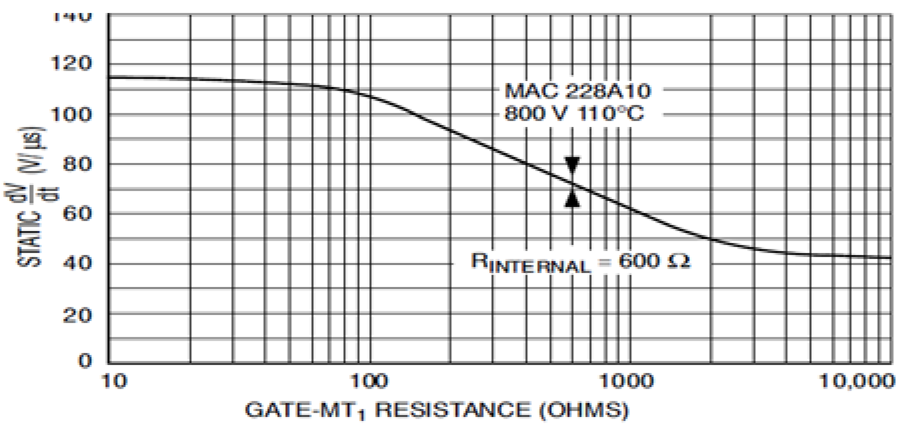


Figure 40: Exponential $(dV/dt)_s$ versus Gate to MT1 resistance [22]

3.1.3 TRIAC commutation

The commutating dV/dt ratings $-(\frac{dV}{dt})_C$ and $(\frac{dI}{dt})_C$ ratings apply when a triac has been conducting and attempts to turn-off with an inductive load. Figure 41 shows an example of these commutation ratings in case of inductive load. In general these commutation ratings are more important when triac is used in switching applications with mains frequency and with inductive load. Accordingly to improve the commutation $(\frac{dV}{dt})_C$ so as to limit rate of rise of commutating voltage during turn-off, dv/dt limiting R-C snubbers are used in parallel with the triac [22] [25].

However with new technology, we can operate triacs without snubber circuits [24]due to the problems associated with using snubbers. Moreover since this design project is to design hybrid relay system for TLED, which runs on high frequency and voltage from HF ballast, the primary function of triac is to block these high dV/dt signals, the commutation problems are not important .Since commutation problems are associated with switching triac with mains voltage and frequency (low) and inductive load, where as in TLED triac have to deal only with its blocking capability and its operated with almost resistive load (LED load).

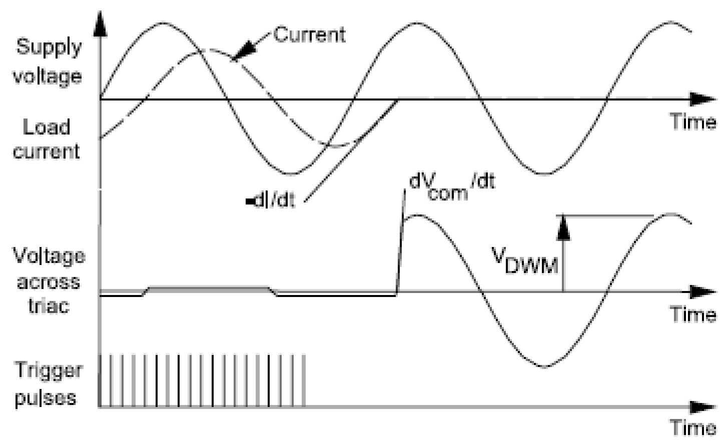


Figure 41: Inductive load commutation with triac [19]

3.1.4 Static (dV/dt) tests on few samples of TRIACs

3.1.4.1 Test setup with combination of high frequency signal generator and high power amplifier

Using triac to switch mains voltage (AC load) is very common in many design circuits. But using triac as a safety switch to block high frequency and high voltage is very uncommon. The main issue related to this new type of application of triac for high frequency is its static dV/dt capability. Hence to test triac for its blocking capability when HF ballast applies a high frequency and voltage signal, a test was performed on 5 different triac samples which are available in the market. The test setup and results are discussed in this section. To test for static dV/dt blocking ability of given samples, a test circuit was designed as shown in Figure 42:

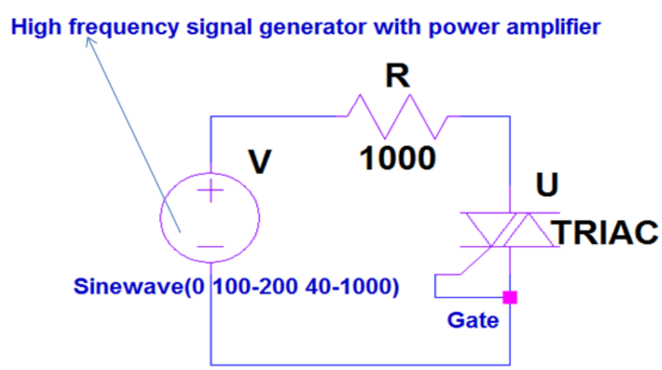


Figure 42: Experimental test circuit up for testing static dV/dt.

Table 3: TRIAC switch samples categorized (named)

Switch type	Switch name
ACTT2X800E(800V)	Switch A
ACST830-8FP(800V)	Switch B
BTA204-800C(800V)	Switch C
ACT108-600DTo92(600V)	Switch D
ACT108600DS0T223(600V)	Switch E
ACT108W600ESoT223(600V)	Switch F

In this experimental set up, to generate a high frequency signal, signal generator is used. To produce high voltage (100-200V) from high frequency signal a power amplifier is used. For electrical safety during experiment, an isolation transformer is built and connected between mains and power amplifier to isolate mains from the circuit. Experimental test setup is built as shown in Figure 43. The triac gate terminal is connected to ground to eliminate any influence of external leakage current to be injected in to the gate terminal and that can lead to false triggering of triac as discussed in (3.1.2).To make testing procedure easy each triac sample is assigned a name starting from a,b,c,d,e ,f as shown in Table 3.These samples are selected from most common manufactures and cost of each sample type was analyzed, after that cheap and most reliable samples with high voltage and static dV/dt were ordered. The triac sample types, ratings were listed in Table 4.

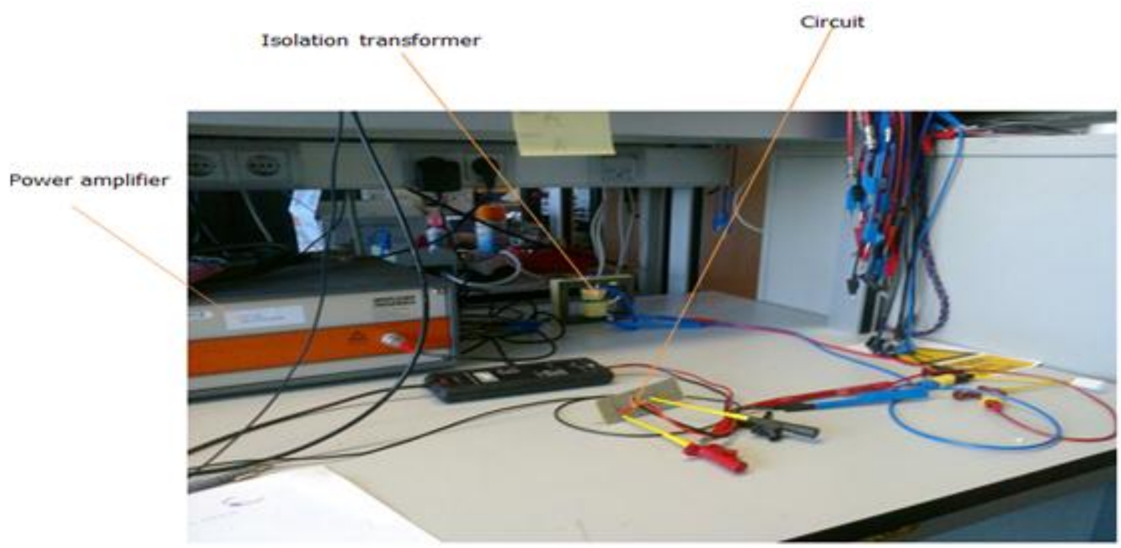


Figure 43: Experimental test setup in lab for testing static dV/dt capability of TRIAC switch samples.

In lab maximum of only (100-200) V power supply equipment's are available for testing purpose. And also due to safety issues higher voltage supply (>200V) are not allowed to test in the Philips lab. Hence by applying (100-200) V on triac samples with high frequency signal generator ([40-3000] kHz) dV/dt tests are performed.

Table 4: TRIAC switch types and ratings

Switch type	I-load(A)	VDM(V)	dV/dt Static-given(v/µs)	Insulation max(v)	Calculated max frequency (KHz)that can be applied at 100V
ACST830-(8FP)	8	800	2000	1500	3180
ACTT2X800E	4	800	500	1500	796
BTA204-(800C)	4	800	1000	1500	1590
ACT108-600D(T092)	0,8	600	300	2000	470
ACT108600D(S0T223)	0,8	600	300	2000	470
ACT108W600E(SOT223)	0,8	600	1000	2000	1500

. To calculate dV/dt applied on triac, we can use the equation 6.

$$\frac{dV}{dt} = \sqrt{2} * V_{rms} * 2 * \pi * f \tag{6}$$

Where f is the frequency of signal applied.

Since the rated static dV/dt values are given in data sheet, using this value and equation 6 we can calculate the maximum frequency that can be applied on triac is calculated as shown in Table 4, without triggering it due to false turn-on effect.

3.1.4.1.1 Test results and observations

Figure 44 shows few dV/dt test results, performed in lab. The observation from the test results are as follows:

1. All the five triac switch samples tested found to have decreased voltage drop across them, when 100V sinewave (AC) voltage is applied across it with increasing frequency in steps. This indicates that triac is influenced by false turn on.

2. 600V rated switches- started conducting at a frequency 2000 KHz. The dV/dt capability measured during test at-(2000 KHz, 100V) is found to be 1776V/µs, which is above the rated value given in data sheet. Hence these devices show good blocking capability than the rated values as in data sheet with this experiment.

3. Two of the 800V rated switches (ACST830, BTA204800C)-able to block high [dV/dt] till 2500 KHz which is very interesting property of switch samples tested at 100V, and hence its dV/dt measured during testing is 2200V/µs, which is above the rated value of 2000V/µs and 1000V/µs respectively of ACST830 and BTA204800C Switch as in data sheet and are better than 600V rated switches.

4. When tested with 200V by using power amplifier and high frequency signal generator combination, the frequency at which triac starts loosing blocking capability is lower compared to the test done at 100V.Hence by assuming this kind of typical behavior shown by triac at different frequencies and different voltages and also using equation 6, we are not really sure of its behavior at typical voltage and frequency profiles for warm start(1000V,(40-100)kHz) and cold start(1.5kV,(40-60)kHz).

Hence by the above experiment, it’s not sure, whether triac can block High dV/dt –high frequency and high voltage signal from HF ballast. Hence next step in the project is to design a test circuit with actual HF ballast.

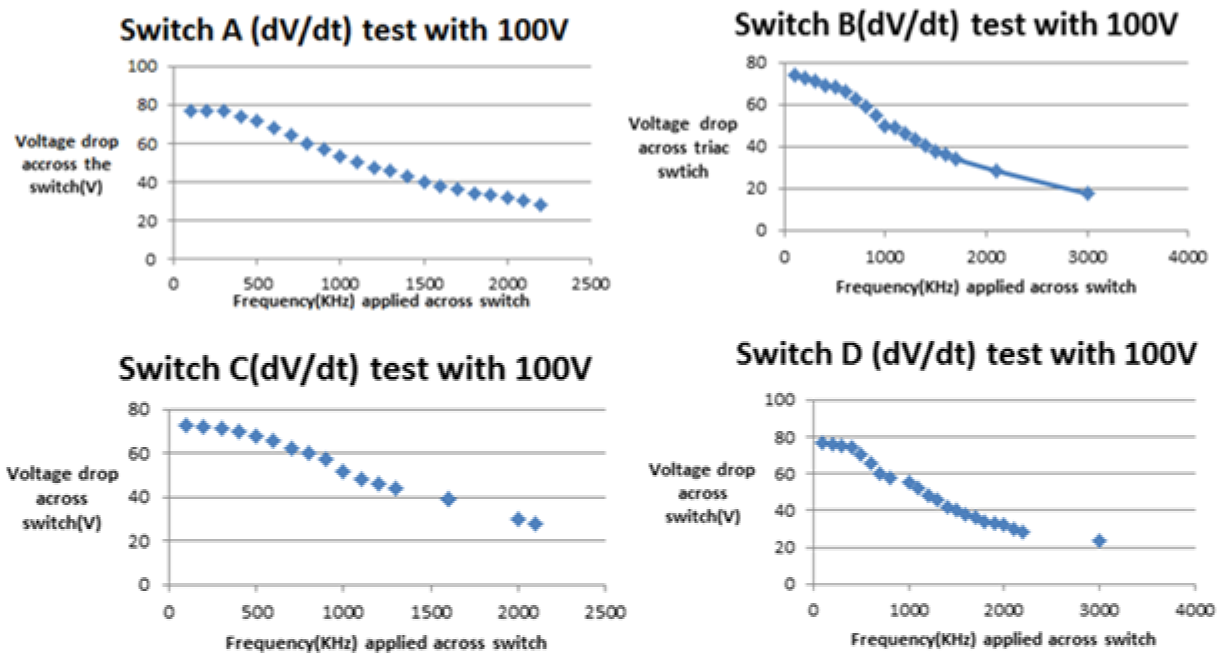


Figure 44: dV/dt test with switch samples

3.1.4.2 Design test circuit with HF ballast

To test with actual HF ballast, a test circuit was designed as shown in Figure 45.Table 5 Shows the type of triac switches tested and there ratings.

Table 5: Switch types and their ratings

Switch type	dV/dt rated(V/µs)	Voltage(V) -rated	Current-Rms-rated(A)
BTA204-800C	1000	800	4
ACTT2X-800E	500	800	2
ACST830-8FP	2000	800	8

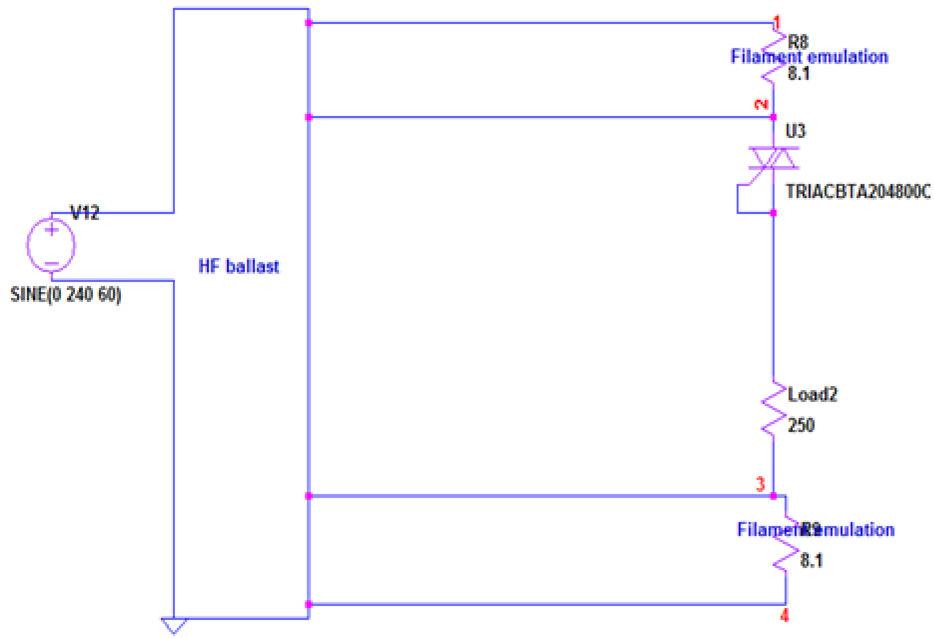


Figure 45: dV/dt capability test circuit with HF ballasts.

3.1.4.2.1 Test results with HF ballast

Table 13 (appendix D) shows the specifications of the ballasts tested. Table 14 shows full results of testing for high voltage blocking capability of three different triac switches, when tested with different HF ballasts-warm and cold. Some of the results of this test are shown in Table 6. Warm start ballasts have a preheat stage and hence to ignite the lamp it provides a lower voltage across the electrodes compared to cold start ballasts .Where as cold start ballast doesn't have preheat stage and hence to ignite the lamp it provides high voltage across the electrodes. During the test voltage and current waveforms are captured in oscilloscope, some of them are shown in Figure 46,Figure 47,Figure 48,Figure 49.This figures shows the voltage across the triac switch and leakage current flowing through the switch due to dV/dt false turn-on effect and other circuit leakage currents.

Table 6: Test results with different HF ballasts

Ballast type	BTA204-800C	ACTT2X-800E	ACST830-8FP
HF-E 158 TL-D(9137130389)	✗	✗	✓
QTP81*58	✓	✓	✓
HF-S 158 TLD-II(9137130322)	✓	✓	✓
QTP-OPTIMAL	✓	✓	✓
TRIDONIC(1*58 T8 PRO lp)	✗	✗	✗
VS(VOSSLOH SCHWABE)-ELXE-258.222	✗	✗	✗
HF-BASIC-II(HF-B 158 TLD EII 220-240)	✗	✗	✗
HF-BASIC-II(HF-B 258 TLD EII 220-240	✗	✗	✗

Where,

✓ indicates that triac is able to block the signal from HF ballast

✗ indicates that triac is unable to block the signal from HF due to false turn on effect (miller effect).

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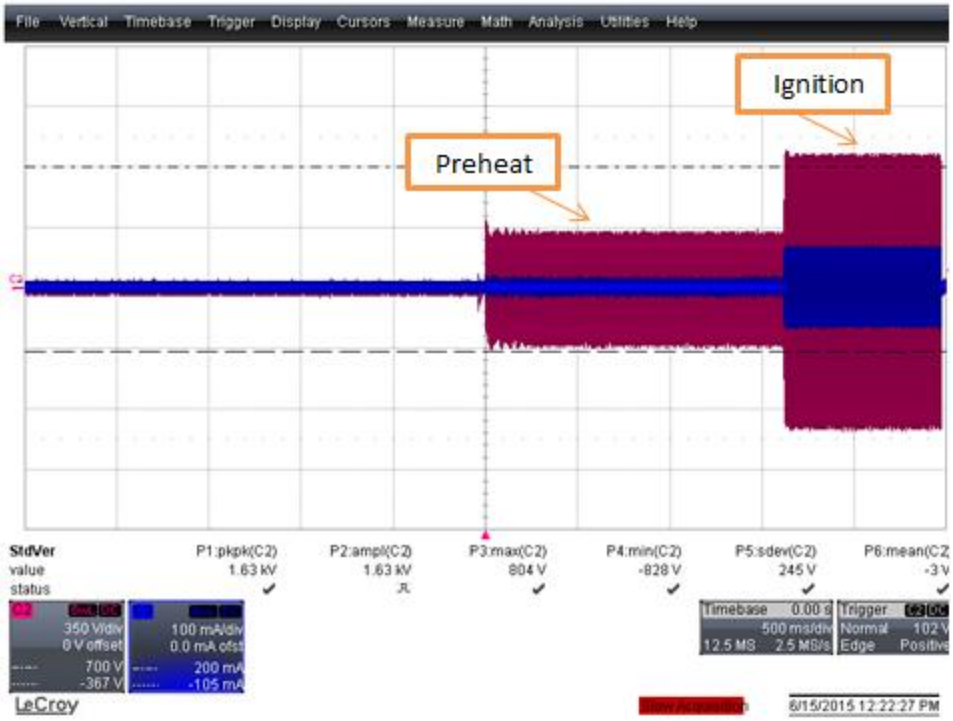


Figure 46 : Voltage (pink) and leakage current (blue) waveforms captured during tests on BTA204800C with QTP8-OSRAM ballast

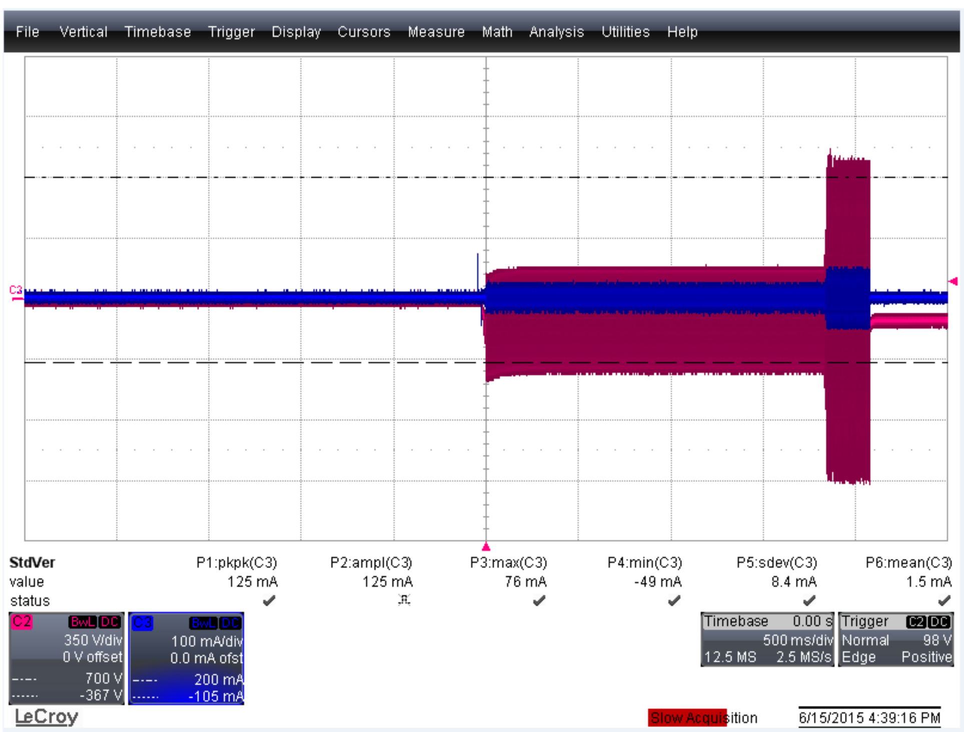


Figure 47: Voltage (pink) and leakage current (blue) waveforms captured during tests on ACST830-8FP with HF-E 158 TL-D.

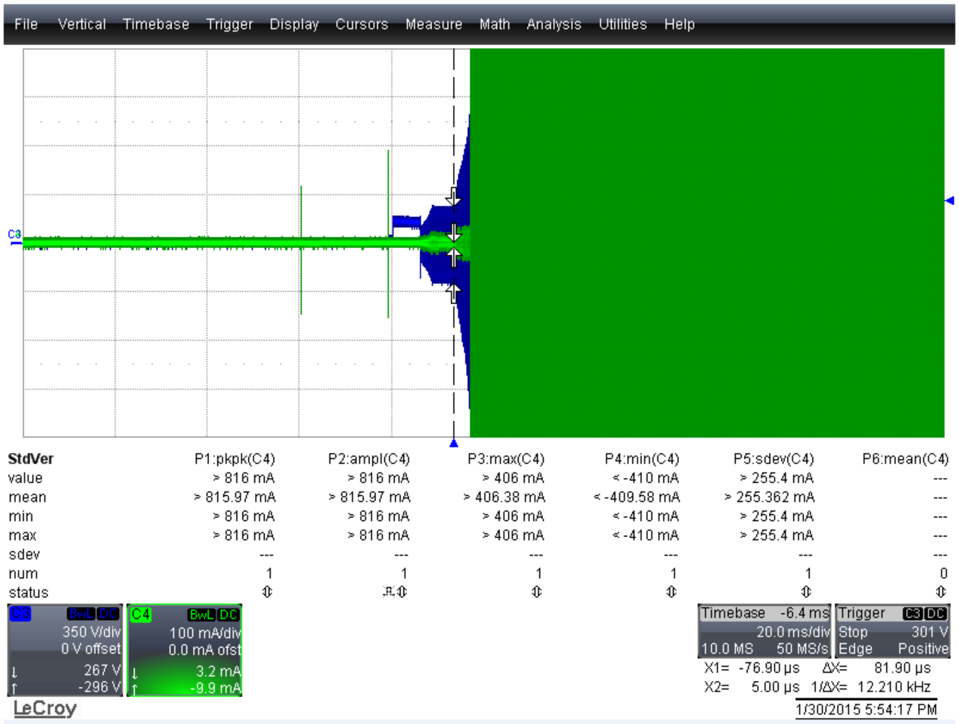


Figure 48: Voltage (blue) and leakage current (green) waveforms captured during tests on BTA204800C with HF basic-II (158)

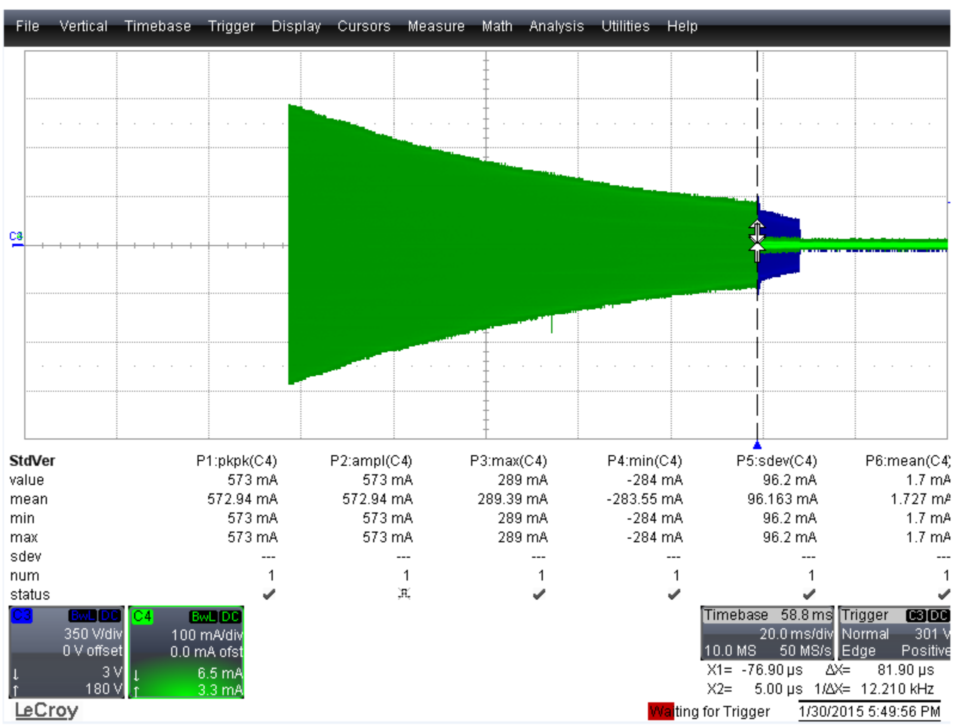


Figure 49: Voltage (blue) and leakage current (green) waveforms captured during tests on BTA204800C with VS ELXE-258.222.

3.1.4.2.1.1 *Conclusions from the test results*

- Single triac (800V) (BTA204800C, ACST8308FP, ACTT2X-800E) can block high dV/dt from only few of the warm start ballasts (refer Table 6, Figure 46,Figure 47), Since the leakage current flowing through the switch during application of high dV/dt signal from few warm start HF ballasts are very less < 50mA.Hence these triacs are not much influenced by false turn-on effects due to these few warn start ballasts.
- However these triacs cannot block high dV/dt from most of the warm start ballasts and also cold start ballasts .This is because the leakage current flowing through the switch during application of high dV/dt from HF ballasts are very high>200mA (refer Figure 48,Figure 49).Hence triacs are very much influenced by false turn-on effects due to high dV/dt effects from most of the warm start and cold start ballasts.

Hence after carefully analyzing to solve this problem and referring few literatures [21], proposed an idea to connect two triac switches in series with each other for increasing the blocking capability (800V to 1600V) and static dV/dt capability. Next section deals briefly about the testing circuit with two series connected triacs with HF ballast for blocking high dV/dt from all the warm and cold start ballasts.

3.1.4.3 Test circuit design using two TRIACs in series with HF ballast

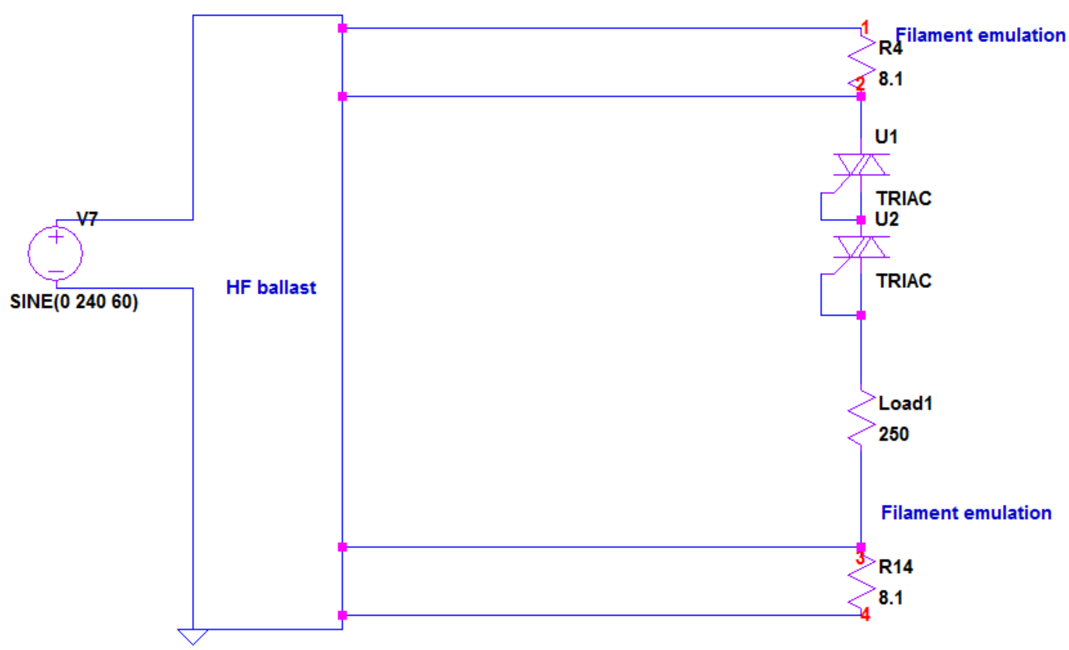


Figure 50: Test circuit with two TRIACs in series with HF ballast.

Figure 50 shows the design circuit for testing series connected triacs with HF ballast. Table 14 shows the full results of this test. Table 7 shows few of the results of the test. Some of the graphs captured in oscilloscope are shown in Figure 51, Figure 52,Figure 53.

Table 7: Results with two TRIACs in series with HF ballasts (cold and warm)

Ballast type	BTA204-800C	ACTT2X-800E	ACST830-8FP
HF-E 158 TL-D(9137130389)	✓	✓	✓
QTP81*58	✓	✓	✓
HF-S 158 TLD-II(9137130322)	✓	✓	✓
QTP-OPTIMAL	✓	✓	✓
TRIDONIC(1*58 T8 PRO lp)	✓	✓	✓
VS(VOSSLOH SCHWABE)-ELXE-258.222	✓	✓	✓
HF-BASIC-II(HF-B 158 TLD EII 220-240)	✓	✓	✓
HF-BASIC-II(HF-B 258 TLD EII 220-240	✓	✓	✓

Where,

✓ indicates that two triacs operated in series is able to block the signal from HF ballast

✗ indicates that two triacs operated in series is unable to block the signal from HF due to false turn on effect (miller effect).

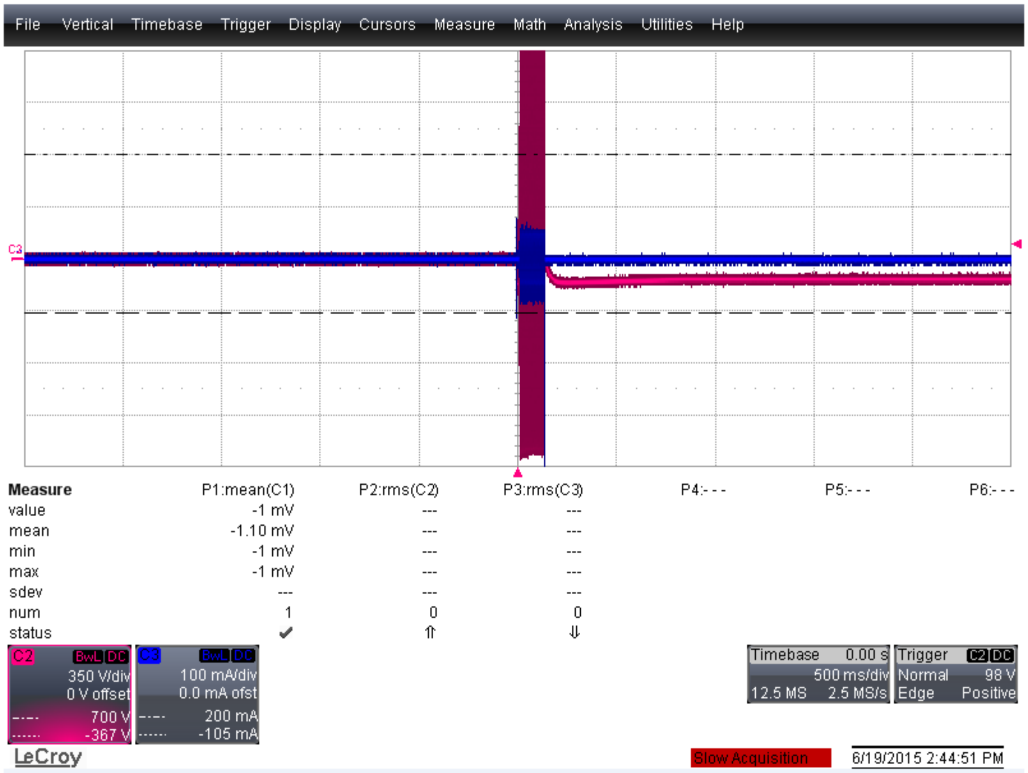


Figure 51: Voltage (pink) and leakage current (blue) waveforms captured in oscilloscope during testing of two series connected triacs(ACST830-8FP) with HF basic-II ballast

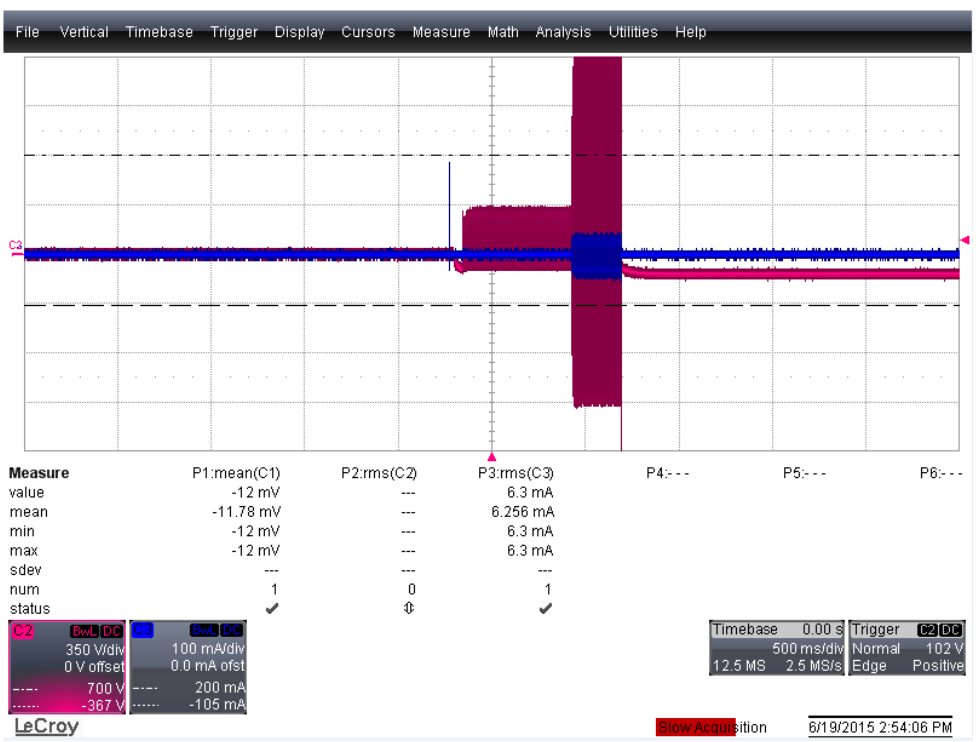


Figure 52: Voltage (pink) and leakage current (blue) waveforms captured in oscilloscope during testing of two series connected triacs(ACST830-8FP) with HF-Perfomer-HFP158.

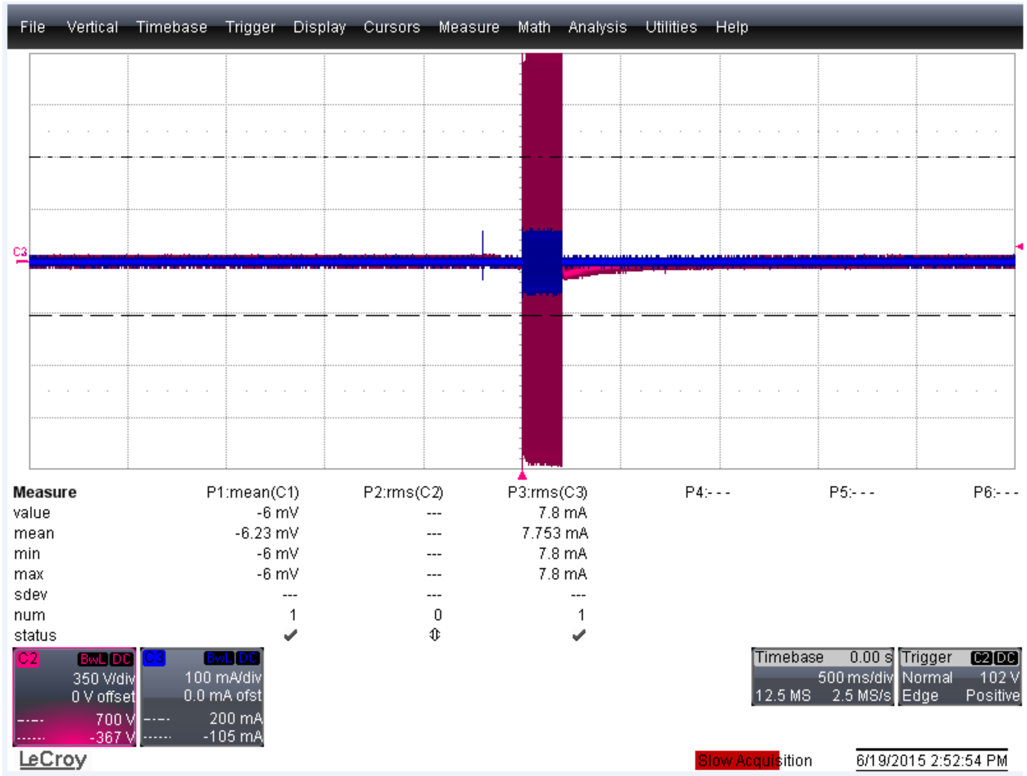


Figure 53: Voltage (Pink) and leakage current (blue) waveforms captured in oscilloscope during testing of two series connected triacs(ACST830-8FP) with VS Elxe 258.222 ballast.

3.1.4.3.1 Conclusion of the experimental results with two triacs in series

As seen from above table and figure, it is very clear that by connecting two triacs in series ,the voltage blocking capability and static dV/dt capability of triacs combination increased and hence able to block high dV/dt from all both cold start and warm start ballasts. This is because, the leakage current flowing through two triacs in series combination is very less than <30 mA, which proves that the series combination are not much influenced by false turn-on effect and hence series combination has improved static dV/dt capability. From the results observed during these tests for static dV/dt and also results of the thermal tests discussed in chapter 2, it is concluded that BTA204800C and ACST8308FP are the best possible high voltage triacs that can be used in design project.

Hence next phase in the project is to design triggering circuits for triggering series connected triacs. Next chapter is about design process discussed in detailed.

Chapter 4: Design and Testing

4 Chapter 4: Design and Testing

From the previous chapter 3, we discussed about the TRIAC and its application as a safety switch in TLED. From the previous chapter, it is also very clear that single TRIAC cannot block high dV/dt from most of the warm start and cold start ballast. Hence to block high dV/dt from both cold and warm start ballasts, two TRIACs in series are necessary. In this chapter first section deals with the design and testing aspects of driving two TRIACs in series, and next design and testing process for integrating this hybrid relay system with TLED is discussed.

4.1 Design approach:

The design approach followed for designing circuits and testing were shown below in figure:

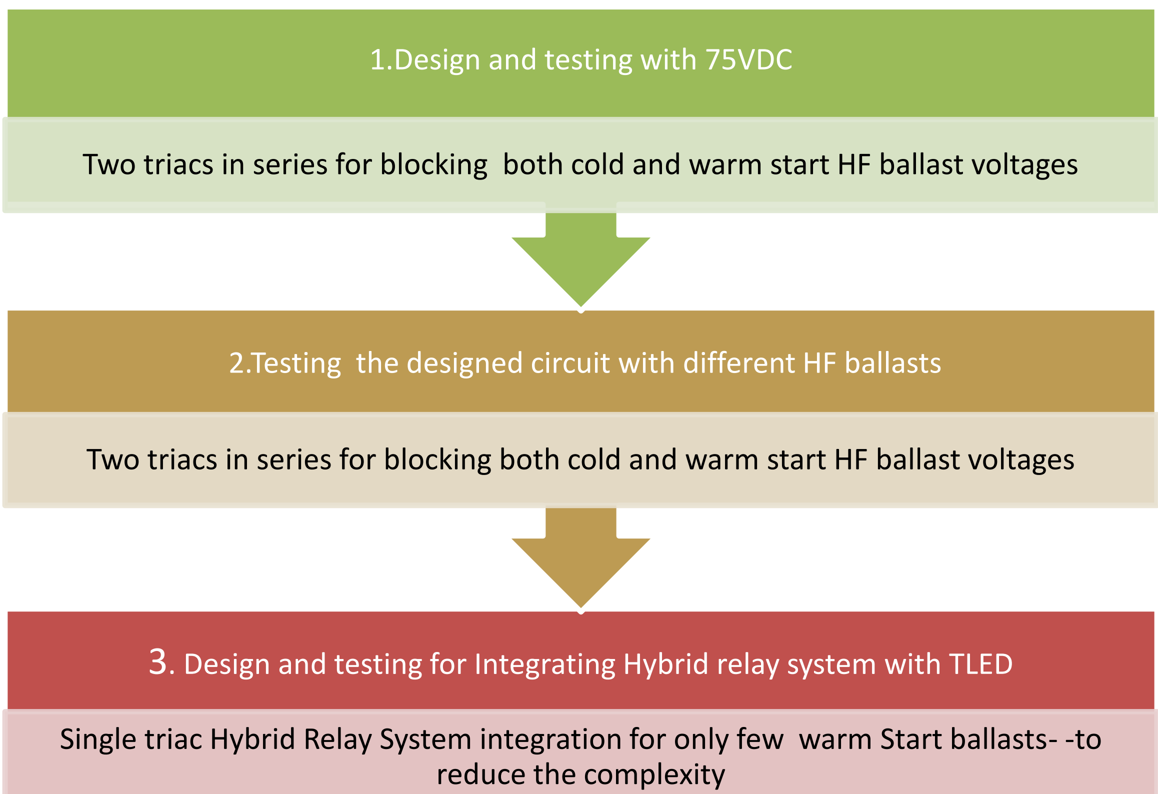


Figure 54: Design approach for Hybrid safety relay system

From the above figure, it's clear that design approach has 3 steps.

- The first step is to design and testing of two triacs systems with 75VDC: The first circuit was designed using only 75VDC, for making circuit design and testing process simple and easy to understand, rather than testing directly on HF ballast which is complex to understand its different frequency and voltage characteristics varying with time. This circuit designed with two triacs in series was mainly to block most of the warm and cold start HF ballast voltages. Since single triacs is only enough for blocking HF signals from few warm start ballasts, hence this circuit gives the intended functionality for both warm and cold start ballasts.
- The second step is to test the designed circuit with different HF ballasts. The results were analyzed to check for the intended functionality.
- The third step is to integrate the designed hybrid relay system with the present TLED relay board. After studying the present safety relay solution of TLED, understanding and analyzing the present relay board architecture of TLED for integrating two triacs system for most of the cold and warm start ballasts, realized the level of Complexity of problems to be solved in order to integrate this solution with TLED, keeping in mind of the time limitations of the project. Hence to reduce the complexity, Hybrid safety relay system consisting of only single triacs and one electromechanical relay was designed for few warm start ballasts. Since warm start ballasts share a huge percentage of share in present EMEA (Europe, the Middle East, Africa) market for fluorescent lighting compared to cold start ballast, it's very essential to design and test a model for integrating Hybrid relay system for at least few warm start ballasts .And then, proceed with two triacs system integration to TLED in future, for further research on this project.

4.2 Driving two TRIACS in Series operation

As discussed in chapter 3, driving two triacs in series is necessary for blocking high frequency and high voltage signals from both cold start and warm ballasts. However driving two triacs in series is very rare in engineering practice due to various design requirements .Next section deals with principles involved in driving two triacs in series for higher blocking capability.

4.2.1 Driving two TRIAC switch in series for blocking high voltages

For increasing high voltage blocking capability of triacs switch, two of them are connected in series, each of them is 800V rated switch, such that total blocking capability of this combination is 1600V. For studying the design requirements for driving two triacs in series, a literature survey was performed and only few application notes were found. One of the most important references was [21] [27] .From [21] a brief overview can be made discussed below:

The advantages of series operation include:

- Higher blocking voltage
- Reduced leakage
- Better thermal stability
- Higher dV/dt capability, reduced snubber costs, possible snubberless operation.

An example of series triac operation is given in Figure 55: Series operation of two triacs. Wherein, in this circuit the first (top) triac is triggered in quadrant 1 and second (bottom) triac in quadrant 3. When the optocoupler is turned on, gate current(I_G)flows in to both triacs through a gate resistor(R_G).

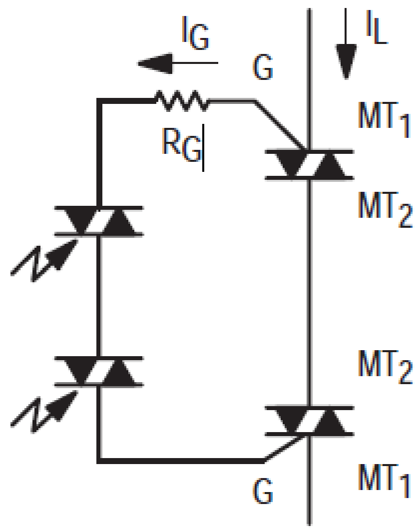


Figure 55: Series operation of two triacs [21].

When operating two triacs in series, the following major issues and problems need to be understood-Static voltage sharing and dynamic voltage sharing. Next section details more about these two concepts.

4.2.1.1 Static voltage sharing

When SCR(Thyristor) or TRIAC s of identical ratings are connected in series , variations in their forward blocking and reverse blocking voltages characteristics causes unequal distribution of voltage in steady state. This is called unequal voltage sharing in static condition. The main reason for this unequal sharing of voltage is due to unequal leakage resistances of each TRIAC/SCR. When voltage applied on the each device is divided by its leakage current, leakage resistance is obtained for each device. It can range from 200 kohm to 2000 mega ohm depending upon device characteristics, temperature, and applied voltage.

An example of how leakage current of each device sample effects the total voltage blocking capability of two triacs connected in series can be seen in the Figure 56: Leakage matching versus temperature .In this example two triacs of each 600V rated are connected in series.

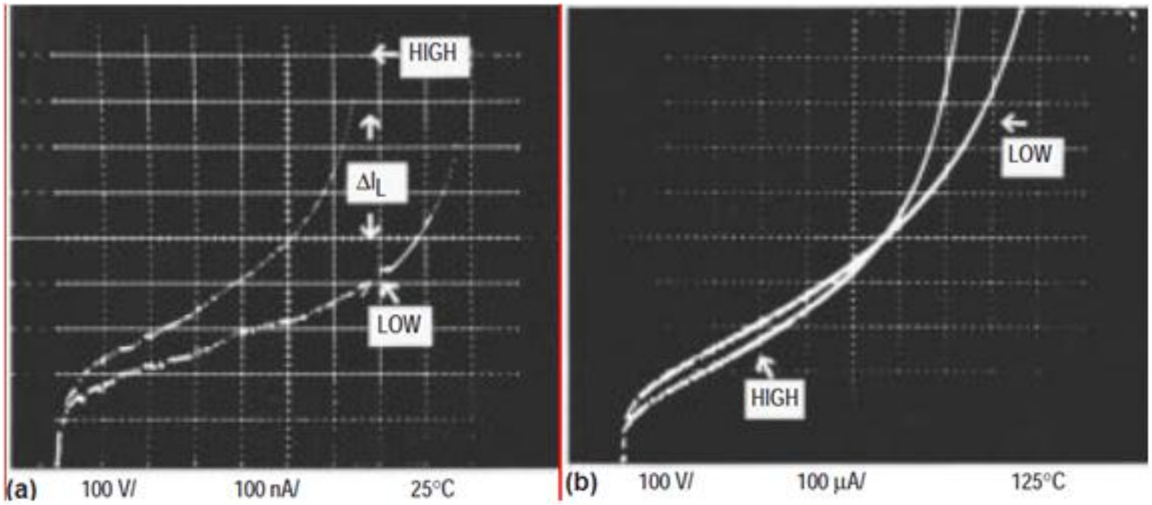


Figure 56: Leakage matching versus temperature [21]

From the above Figure 56(a), it shows the highest and lowest leakage units from a sample of 100 units. At room temperature, a leakage of 350nA results at total applied voltage of 920 Volts. The lowest leakage units block at the maximum of specified value of 600 Volts, while the highest blocks only 320 Volts. Figure 56(b), it is shown that the same two triacs operated at T_{Jmax}. In this the magnitude of their leakage increased by an almost factor of 1000, but the matching of leakage currents improved a lot allowing the operation to 1100 Volts without exceeding the 600 V rating of either device.

The most important conclusions from the above experimental results are as follows:

- Identical case temperatures are necessary to achieve good matching of their leakages.
- Operating two triacs in series improves thermal stability.
- When two triacs are having matching leakage currents (resistances),each triac sees half the voltage and current .
- *"The additional voltage margin resulting from the higher total blocking voltage reduces the chance that either device will operate near its breakdown voltage where the leakage current increases rapidly with small increments in voltage. Higher voltage devices have lower leakage currents when operated near breakdown. Consequently, the highest break over voltage unit in the pair will carry the greatest proportion of the burden*" [21].

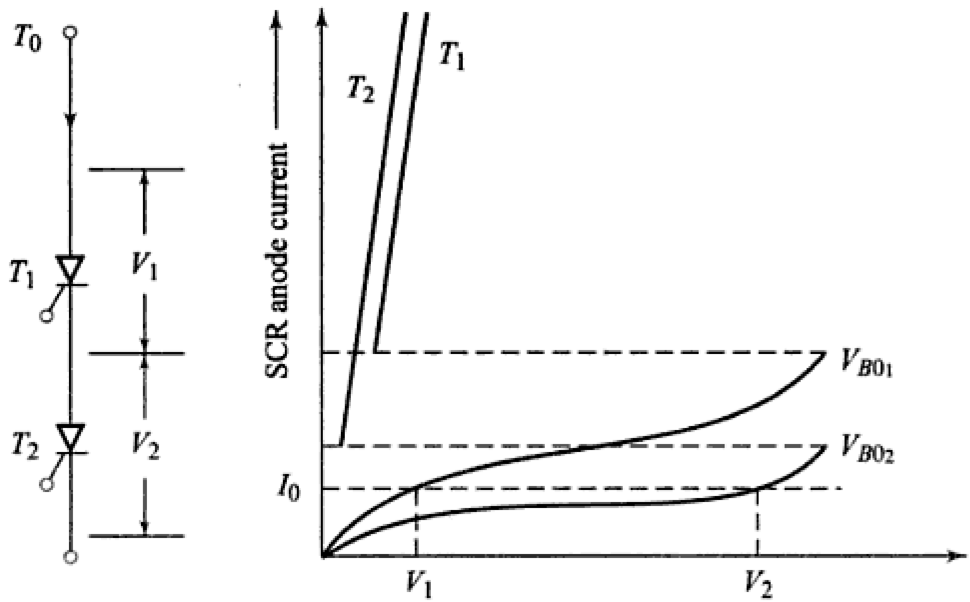


Figure 57: Distribution of voltage between two series connected SCRs [27]

Figure 57 shows the typical voltage sharing profile between two series connected SCRs. Since TRIAC is like a two SCRs connected back to back, TRIAC voltage sharing profile also looks almost same. Here T1, T2 corresponds to top and bottom placed SCR respectively. VBO_1 ,VBO_2 are the forward break over voltages for SCR T1 and SCR T2 respectively .leakage resistance of SCR T1=$\frac{V1}{I_O}$ and for SCR T2=$\frac{V2}{I_O}$. Where leakage resistance of T1 is lesser than T2.For net I_O leakage current from both of the SCRs, T2 supports a rated voltage V2 ,which is almost near the break over voltage ,whereas T1 supports a very less voltage V1 compared to its rated voltage. Hence by this discussion, it shows that ,the SCR/TRIAC with higher leakage resistance supports higher voltage compared to the one which has lower leakage resistance.

To enforce equal voltage sharing in steady state, equal leakage resistances of each TRIAC/SCR placed in series have to be ensured. For this one of the method is to have an ideal case temperatures, heat sink is necessary. But in the present project use of heat sink is very expensive and it requires a tedious thermal analysis. Hence in the present project using heat sink is not a good idea to provide equal voltage sharing in steady state. However an effective way to realize the equal voltage sharing concept in the project is to use identical value parallel resistors across each triac that will prevent breakdown resulting from mismatched leakages. This method is further described in detail in next section of this chapter.

4.2.1.2 Dynamic voltage sharing:

Unequal voltage sharing in series connected SCR/TRIAC also occurs during transient periods of turn -on and turn- off and also during high frequency operation. A SCR that has higher turn on time in the series string network will momentarily take up the full string voltage. One of the methods to reduce unequal voltage distributions during transient condition due to unequal turn-on delay times is to drive a SCR/TRIAC with agate signal which has faster rise-time. If one of the SCR has shortest reverse- recovery times in a string, then this SCR has to support full reverse string voltage. The unbalanced voltage sharing resulting from different reverse recovery times of SCRs in string are shown in Figure 58.In this SCR T1 has shortest reverse- recovery time compared to T2.Hence T1 supports the whole string voltage for a while till the T2 has recovered. Here ΔQ is the difference in reverse recovery charges of two SCRs. During turn-off, the capacitance of the reverse biased junction [Self capacitance] determines the voltage sharing profile in a series connected SCR/TRIAC string. Since Self capacitance of each SCR is different and vary for each device, voltage sharing during turn-on and turn off are different. One of the general method to reduce the unequal voltage sharing profile during turn-on, turn-off period is to use a connect capacitor parallel to each SCR/TRIAC in a series connected string. The details of how it's connected are discussed in next section.

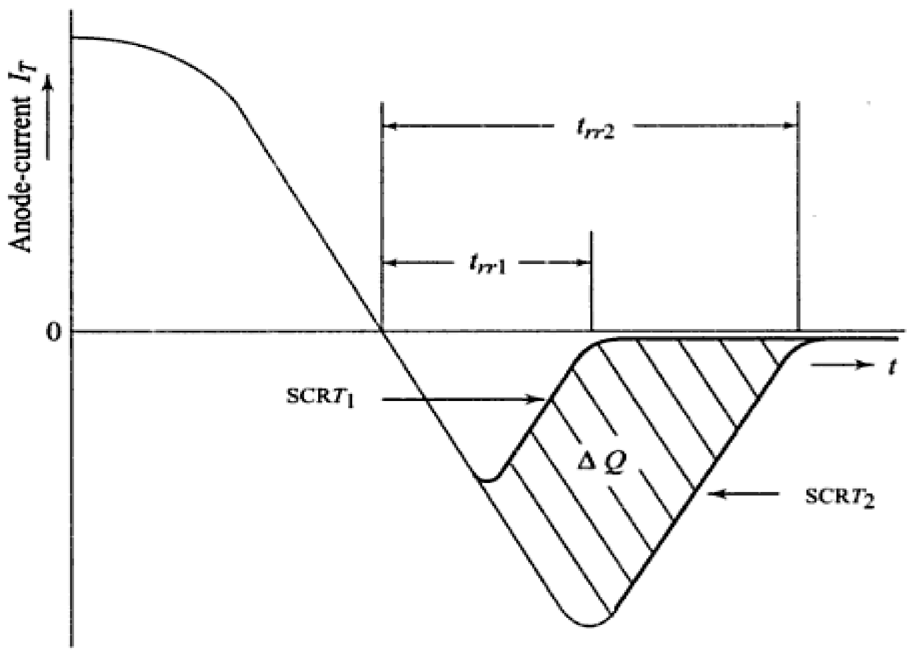


Figure 58: Reverse recovery currents of two SCRs of same type [27]

4.2.1.3 Ensuring equal voltage sharing during steady state and transient period

To ensure both static and dynamic voltage sharing in a series connected SCR/TRIAC string, a special network of resistors and capacitors should be connected in parallel to each device in the string as shown in the Figure 59. For ensuring equal voltage distribution during steady state (static), an external resistance R is connected in parallel with each SCR, so as to make the parallel combination have the same resistance values. This resistance R is called the static equalizing circuit, where same R is connected across each SCR rather than connecting different values of R.

For ensuring dynamic voltage sharing, a shunt capacitor is connected across each SCR. This capacitor equalizes the differences in self capacitances of SCR during turn-off, by making the resultant of self-capacitance and shunt capacitance in a string equal. When SCR is in the blocking state, this capacitor charges to the voltage level that is applied on the SCR .During turn-on, this capacitor discharges a large amount of current through this SCR, hence to limit the current magnitude during this time a damping resistor R_C is used in series with the capacitor. To charge the capacitor effectively during turn-off period (forward voltage applied) a diode D is used in parallel to R_C .Hence the combination network consisting of C,R_C ,D is called the dynamic equalizing circuit. This circuit is also used to control dV/dt across SCR/TRIAC. The design methods for selecting static and dynamic equalizing circuit are detailed in references [21], [27].

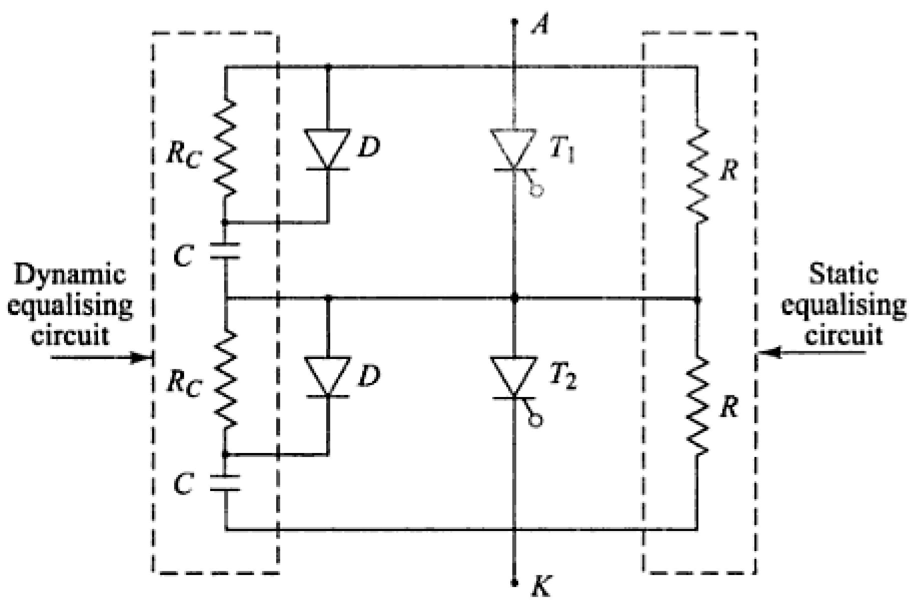


Figure 59: Equalizing circuit network for series operation [27]

4.2.2 Triggering of series connected TRIAC/SCR:

This section gives a brief overview of methods to trigger series connected SCR/TRIAC. For exploring the ways to trigger the TRIAC/SCR in series few application notes from industry [28] and [27].

The main important aspect that needs to be considered ,while triggering series connected SCR/TRIAC devices is to make sure that all the series connected devices are triggered at same instant and not even few micro seconds delay gate triggering pulse between them. To make this possible generally, single pulse generating source is used for triggering all devices. In most of the cases when there is a requirement of high voltage isolation from gate circuit and high voltage side, isolation transformers or gate driver transformers are used.

While operating SCRs in series, the following points needed attention for triggering system:

1. All the SCRs should act as one: This indicates that if one of the SCR in the string is not triggered at expected time, the full circuit will be over stressed and can lead to breakdown and as result circuit fails.
2. While operating series connected string of SCRs, each SCR will be at different voltage levels with respective earth and hence high voltage insulation is necessary between gate triggering circuits. This requires a more complex design of gate drive transformer, since more isolation means slower rate of rise of gate pulse to SCR, which will finally effect the dynamic voltage sharing. Hence to solve this issue, an optically isolated triggering pulse system can be used instead of gate drive transformer. But in case of optically isolated gate triggering system, only small amount of energy can be passed to the gate through isolation gap which is not sufficient to trigger a high voltage SCR/TRIAC series connected string system.

There are primarily three common methods to trigger series connected SCRs, they are:

1. Simultaneous triggering.
2. Sequential triggering.
3. Optical triggering.

4.2.2.1 Simultaneous triggering

Figure 60 shows one of the methods to trigger SCRs simultaneously and independently using a multiple winding gate pulse (gate drive) transformer.

In general for triggering two SCRs in series connected string, with one primary winding and two secondary winding transformers.in this method, the main triggering pulse is applied on the primary and each of secondary windings are connected to the respective gate terminals of SCRs in a series connected string. To trigger SCRs with equal gate current, a gate resistor R_g has been added. A typical example of triggering simultaneously is shown in Figure 61.

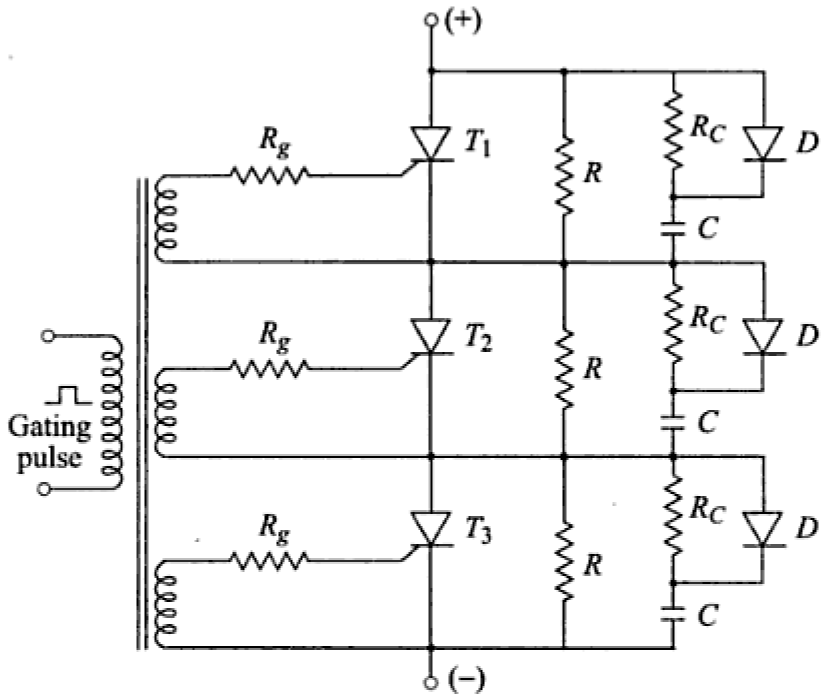


Figure 60: Simultaneous triggering [27]

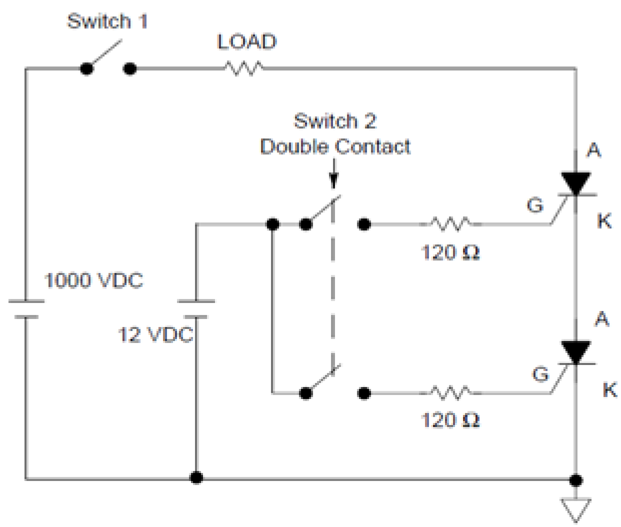


Figure 61: Typical example of simultaneous triggering [28]

4.2.2.2 Sequential triggering

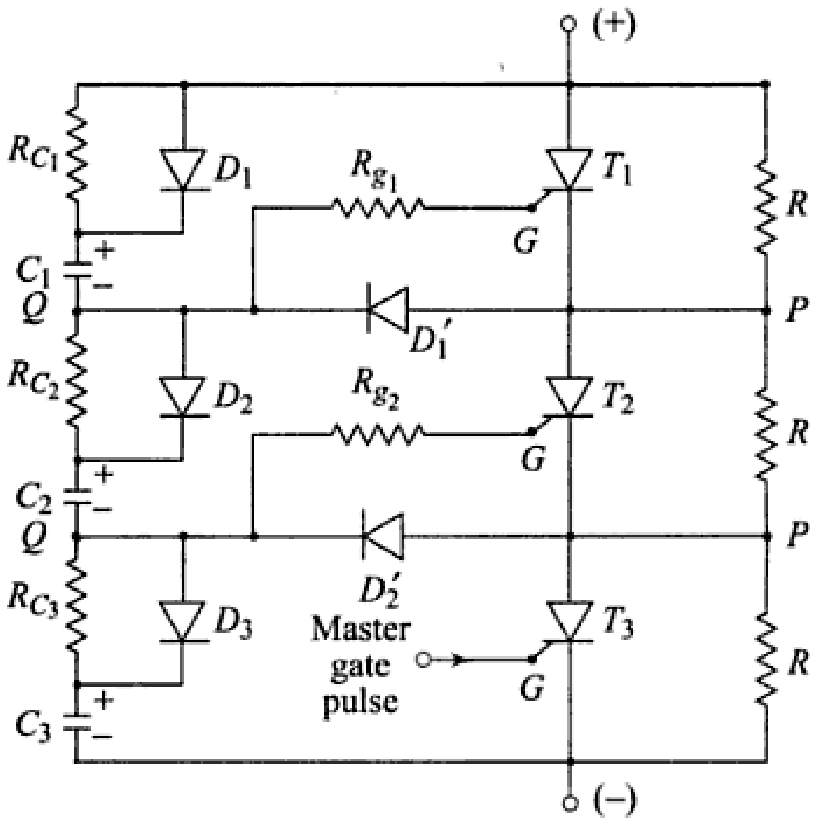


Figure 62: Sequential triggering [27]

Figure 62 shows the circuit for sequential triggering. In this method, first a "master "SCR is triggered, and then when forward –blocking voltage of this master SCR begins to reduce (turn-on), as a result a gate signal is applied to the "slave" SCR at this time. Hence this method of triggering is called sequential triggering and it is not independently triggered.

4.2.2.3 Optical triggering

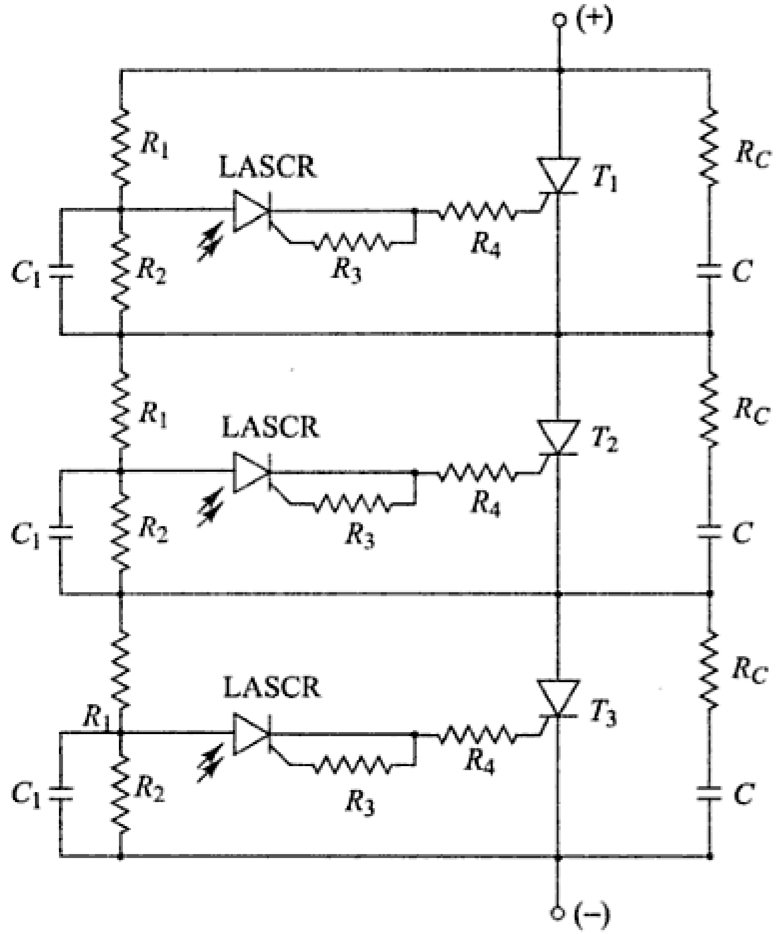


Figure 63: Optical triggering [27]

Figure 63 shows a method of triggering series connected SCRs optically using a light activated silicon controlled rectifier (LASCR).This is also one of the method of simultaneous triggering since, all the gate circuits are triggered at same time via single light source triggering all LASCR at same time. This optical triggering also provides necessary isolation between gate circuit and high voltage, but this cannot be used to transfer large amount of power across the gate circuits.

Hence by the above discussion, most common methods of triggering series connected SCR/TRIAC devices are explored.

4.3 Testing for static and dynamic voltage sharing when two TRIACs are operated in series

After studying the problems associated with operating two triacs in series, it is clear that static and dynamic voltage sharing are important effects to be considered. This section deals with the testing of triacs in lab in order to test for both these effects.

After exploring the ways of triggering TRIACS in series from previous section, many possible topologies for simultaneous triggering using gate drive transformer were studied that is suitable for hybrid relay system for TLED.

4.3.1 Testing for static voltage sharing

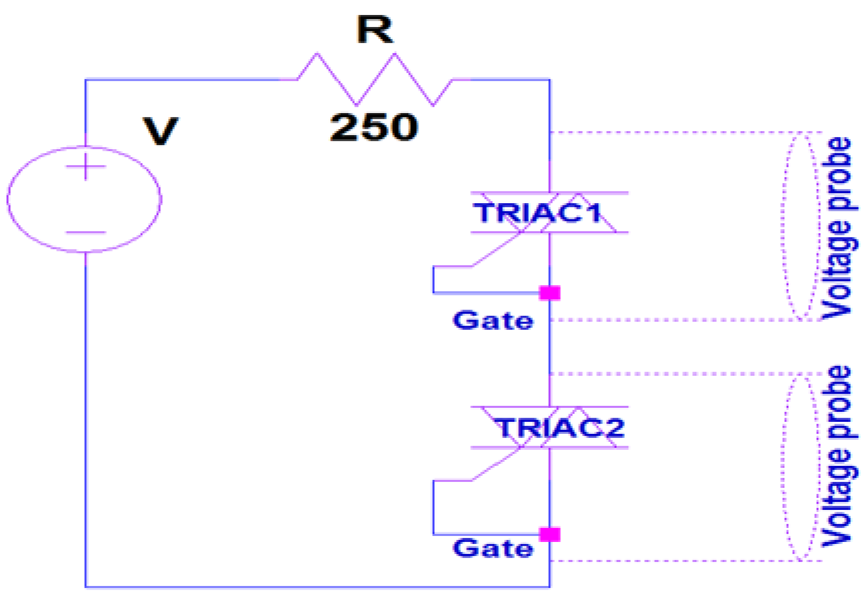


Figure 64: Testing circuit for static voltage sharing

Figure 64 shows the schematic of a test circuit built in hardware for testing the static voltage sharing of TRIACS in series operation. First 75VDC is applied across two triacs(800V rated-ACST830FP) in series as shown in figure, where both the triac gates are shorted to cathode, to reduce the capacitive currents injecting in to gate by miller effect.

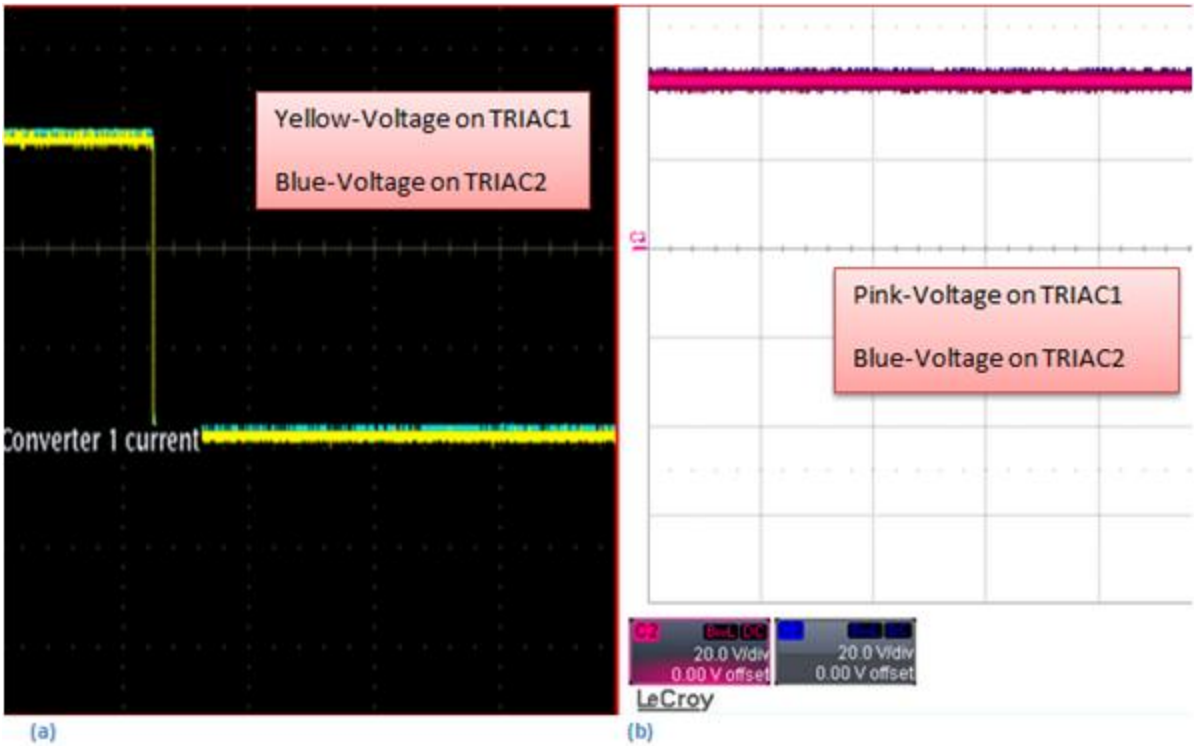


Figure 65: Static voltage sharing in series connected TRIAC (a) without equalizing circuit (b) with equalizing circuit

The results of this test are given below in Figure 65 (a) and (b). Figure (a) shows the voltage sharing between two traics when no equalizing circuit is connected across them, yellow color voltage signal is the voltage shared by first triac and blue one is voltage shared by second triac. The voltage on first triac is 36V and second one is 39V.The applied voltage is 75VDC.Hence in this experiment the voltage sharing of triacs are not equal and a difference of 3V is observed. However when experiment was performed with different voltage levels in different testing, voltage difference of almost (5-10) V is observed .Figure (b) shows the voltage sharing of triacs when equalizing circuit is connected across each triac .The equalizing resistor value used after approximate calculations was 1 megaOhm. Here each triac share an equal voltage of 37.5 volts for applied voltage of 75VDC.Even when tested with higher voltages with HF ballast, the voltage sharing between triacs showed equal distribution with the use of equalizing circuit.

4.3.2 Testing for dynamic voltage sharing-Test for synchronization of turn-on, turn-off transients

Figure 66 shows the hardware test setup schematic for testing the dynamic voltage distribution of series connected triacs. In this experiment, two triacs (800V-ACST830FP)are connected in parallel to each other such that, when a 30V DC power supply is switched on and off continuously ,triac is switched ON and OFF respectively. The 12V battery is switched off at first. When battery is switched on current is supplied to gate of both TRIACs at the same time and the triacs starts conducting. This test is actually designed to test for time synchronization of triacs during rapid turn-on and turn-off conditions. Test results of this experiment are shown in the Figure 67.

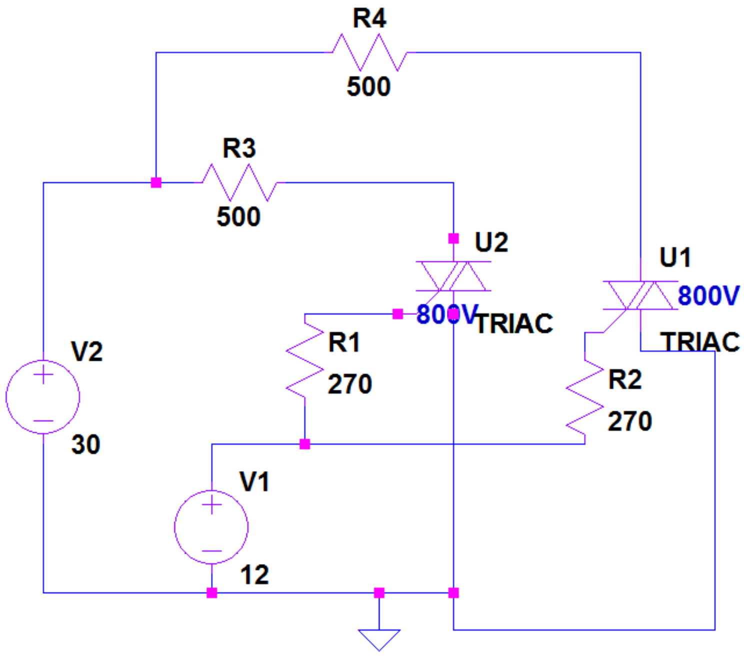


Figure 66: Test setup for dynamic voltage sharing.

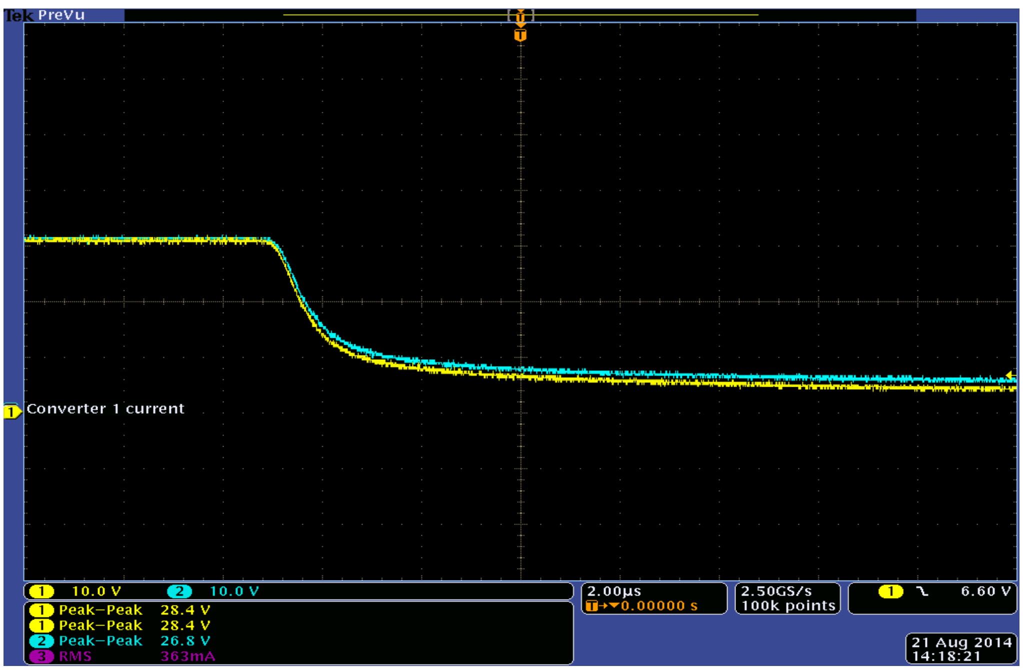


Figure 67: Test for time synchronization (dynamic voltage sharing)

From the Figure 67, it is observed that delay in conduction times between two triacs is almost 100 nanoseconds. Since the delay in conduction times of these triacs due to difference in self-capacitances (as discussed in previous section) is less than 1 microsecond, hence this delay in turn-on and turn-off times, doesn't relay affect the voltage sharing between two triacs during transient period.

Hence by these results it can be concluded that, there is very good dynamic voltage sharing and no need of dynamic voltage equalizing circuit and snubbers, which will otherwise add component costs. After testing the two triacs series connected string for its static and dynamic voltage sharing, it is concluded that it only requires static equalizing circuit .but no need of dynamic equalizing circuit.

4.4 Main components used in designing circuit for triggering two TRIACs in series for a proposed Hybrid safety relay system

After exploring the ways of triggering triacs in series from previous section 4.2, many possible topologies for simultaneous triggering using gate drive transformer were studied that is suitable for hybrid relay system for TLED. This section deals with brief discussion on two main components- 555 timer and gate drive transformer used in designing the circuit and then next section 4.5 in detail about the design circuit.

4.4.1 555 Timer and Gate drive transformer basics

4.4.1.1 555 Timer:

In this design project 555 timer is used for generating pulse signal to primary of isolation transformer. To learn about the 555 timer and its basic operation modes, references [29] [30] were in the project as a source of literature. In this design 555timer is operated in "Astable" mode for generating required high frequency pulse train to trigger two triacs series connected system.

A 555 timer is the most popular IC that is used to generate two comparators reference voltage. "It is a very cheap and useful precision timing device that can act as either a simple timer to generate single pulses or long time delays, or as a relaxation oscillator producing stabilized waveforms of varying duty cycles from 50 to 100%" [30].The 555 timer IC is an 8-pin device that can be operated in Monostable, Bistable or Astable Multivibrator to produce signals that are used in various applications. In this project 555timer is used in Astable operation mode to generate a continuous train of pulse to trigger the series connected triac system. Next section gives a brief overview of operating 555timer in Astable mode and associated calculations for choosing the frequency of oscillations.

To operate 555timer in astable multivibrator mode, the pins were configured as shown in the below Figure 68 .In the above circuit, pin 2 and 6 are connected together so that the 555 timer circuit runs as a free oscillator, retriggering itself in every cycle. In each cycle, capacitor C1 charges through both R1and R2 timing resistors, but discharges only through R2 resistor. In this mode, capacitor charges to (2/3)Vcc through R1 and R2 and discharges to (1/3)Vcc in every cycle.For basic schematic and calculations for 555 timer refer to appendix A.

4.4.1.1.1 Astable operation Mode

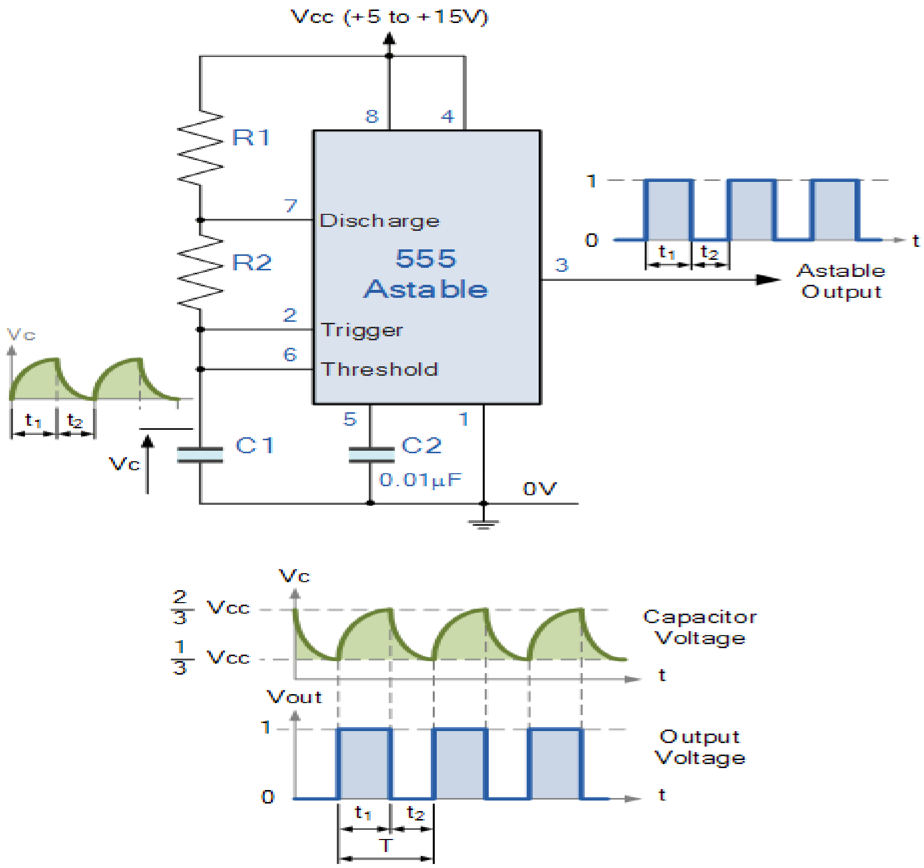


Figure 68: Astable operation pin connection diagram [30]

4.4.1.2 Gate drive transformer (Isolation transformer)

For triggering two series connected triacs using a 555 timer square wave pulse train, a three winding gate drive transformer is necessary to transfer power from 555timer to gate terminals of triacs with galvanic isolation of 1.5KV between high voltage switching side and gate drive circuit. First a general study on gate drive transformers was made and after that how to control triac by using this isolation transformer is studied and understood using [20] [26] [31] [32].

A gate drive transformer is used for driving TRIAC/MOSFET /BJT and has major functions associated with it like:

- Galvanic isolation
- Voltage transformation

In the present project, a three winding transformer is used for triggering simultaneously two triacs connected in series .A simple schematic showing three winding transformer is shown in Figure 69.

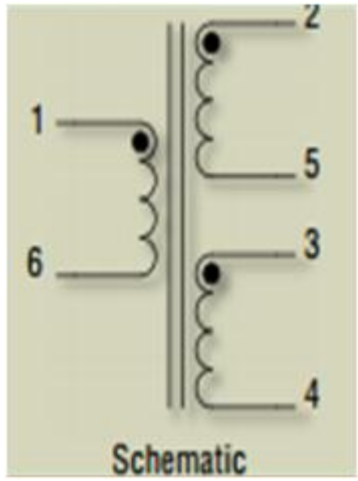


Figure 69: A schematic of three winding gate drive transformer [20]

To understand the three winding transformer models accurately, first 2 winding gate drive transformers need to be understood. More detailed study is made and discussed in appendix B.

4.4.1.2.1 Designing a gate drive transformer (Pulse transformer)

After understanding the basic models of gate drive transformer (Isolation/Pulse transformer), next design principles are explored for designing a transformer for this project. References [20] [26] were used as guides for designing.

To design a gate drive transformer, certain number of parameters should be known; they are given below [26];

- Voltage
- Turns ratio
- ET (V μs)
- Operating frequency
- Duty cycle
- Power level
- Dielectric strength
- Operating temperature
- Safety requirements

Most of the gate- drive transformers are designed with ferrite core to reduce the cost. The selection of ferrite core material type (different vendors) with regards to frequency of operation is listed in Table 11 (appendix B). The selection of primary inductance of transformer with operation frequency range is shown in Table 12 (appendix B).Since the frequency of operation is selected from 555timer astable mode, which is 114 kHz, the suitable vendor is Ferroxcube 3C90. Hence primary inductance necessary for this frequency is (0.5-2) mH.

While designing gate-drive transformers, two important parameters have to be controlled, they are: leakage inductance and winding capacitance. A high leakage inductance and winding capacitance results in undesirable output signal like timing error and overshoot. A poor coupling between windings results in high leakage inductance and high winding capacitance results when there are many turns and these turns are not uniformly winded. To design the transformer for low leakage inductance, a number of design principles are involved, that are discussed in [20].However one common rule in engineering practice is to avoid half-turn, which results in high leakage inductance due to improper coupling.

Next important step in designing gate-drive transformer, after choosing the right core and bobbin is calculating the number of turns required. Formula for calculating the number of turns N is given below:

$$\boldsymbol{N = \frac{Volt * Time(V\mu s)}{B * A_{core} * 10^{-8}}} \quad \textbf{(7)}$$

Where B is the flux density in Gauss; A_{core} is the area of the core; Volt*time product is called Volt-microsecond constant –which is the measure of energy handling capacity of a transformer, which mainly depends upon type of core material used, area of the core, and duty cycle of the applied pulse.

Next step is to determine the wire gauge, according to the formula:

$$\boldsymbol{I = \frac{V_{peak}}{2 * \pi * f * L}} \quad \textbf{(8)}$$

Where I is the current flowing through primary of the transformer, V_{peak} is the peak to peak voltage pulse applied on transformer, f is the operating frequency ,L is the inductance value that is selected from Table 12. The wire size on the primary is calculated using the equation below:

$$\boldsymbol{A_{wire} = (circular\ mils\ per\ ampere) * I * D} \quad \textbf{(9)}$$

Where, D is the duty cycle of the pulse.

The final phase in designing is finding out actual inductance of the primary winding, which is calculated by the equation below:

$$\mathbf{L} = (\mathbf{N}^2)(\mathbf{AL} * \mathbf{10}^{-9}) \tag{10}$$

Where, AL is given in the data sheet of the core material.

After exploring the steps in designing gate-drive transformer, a gate drive transformer was designed in lab, by utilizing the above equations and calculating the approximate parameters for designing the transformer. The primary inductance of the transformer calculated was near to 2mH. However, after testing the lab designed gate transformer, it was found that when a primary winding is given a pulse, the pulse peak voltage magnitude in two of the secondary windings were not the same and also there is a delay in time between these two pulses. Hence after few trails in improving this improper functioning, by carefully winding the turns such that parasitic capacitance between windings and leakage inductance is low, the peak pulse magnitude difference was improved little. But realizing the complexity of magnetics involved in designing the transformer, keeping in mind the time constraint and engineering skills required for designing a good transformer, the next idea is try with a commercially available gate drive transformers, that suits the design requirements of the project.

Figure 70: An example of commercially available gate-drive transformers (HM42 series) [33]

Hence a commercially available gate-drive transformer (HM42-40004LF) was used in the project. The turn's ratio of this transformer is 2:1:1, primary inductance (minimum) of 1200µH, leakage inductance (maximum) of 0.6µH, secondary windings inductance of 300µH, galvanic isolation between primary and secondary windings is 1500Vac and primary winding resistance of 0.6Ω.

4.4.1.2.2 TRIAC control by using Gate- Drive Transformers

After choosing the right transformer with right inductance values, next is to explore ways to control triac by using this transformer. The main advantage of using pulse/isolation/gate drive transformer is it provides galvanic isolation between high voltage side and gate drive circuits. The other advantages are:

- Possibilities to drive several triacs at the same time with only one drive circuit.

- Gate drive circuit with only few components.
- Possibility of triggering triac in 2nd and 3rd quadrants for snubberless triacs.
- Possibility of triggering triacs by single pulse and also train pulses.

For controlling the triac by pulse transformer, it is essential to know main characteristics of the transformer, they are [26]:

- The transformer ratio($\frac{N2}{N1}$)
- Primary winding inductance –Lp
- The primary winding resistance- Rp
- The(volt*time) product(V µs)-refer Figure 71.
- The rise time tr
- Gate pulse-peak value
- Gate Pulse duration.
- The Commutation

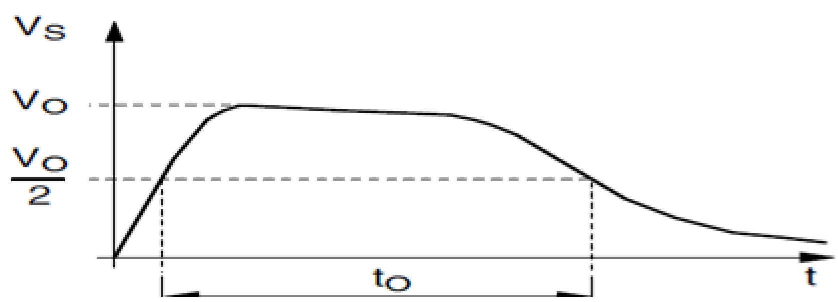


Figure 71: Voltage across the secondary winding for a rectangular pulse across the primary(Volt*time -Vµs) [26]

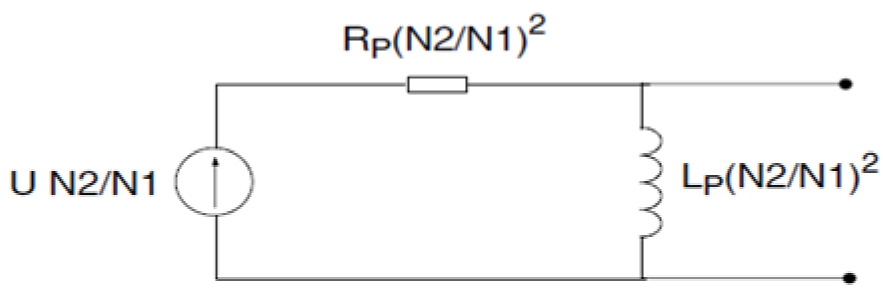


Figure 72: Equivalent diagram of the gate drive transformer [26]

Figure 72 shows the equivalent circuit of the transformer, from which we can derive the output current to the gate terminal of triac with the help of transformers ratio, power supply of the primary and secondary voltage. The output current flowing in to the gate of triac should be higher than the specified gate triggering current (I_{GT}).In order to ensure triggering at all times, the output gate current **(I_G)>2I_{GT}.** The duration of pulse at the output of transformer is in general defined by V_0*t_0 product. The anode to cathode current should reach the value higher than the specified (data sheet) latching current (I_L) at the end of gate pulse. The common rule is that, if a pulse train is used to trigger the triac, then a short duration of pulse (few µs-(10-20)) is enough to keep the triac in conducting state. However when a single pulse is used to drive the triac, larger duration of pulses are required to ensure triac is in conducting state.

Another important characteristic of triac is the commutation capability. When a triac is switched ON and its starts conducting, current flows from anode to cathode(vice versa).During this time, a certain quantity of charges are injected in to the triac. When it is switched OFF, current through it starts falling by recombination of charges. But during this time, if current decreases too fast, all the charges do not recombine and hence some charges stay near the gate area. These charges will try to re -trigger the triac and hence spurious triggering occurs, which is not energy efficient. The parameter which defines the commutation capability of anode current in triac is $\left(\frac{di}{dt}\right)_C$ - which is the slope of the anode current before crossing the zero, generally specified in data sheet. If the anode current slope before crossing zero is above this $\left(\frac{di}{dt}\right)_C$, then spurious triggering occurs. As per the detailed explanation [26], to avoid the spurious triggering in all times when triggering triac in 2nd and 3rd quadrant without use of snubbers, is to add a diode in series with the gate as shown in Figure 73.

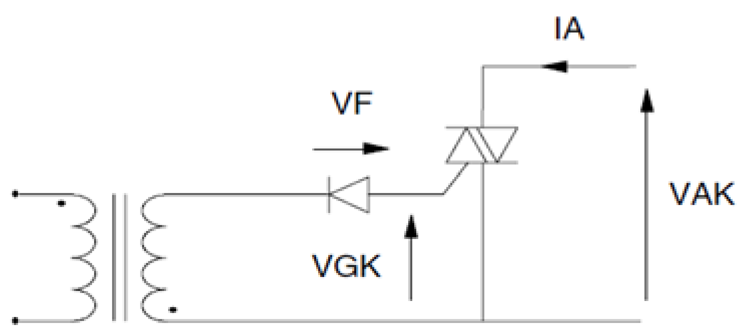


Figure 73: Adding a diode in series with the gate to avoid spurious triggering [26]

Finally to estimate the quantity of gate output current flowing in to the gate of triac is calculated with the help of equivalent circuit of primary referred to secondary of the two winding transformer shown in Figure 74, and the equations 16 and 17.

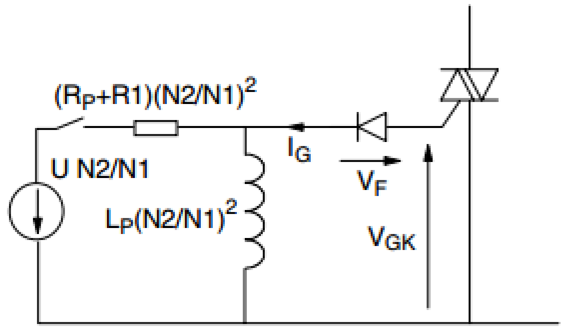


Figure 74: Equivalent circuit of two winding transformer referred to secondary winding for triac triggering [26]

$$\boldsymbol{I_G} = \frac{(\boldsymbol{V_{GK}} - \boldsymbol{V_F})\boldsymbol{t_P}}{\boldsymbol{L_P}(\frac{\boldsymbol{N2}}{\boldsymbol{N1}})^2} + \frac{\boldsymbol{V_{GK}} - \boldsymbol{V_F} + \boldsymbol{U}(\frac{\boldsymbol{N2}}{\boldsymbol{N1}})^2}{(\boldsymbol{R_P} + \boldsymbol{R_1})(\frac{\boldsymbol{N2}}{\boldsymbol{N1}})^2} \tag{11}$$

$$\boldsymbol{t_P} = \frac{\boldsymbol{0.7} * \boldsymbol{V_O} * \boldsymbol{t_O}}{\boldsymbol{V_F} - \boldsymbol{V_{GK}}} \tag{12}$$

Where I_G is gate current; V_{GK} is the gate cathode voltage; t_P is pulse duration; R_P is the primary winding resistance;R_1 is the gate resistor;

By using the above equations, approximate calculations for gate pulse duration and gate pulse current magnitude are made for 3 winding transformer for this project for triggering two triacs in series.

I_G= 52mA,t_p=5μs:

4.5 Design circuit for triggering two TRIACs in series for a proposed hybrid safety relay system

4.5.1 Design circuit using 75VDC power supply

4.5.1.1 LTSPICE Simulation Model

After studying and analyzing various ways to design gate driving circuit for two series connected triacs for a proposed hybrid relay system, a best possible design was evaluated considering various design requirements and most importantly energy actually available from TLED. For evaluating the design, a LTSPICE software model was first simulated and based on this results, a hardware model was built and tested in lab. This section describes the simulation model and explains the various functions of each component in the design. The LTSPICE simulation model is shown in Figure 75.

In this design many components are used for different functions. The major functional blocks as shown in Figure 75 are:

- **Time delay and amplifying network**: this network is used for delaying the signal from 9V by 7 ms.
- **Gate drive transformer**: A three winding gate drive transformer: this is used to transfer high frequency voltage pulse from 555 outputs to gate terminals of both triacs
- **Flux resetting network**: to reset the flex in primary of the gate drive transformer this network is used.
- **555 timer circuit**: this circuit is used to set up 555 timer frequency of oscilloscope in astable oscillator mode.
- **Timing circuit for switching of voltage supply**: this network is used for witch off the power supply 9V after 1 second, so as to cut off the gate pulse to the triacs.

More detailed description of the circuit functions is given in next section 4.5.1.1.1.

4.5.1.1.1 Description of the circuit

1. V1-9V DC supply is used as power supply source for triggering two triacs in series.
2. V2-75VDC supply used as high voltage side, this voltage has to be blocked by bot triacs in switched off condition.
3. R1, C1, D1 in combination with Q1(NPN) transistor are used to switch off the power supply 9V after 1 second ,so as to cut off the gate pulse to the triacs. This is done because , once both the triacs are triggered and anode to cathode current magnitude reaches above latching current(I_L) ,the triacs continue in being in conducting state until an external circuit forces the conducting current fall below the holding current. Hence by switching off the gate pulse to both triacs after 1 second, saving of energy is achieved.
4. R2,C2,D2 are used as time delay circuit for delaying the signal from 9V by 7 ms. This delay is introduced because, the main idea of the design is to switch on the electromechanical relay first and then switch on the both triacs after 7ms.This kind of timing control for signal is to ensure the safety of TLED in all cases .If triacs are switched on first and then electromechanical relays, in this case the triacs doesn’t comply with IEC safety standards of clearance and creepage requirements and also isolation requirements.

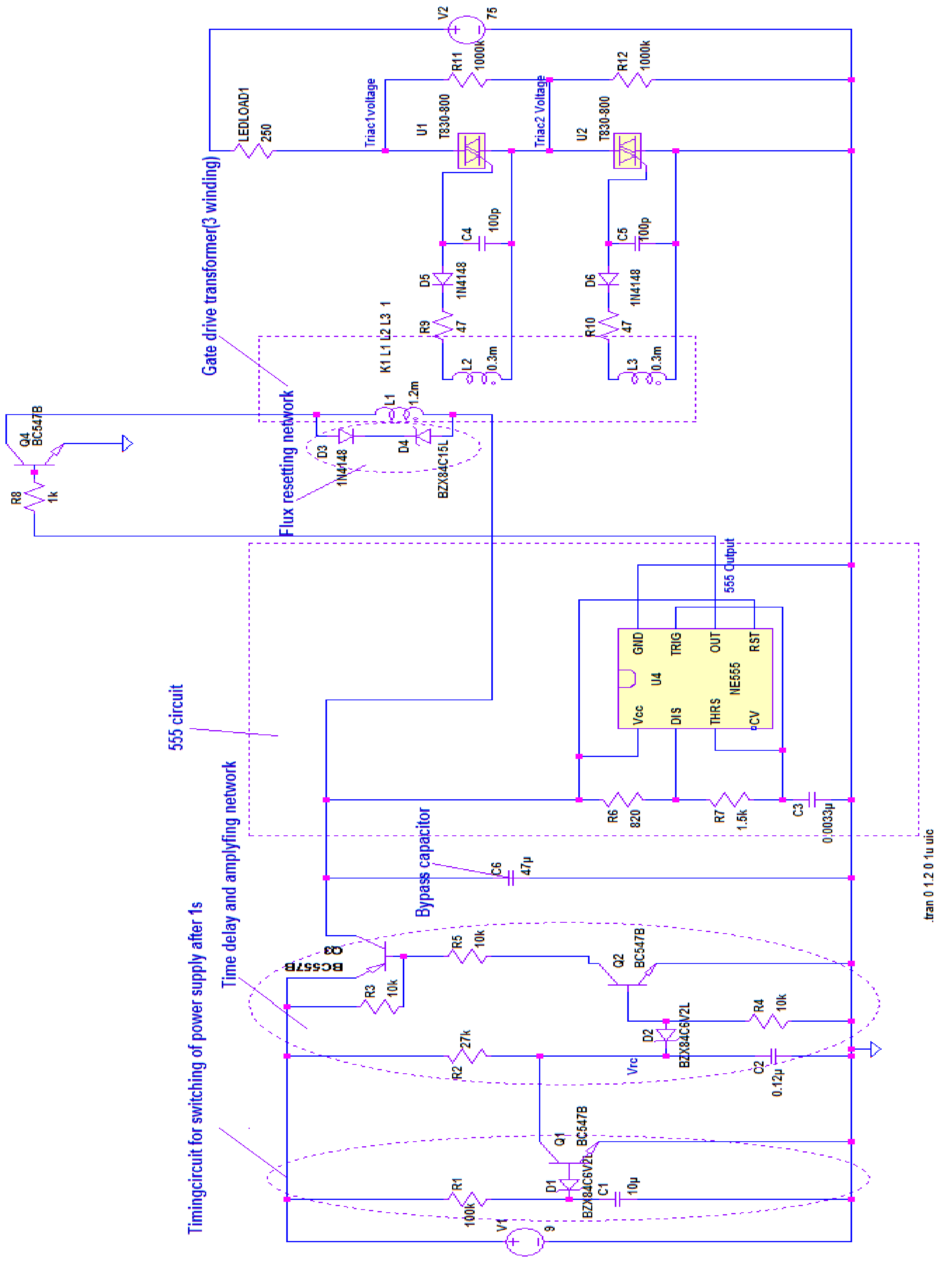


Figure 75: LTSPICE model for triggering two triacs in series..

5. Combination of NPN transistor Q2 and PNP transistor Q3 is used to amplify the current with certain gain, such that the gate drive circuit doesn't draw large amount of current from 9V supply.R3 and R4 are used as leakage current resistors for transistors.
6. C6 capacitor is used as bypass capacitor, which is used to reduce the ripples in the voltage supplied to input of 555 timer.
7. R6,R7,C3 are used to set up 555 timer frequency of oscilloscope in astable oscillator mode. The designed frequency of 555 timer voltage signal is 114kHZ.The calculations of frequency calculation-ON time and OFF time of 555timer is described in appendix A.
8. Transistor Q4 NPN is used for amplifying current from 555 timer output terminal with certain gain such that, the circuit doesn't draw a current from the 555 timer output above the ratings of 555 timer output stage.
9. A three winding gate drive transformer is used to transfer high frequency voltage pulse from 555 outputs to gate terminals of both triacs. Primary winding L1 and secondary windings L2 and L3.The coupling factor in simulation used is 1.The isolation between primary and secondary windings required is 1.5 KV. The inductance of primary winding used was L1=1.2mH, and secondary winding L2=0.3mH, L3=0.3mH.The calculations for choosing the right value of inductance with the operating frequency of 555 timer were made. A brief introduction about isolation transformer and required mathematical calculations for choosing the inductance and frequency for transformer are discussed in 4.4.1.2.1 and in 4.4.1.2.2 section also refer appendix B.
10. The combination of diode D3 and D4 Zener diode is used as a flux resetting network across primary winding. The 555 timer generates a signal that oscillates between 9 and 0 Volts. Hence to have a positive and negative pulse symmetry, a 15 V Zener is connected in parallel to primary as shown in the above figure.
11. R9 and R10 are gate resistors connected to gate terminals of triacs so that equal gate currents are flowing through them.
12. Didoes D5 and D6 are connected in such a way that, current direction is from gate terminal of triac to secondary winding of transformer but not vice versa. This is because triacs are designed to be triggered in 3^{rd} quadrant and not in 1^{st} quadrant .Triggering in 3^{rd} quadrant requires less energy than 1^{st} quadrant as discussed in chapter 3.
13. R11 and R12 are used as static equalizing circuit, to ensure equal voltage distribution during steady state.
14. U1 and U2 are two triacs(800V,ACST830FP) connected in series.
15. LED load is used as 250 ohm, since this the approximate LED load that perfectly emulates the real LED load in TLED.

4.5.1.1.2 Simulation results:

Figure 76,Figure 77,Figure 78,Figure 79 shows the simulation results of various voltage and current and power waveforms. For more waveforms refer to appendix C.

Figure 76: 555 timer output voltage (frequency 114 kHz)

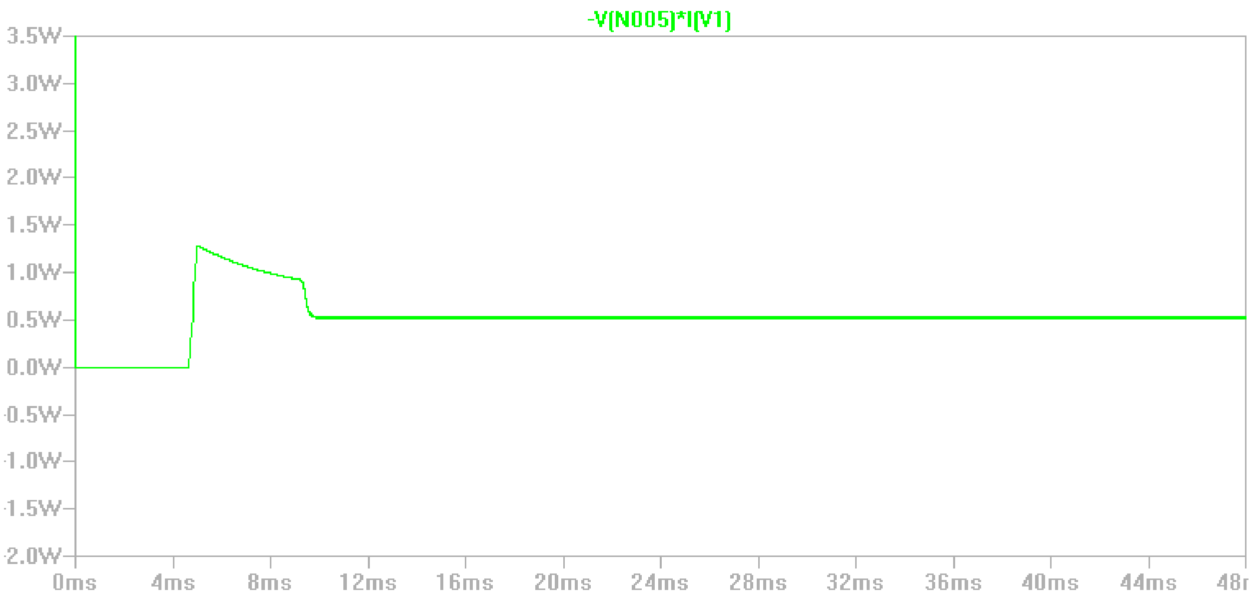


Figure 77: Power consumption from 9V supply

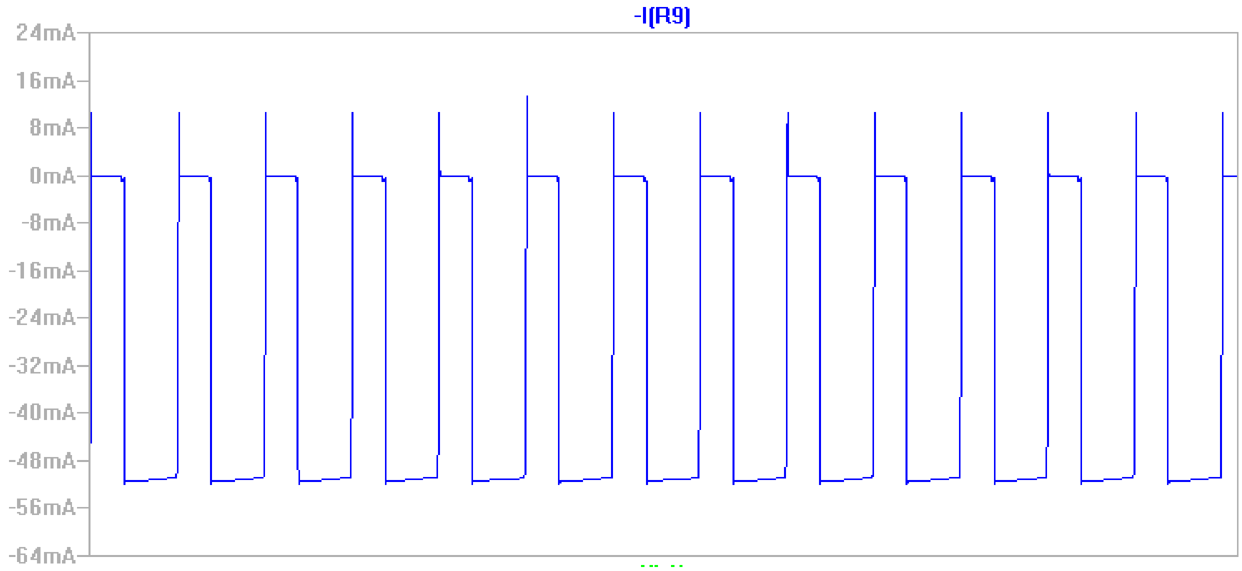


Figure 78: Gate current flowing through the TRIAC

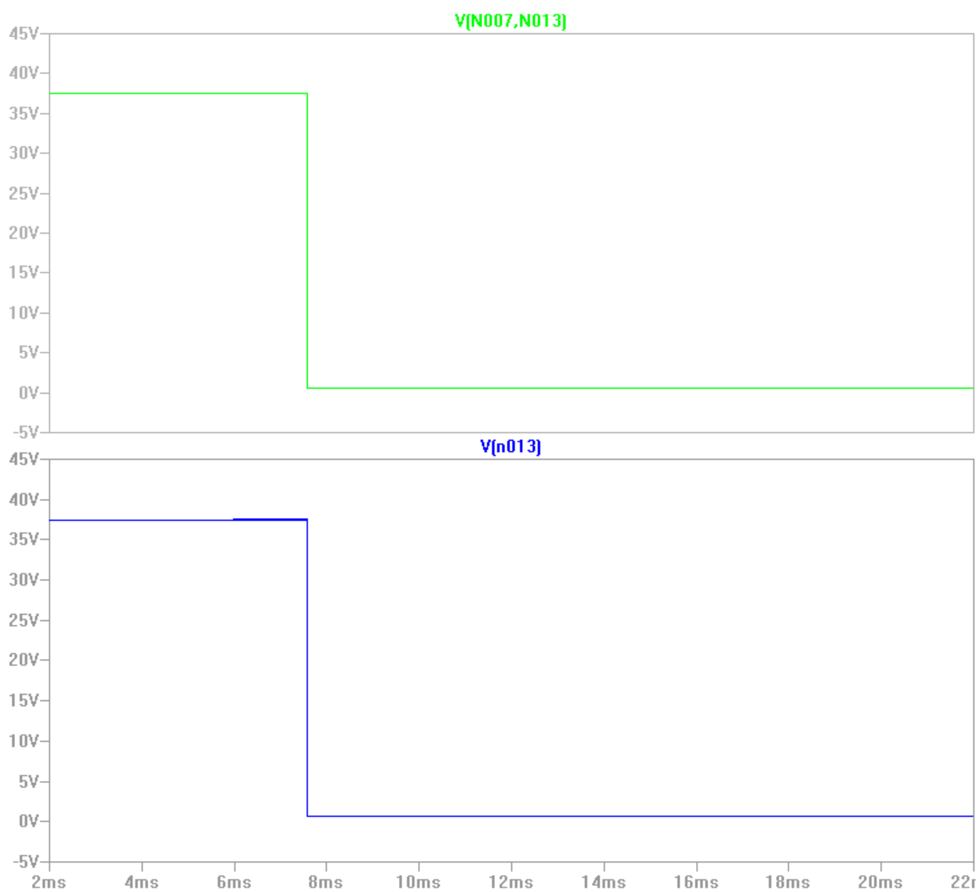


Figure 79: Voltage on TRIAC 1(green color) and on TRIAC 2(blue color) showing the delay in turn-on by 7.5ms

Observations:

- Frequency of 555 output voltage designed is for 114KHz
- Primary winding current peak is=100mA
- Gate current pulse peak=50mA- 3rd quadrant triggering for lower energy consumption during triggering. Duration of pulse t_P=5µs.
- TRIAC triggers around 7-8ms.
- The total circuit stops conducting after 1s.This is done because once the triac triggered, and anode current reaches above latching current (I_L) specified on data sheet, its keeps itself in conducing state. Hence no gate pulse is required.
- Choosing the right inductance value for transformer in relation with the operating frequency of 555 timer is studied carefully (refer to 4.4.1.1 section and appendix B).
- Power consumption from 9V supply is initially peak of 1.1W and after 7 ms it consumes average power of 0.5W.

4.5.1.2 Hardware test setup and results

After analyzing the LTSPICE simulation model results, a hardware prototype was built in lab, refer Figure 80.

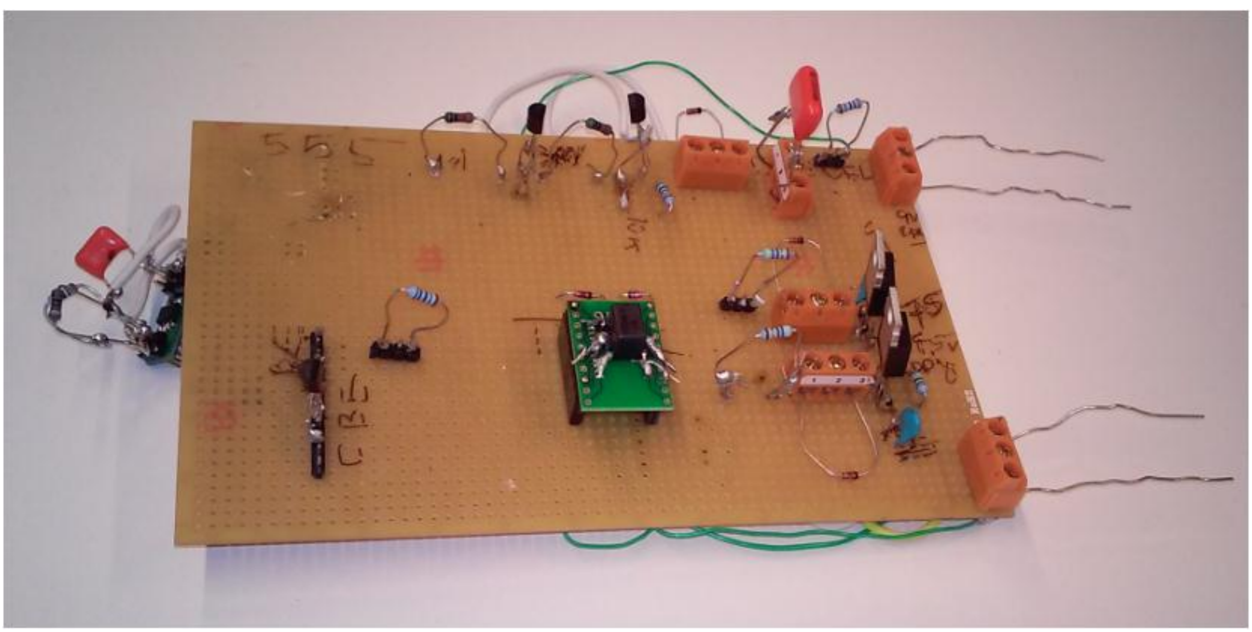


Figure 80: Hardware prototype test circuit

Figure 81,Figure 81:555 timer output voltage (103 kHz)Figure 82,Figure 83,Figure 84,Figure 85 shows the hardware test results:

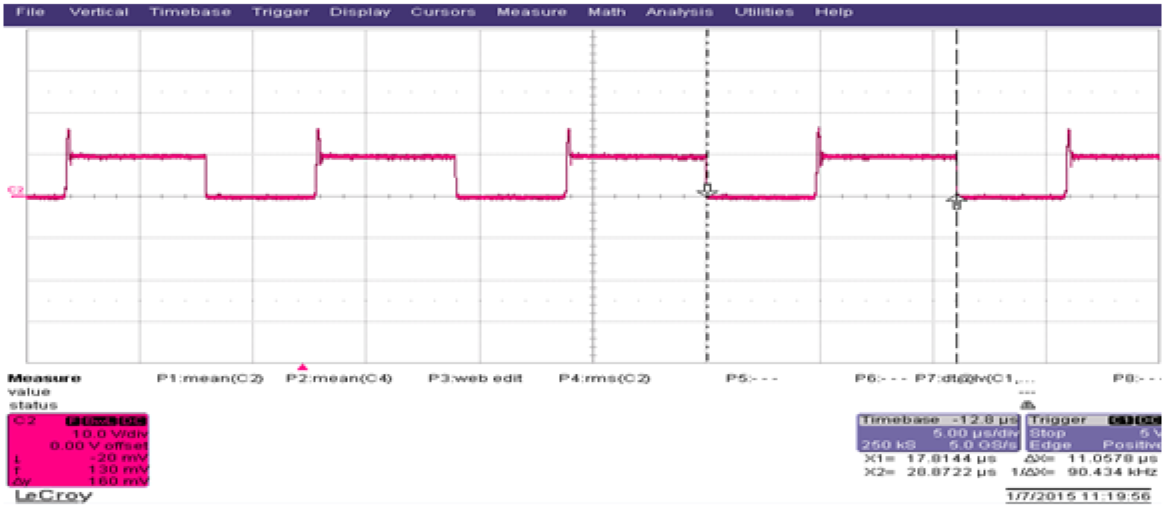


Figure 81:555 timer output voltage (103 kHz)

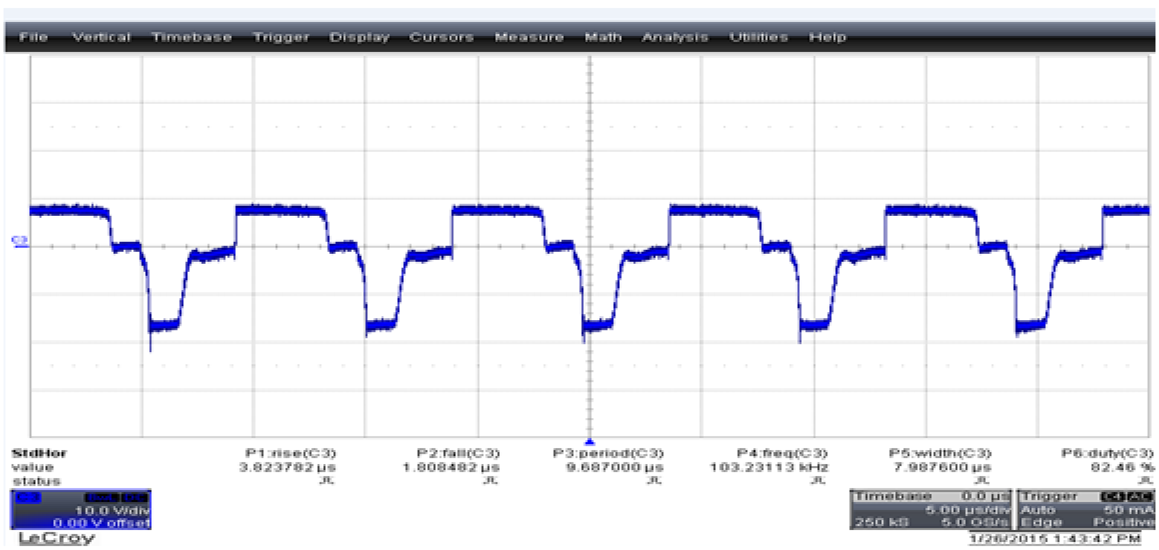


Figure 82: primary winding voltage signal (Volts)

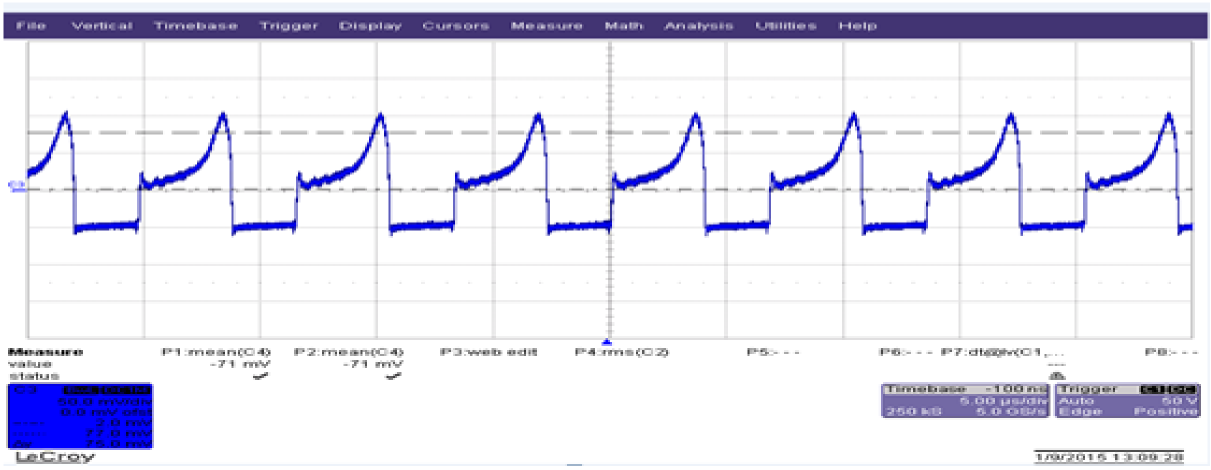


Figure 83: Current in the primary winding (mA)

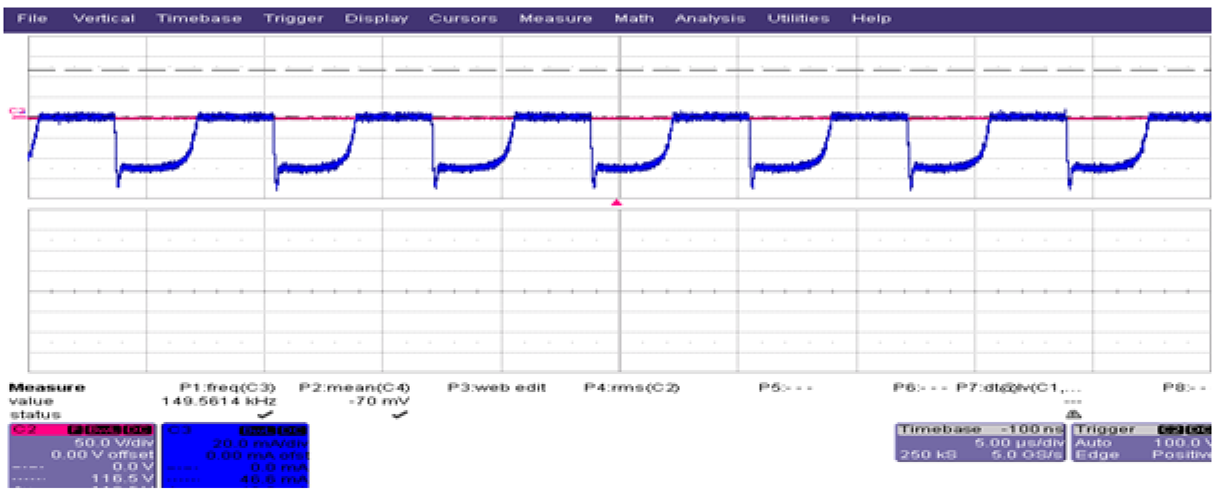


Figure 84: Gate current pulse (mA)[3rd quadrant triggered]

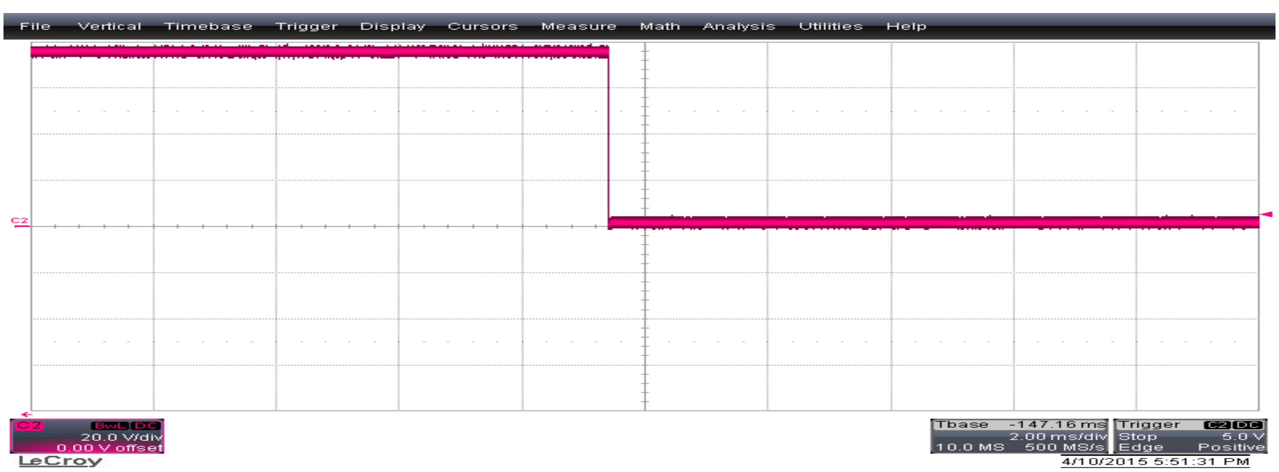


Figure 85: Voltage on the single TRIAC showing delay in conduction by 8ms.

4.5.1.2.1 Conclusion of hardware results

- The actual design parameters for 555 timer in simulation model were: $R6=820\Omega, R7=1.5K\Omega, C3=0.0033\mu F, Ton=5.306\mu s, Toff=3.430\mu s, D=60.73\%, F=114KHz$
  The theoretical calculated and observed frequency in simulation was 114 KHz. But the actual frequency of oscillation of 555 timer output voltage signal from the hardware circuit was found to be 103 KHz.[Ton=5.4μs,D=56.2% ,Ton+Toff=9.67μs].The reason for this slight change in frequency is due to tolerance values of components used in hardware prototype , and also due to parasitic effects on 555 timer itself.

- 3^{rd} quadrant TRIAC triggering power consumption from 9V supply was 270mW, whereas 1^{st} quadrant TRIAC triggering power consumption was 360mW.Thus it is observed that triggering TRIAC in 3^{rd} quadrant is energy efficient compared to 1^{st} quadrant triggering.

- The delay introduced in gate trigger pulse is around 8 milliseconds .But the designed RC delay time in simulation was 7.5 milliseconds. Again this difference in simulation and hardware results can be attributed to tolerance values of components and parasitic.

Thus design and testing of triggering circuit for the proposed hybrid safety relay system using a 75VDC was successfully performed. Results thus obtained were analyzed, and thus the design circuit performs the intended functionality as per design requirements for TLED.

4.6 Testing the designed triggering circuit with HF ballasts

After testing the triggering circuit with 75VDC supply, next phase in testing is to test with different HF ballasts. The design circuit for testing with HF ballast remains same as with 75VDC, only change was with the use of filament emulation resistors across each end of ballast. The schematic for hardware testing with HF ballast is given in Figure 86.First, conduction tests were performed on this designed circuit, for choosing the best suitable triac switch type among few commercially available (different manufacturers) high voltage TRIAC switch types. Next, test for blocking capability of this chosen switch type with different HF ballasts were performed and results were analyzed.

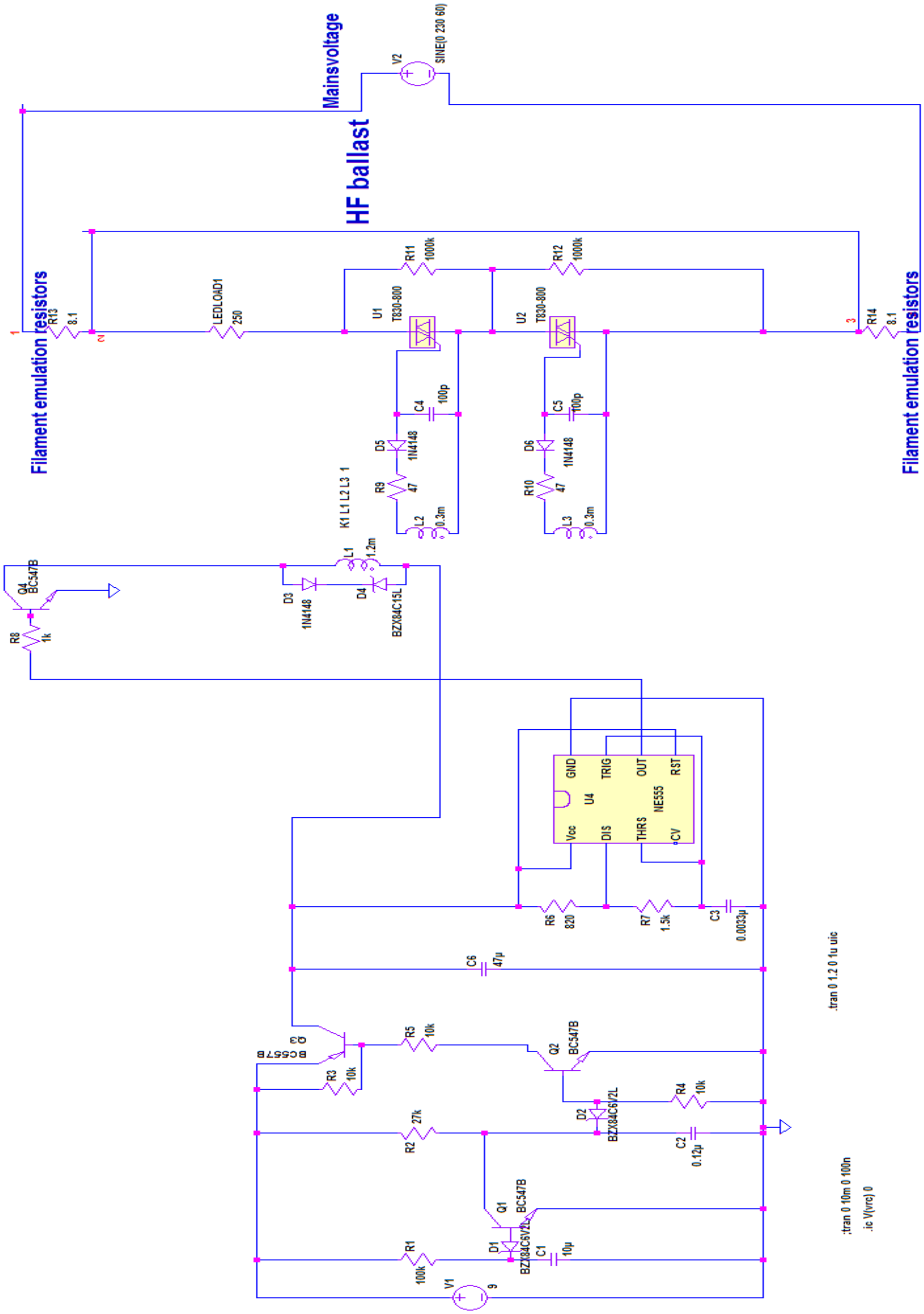


Figure 86: schematic of circuit- test with HF ballast

4.6.1 Test for conduction with different TRIAC switch types (Two TRIACs connected in series) with HF ballast (QTP-OSRAM)

To choose the best triac switch type among few commercially available switch types, a conduction test was performed to analyze the current flowing through the triac(Anode to cathode) when it is triggered by the triggering circuit designed as above in the figure. The Table 8 gives a list of available switch types and its ratings.

Table 8: Comparison of three different TRIAC high voltage switch types

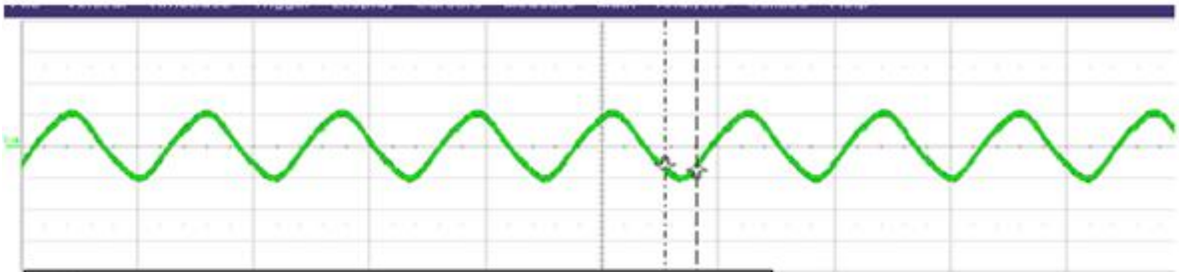
Switch type	Latching current-rated-mA	dV/dt(V /µs)	Gate current(IGT) mA	Rated current(A)	dI_T (rate of rise of on state current)A/µs	dI_{com}/dt-rated(commutating current) A/ms
BTA204800C	20	1000	35	4	100	3
ACTT2X800E	25	500	10	2	100	3
ACST830FP	50	2000	30	8	100	8

Test with three different switches were performed with HF ballast (QTP-OSRAM) in order to observe the conducting current through 250 ohm load-(waveform captured in oscilloscope) when the two triacs are triggered with gate pulse. The results of the test were captured in oscilloscope given in Figure 87. After analyzing the results, conclusions are made, they are:

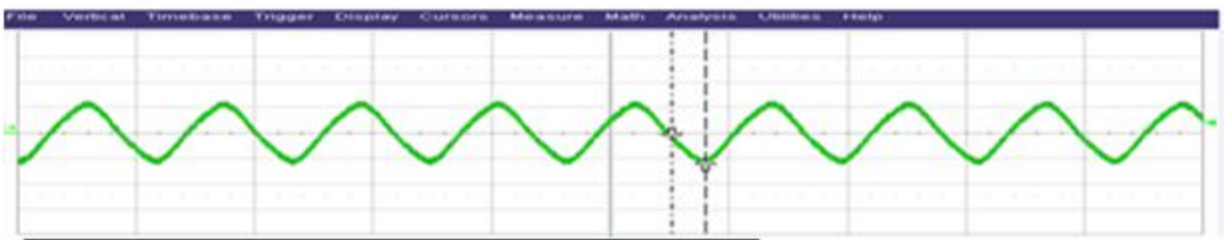
- Switch BTA20480C and ACTT2X800E when triggered in 3rd quadrant, it conducts and the current waveform observed is perfect sinewave as expected. This indicates that, once this both switches are triggered, it keeps in ON state since the latching current required by them is only 20 and 25mA respectively. This low latching current (20-25) mA requirement for TRIAC to be permanently ON state is provided by leakage current in the circuit.
- Switch ACST8308FP is triggered in 3rd quadrant; it doesn't conduct fully in both directions. It conducts fully in one direction and in other direction –it is not conducted fully. The reason for this phenomenon is due to higher latching current requirement (50mA) and internal physics behind triac construction.
- Also triggering in 1st quadrant energy consumption from 9V supply was 360mW, whereas 3rd quadrant triggering consumed only 270mW.This confirms 3rd quadrant triggering is always energy efficient.

Hence to confirm the reason behind the partial conduction of ACST8308FP switch, the load resistance of 250ohm is reduced to 160ohm to increase the load current, that will in turn makes the current flowing through the switch just immediately after its starts conducting reaches latching current level(50mA). So that the conducting current waveform through this switch can be near to sinewave (fully conducting).The resulting waveform for this experiment is captured in oscilloscope shown in Figure 88. After observing this waveform it's proved that, when load current is increased (load resistance decreased), the current waveform through the switch ACST8308FP improves a bit compared to full load at 250ohms. As the load resistance is decreased, the switch conduction improves a bit in both directions of conducting current, proving that switch can move to from a partial to fully conducting state in both directions. However the actual load current flowing the TLED is only around (300-500)mA and thus we cannot increase the load current(decrease the load resistance) beyond this limit ,Hence switch ACST8308FP cannot used in this project for designing a hybrid safety relay system.

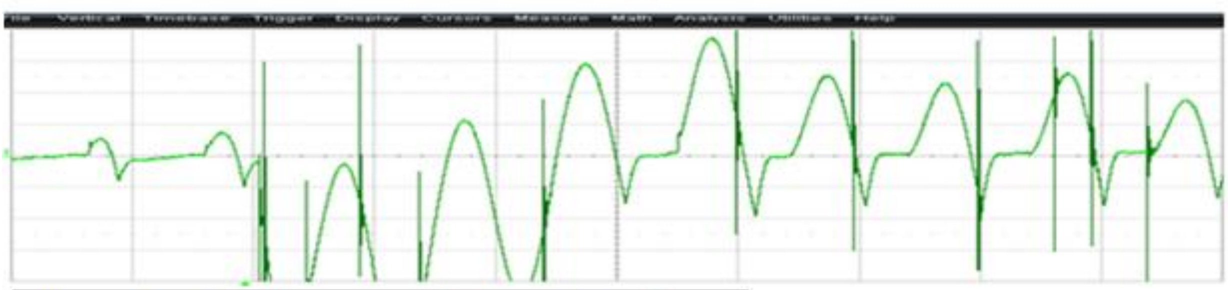
Hence after analyzing the experimental results, the best switch suitable for application in relay in TLED is found to be BTA204800C, considering higher dV/dt , lower latching current, higher rated current, good thermal behavior characteristics.



(a) Current through TRIAC BTA204800C when triggered in 3rd quadrant



(b) Current through TRIAC ACTT2X800E when triggered in 3rd quadrant



(C) Current through TRIAC ACST8308FP when triggered in 3rd quadrant

Figure 87: Conducting current through 3 different TRIAC switch types when triggered. (a)BTA204800C (b) ACTT2X800E (c) ACST8308FP

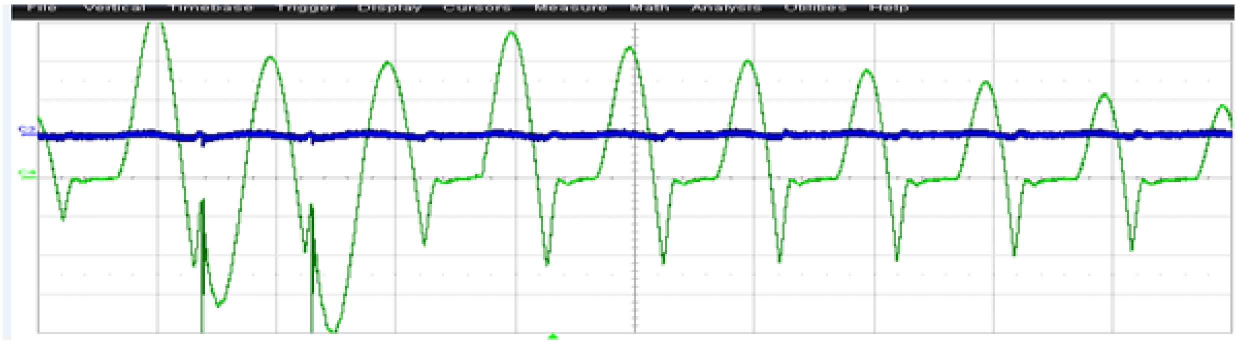


Figure 88: Current (green color) through the switch ACST830-8FP when load resistance is reduced from (250 to 160) ohm

4.6.2 Test for blocking capability of two BTA204800C operated in series with different HF ballasts

After choosing the right high voltage TRIAC switch-BTA204800C, the next task in testing phase is to test this switch for blocking capability with few different HF ballasts available in the market.

Table 14(appendix D) shows the full test results. Table 9 shows few of the test results when two BTA204800C are operated in series with different HF ballasts. Schematic of test setup is shown in Figure 89.

The main conclusion drawn from this test results are:

- The two triacs(BTA204800C) in series combination can block high frequency and high voltage from HF ballast, without being much influenced by false turn-on by miller effect. Thus by connecting two triacs in series can have an increased high voltage blocking capability and also increased dV/dt capability.
- Series combination of BTA204800C can block both warm and cold start ballast high frequency, high voltage signals.
- The leakage current observed during this tests are less than 30mA on average but present TLED electronic boards are designed with leakage protection circuits ,hence the series combination of triacs can be used as a safety relay solution for TLED without posing much dangers to electrical shock.

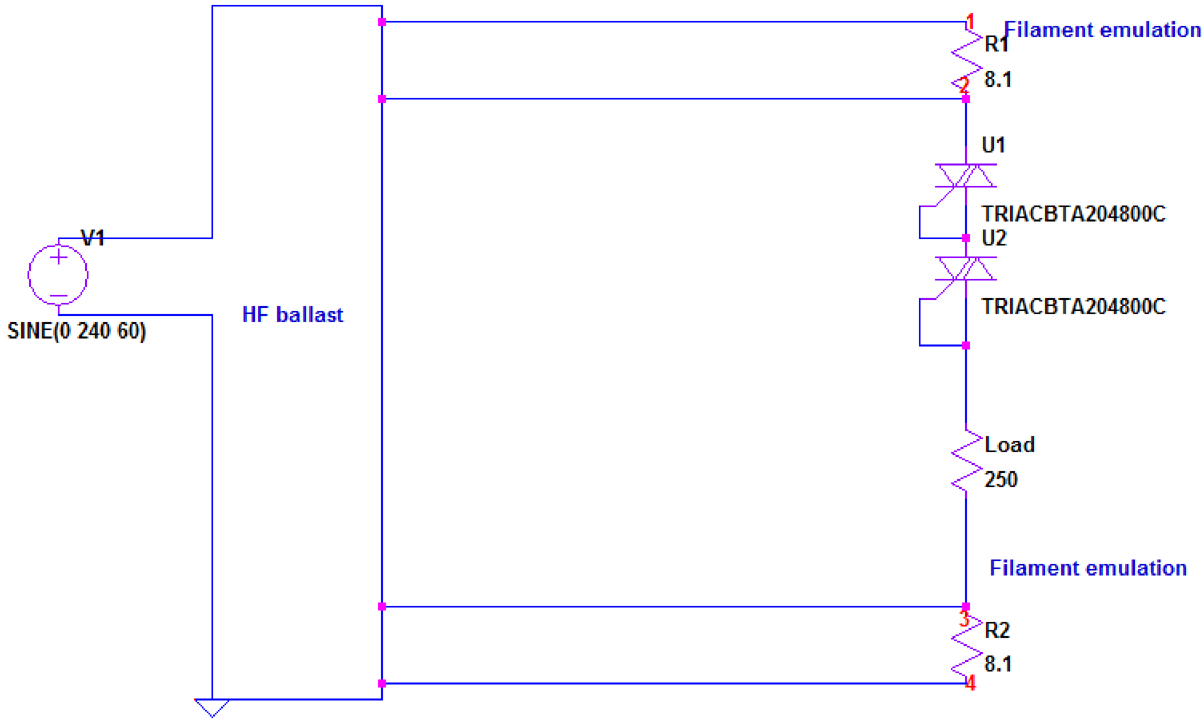


Figure 89: Schematic of test set up for testing BTA204800C TRIACs in series for blocking capability

Table 9: Testing for blocking capability of two BTA204800C in series with different ballasts.

Ballast type	BTA204-800C
HF-Perfomer-II-HFP158(Warm)	✓
HF Performer-II(warm)	✓
HF RegularorII(warm)	✓
Tridonic(cold)	✓
QTP8 OSRAM(warm)	✓
VS(cold start)	✓
HF basic-II(cold)	✓
HF Performer-III(warm)	✓

Where ✓ indicates that triac is able to block the signal from HF ballast.

Chapter 5: Integration of Hybrid Safety Relay System (single TRIAC) with TLED relay driver board

5 Chapter 5: Integration of Hybrid Safety Relay System (single TRIAC) to TLED relay driver board

After studying the present TLED Electronic architecture, the complexity of issues relating to integrating two triacs connected in series for cold and warm start compatible ballasts (hybrid safety relay solution) to TLED driver boards is realized. Hence as thesis project, integration of hybrid relay system to TLED which consists of only single triac solution that can only block few warm start ballasts is studied in detail. The two triac hybrid relay system integration was planned for future research projects keeping in mind thesis project time constraint. Hence this section first deal with understanding present TLED relay solution, and then design and testing of single triac hybrid safety relay integration with TLED is discussed.

5.1.1 Present Relay board description

To integrate hybrid relay system consisting of one electromechanical relay and one triac , with the present TLED relay driver board, lot of changes and redesigning of board is required. After studying carefully the present relay driver board architecture, many ways of integrating hybrid relay system with driver board were explored. Best possible way was studied in detail, considering creepage and clearance requirements and safety standards of IEC. The driver board consists of two boards- Motherboard and Daughterboard (refer Figure 90 below):

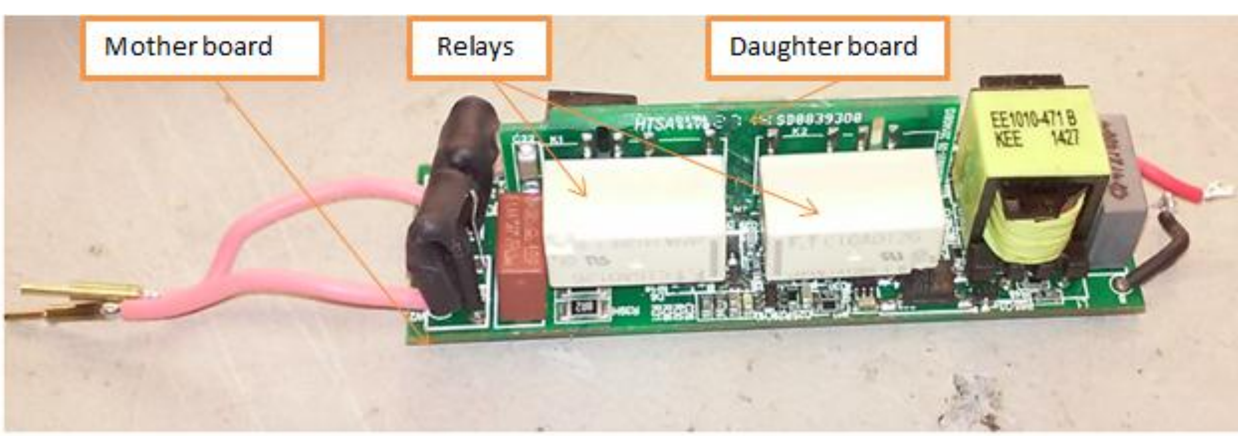


Figure 90: Relay boards

5.1.1.1 Overview of safety relay architecture

For exploring the possible ways of integrating hybrid safety relay system to the present relay board, studying and analyzing present relay board circuit is very essential. This section deals with the description of present relay board consisting of two electromechanical relays and power supply for driving them during startup and in steady state.

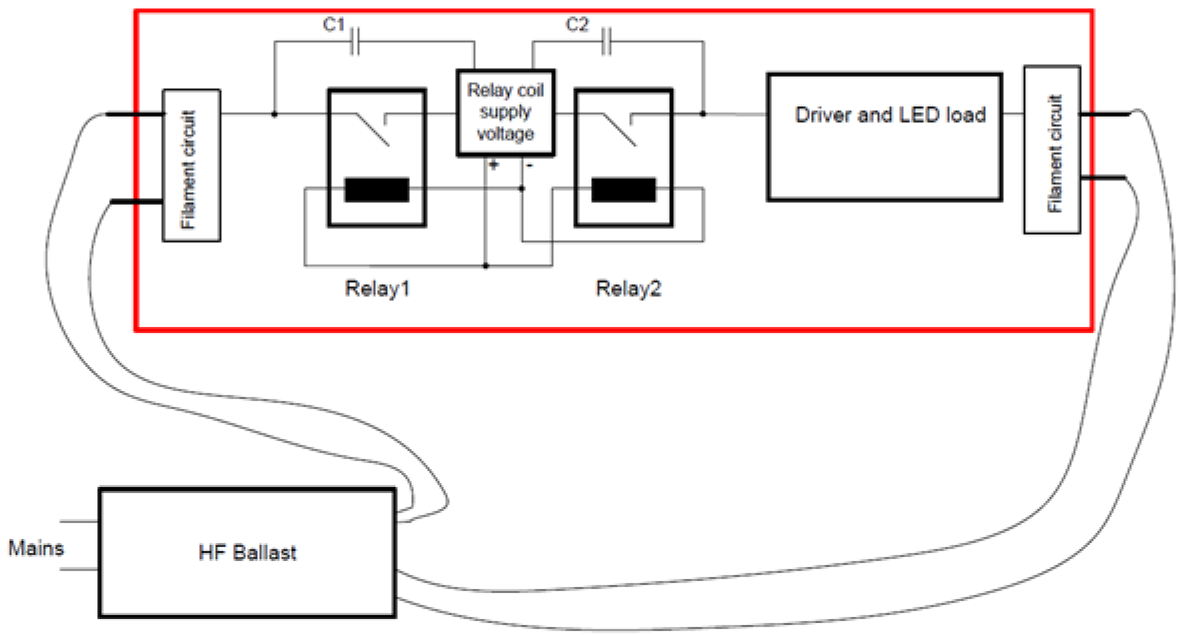


Figure 91: Block diagram of relay pin safety for HF compatible TLED with a shunt supply

The above figure gives an overview of TLED relay pin safety solution. Both the relays stay open when only one side of tube is inserted in to mains. The main current can only flow, when both sides of tube is inserted in to the lamp holders. If only one side of the lamp is inserted, the relay coil will not get a voltage and the open contacts provide safety. The relay contact switches the current from the HF ballast. The HF current from the ballast can be detected via a Y-capacitor (C1, C2) and provide initial voltage to power the relay coil, so that the relay contacts close. The supply is taken over by the steady state coil supply voltage. Insulation barriers for the relay coil voltage supply are served by two Y-capacitors.

The two Y-capacitors (C1&C2- both are used as startup supply for relays and also safety capacitor's) are connected in parallel to the relays. Relay supply voltage during startup phase is arranged via the Y-capacitors. Initial HF current flows via the Y-capacitors. This current energizes the relay coil and closes the contact. In steady-state the relay coil supply voltage is derived from a shunt supply, by using a switching network consisting of a MOSFET and a DIODE, to tape energy from main current flow path **(**Figure 92). The advantage of relay circuit design shown in Figure 91 is that insulation requirements for the relay coil to contact is the only basic insulation.

5.1.1.1.1 Relay shunt supply circuit

The relay coil supply voltage in steady state can be realized by tapping energy from the main current path as discussed in previous section. There are various ways to implement it, but the one shown in Figure 92 is preferred due to less components and lower cost. When the switch (MOSFET) conducts the mains current is bypassed; and when the MOSFET is tuned off the mains current charges the filter capacitor. Therefore by controlling ON and OFF of the MOSFET the low voltage supply can be regulated. This regulated voltage provides energy to the relay coil. The MOSFET gate is controlled by hysteresis loop control shunt. The hysteretic control determines two limits: Threshold1 and Threshold2, with Threshold2> Threshold1. When the (C24) drops below Threshold1, M3 is switched off, and the main current charges the buffer C24. When the buffer voltage increases above Threshold2, M3 is switched on, and the main is bypassed by M3. Then the voltage on the buffer will drop (due to the power consumption of the relay coil).

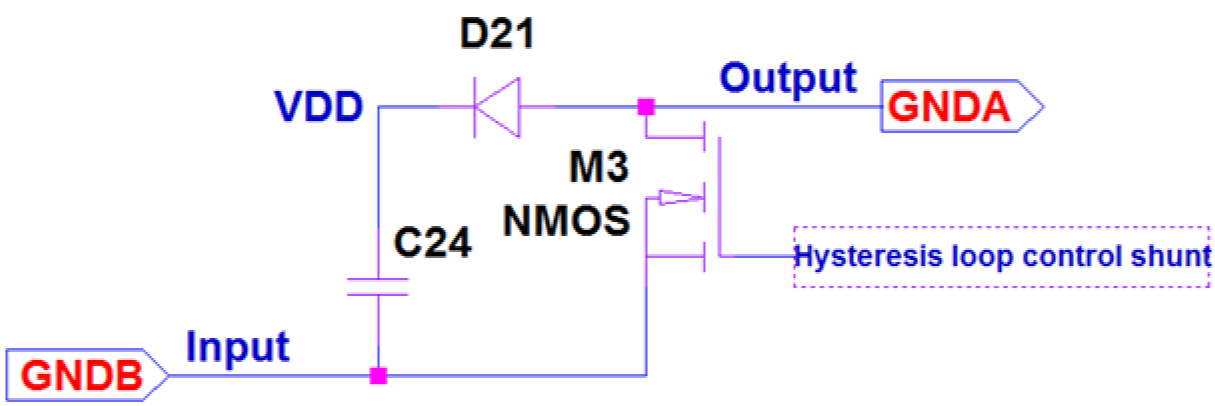


Figure 92: shunt supply for the relay coil voltage

5.1.1.2 Relay circuit detailed description

5.1.1.2.1 Relay startup circuit

This section describes more detailed working of relay circuit and its driving components. Figure 93 below gives the circuit configuration of relay and detection circuit.

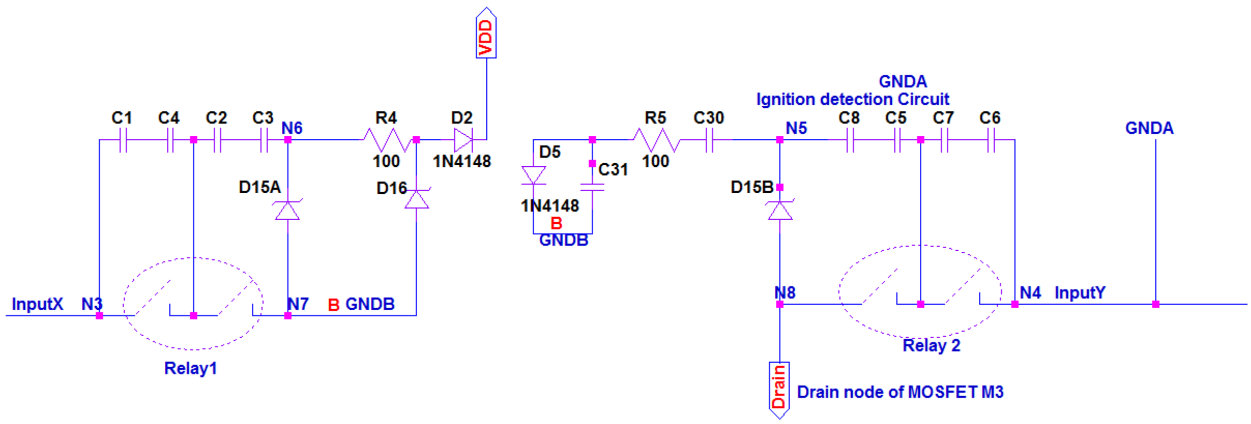


Figure 93: Configuration of the relay and detection circuit

The pin safety circuit consists of two relays. Figure 93 shows the configuration of the circuit. Both the relays (relay 1 and relay 2) are connected in series. The signal InputX is the power input from one end of the tube, whereas InputY from the other end. A string of capacitors (C1,C2, C3,C4,C5,C6,C7,C8) are connected in parallel with each relay to distribute the voltage over the contacts equally. This is done in order to pass the 4kV high voltage test. During startup the relay contacts stay open and the ignition voltage from ballast is applied to the string of the capacitors. The circuit is split into two parts:

i. Capacitive supply for the relay coil during startup: D15A, R4, D16 and D2 form a capacitive supply which provides energy to the relay coil during startup.

ii. Ignition detection circuit: D15B, C30, R5, C31, D19 and D17 form an ignition voltage detector.

The capacitor C31 sets the detection level. This two circuits create an AND function, that is, both the startup supply and ignition detection circuit need to work simultaneously in order to close the relay contacts. The relay will not be energized when one of the relay fails short, either the startup supply can't be built up or the ignition voltage cannot be detected. This important circuit feature prevents operation of the lamp when one of the relay fails short, therefore guarantees pin safety under single fault condition i.e when one of the relay fails.

5.1.1.2.2 Relay Vdd shunt supply

The relay coil is supplied via two sources (as discussed in previous section): During startup it is supplied by a charge pump capacitive supply (as shown in Figure 93) and in steady state (after relay closes) the coils is energized by a shunt supply (as shown in Figure 94). The shunt supply consists of a MOSFET M3, D21, capacitor C24 and a hysteretic control unit. The circuit taps energy from the main current path.

5.1.1.2.1 Principle of ignition detection

In this principle the relay supply voltage Vdd is switched via a thyristor structure built around Q10a and Q10b (see Figure 94). Two conditions have to be met before Vdd is applied to the relay coil: Vdd has to reach 12V, and the scaled ignition voltage has to be higher than 15V peak. Condition 1 is realized by zener D17 and Condition 2 by D19. Both zener diodes have to conduct a negative current in order to trigger the thyristor structure. The startup supply has to charge C24 to 12V and furthermore the detected ignition voltage on C31 has to reach -15V (see also Figure 93). The circuit forms an AND function between these two conditions by the use of the two zener diodes.

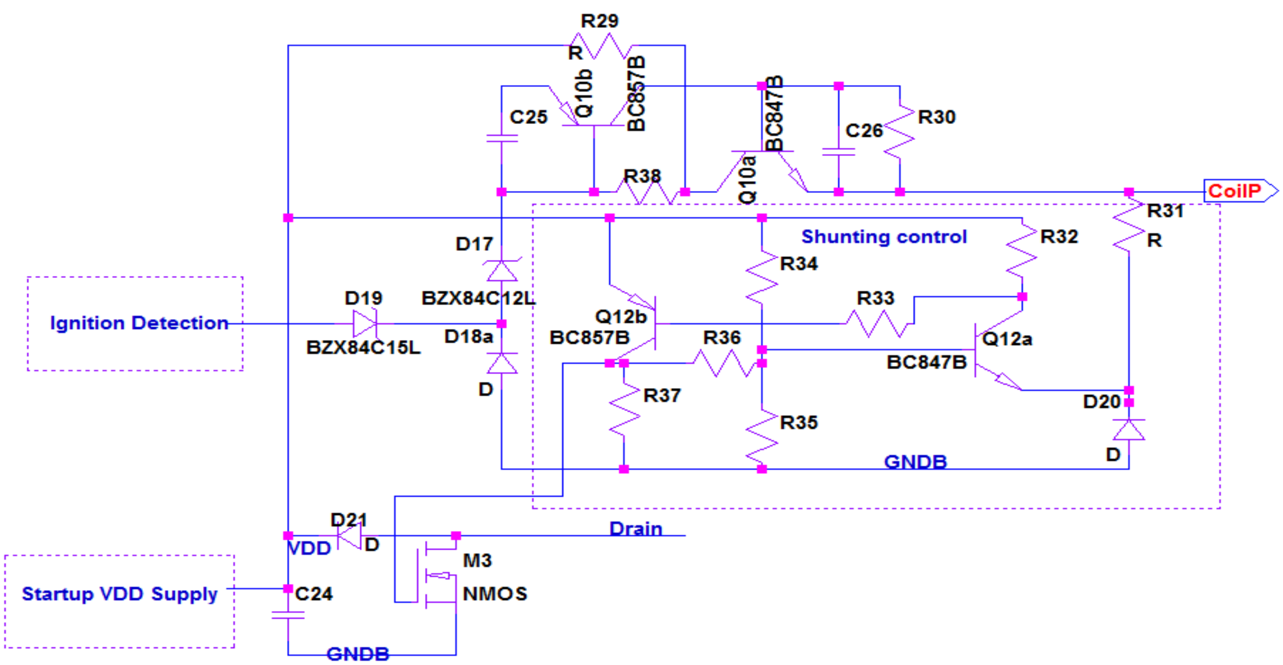


Figure 94: Relay shunt supply circuit

The present relay board architecture is shown in Figure 95. In the present safety relay solution, the startup capacitors and two relays are placed on daughter board, whereas rest of the circuit like ignition detection and startup VDD supply circuits are placed in motherboard.

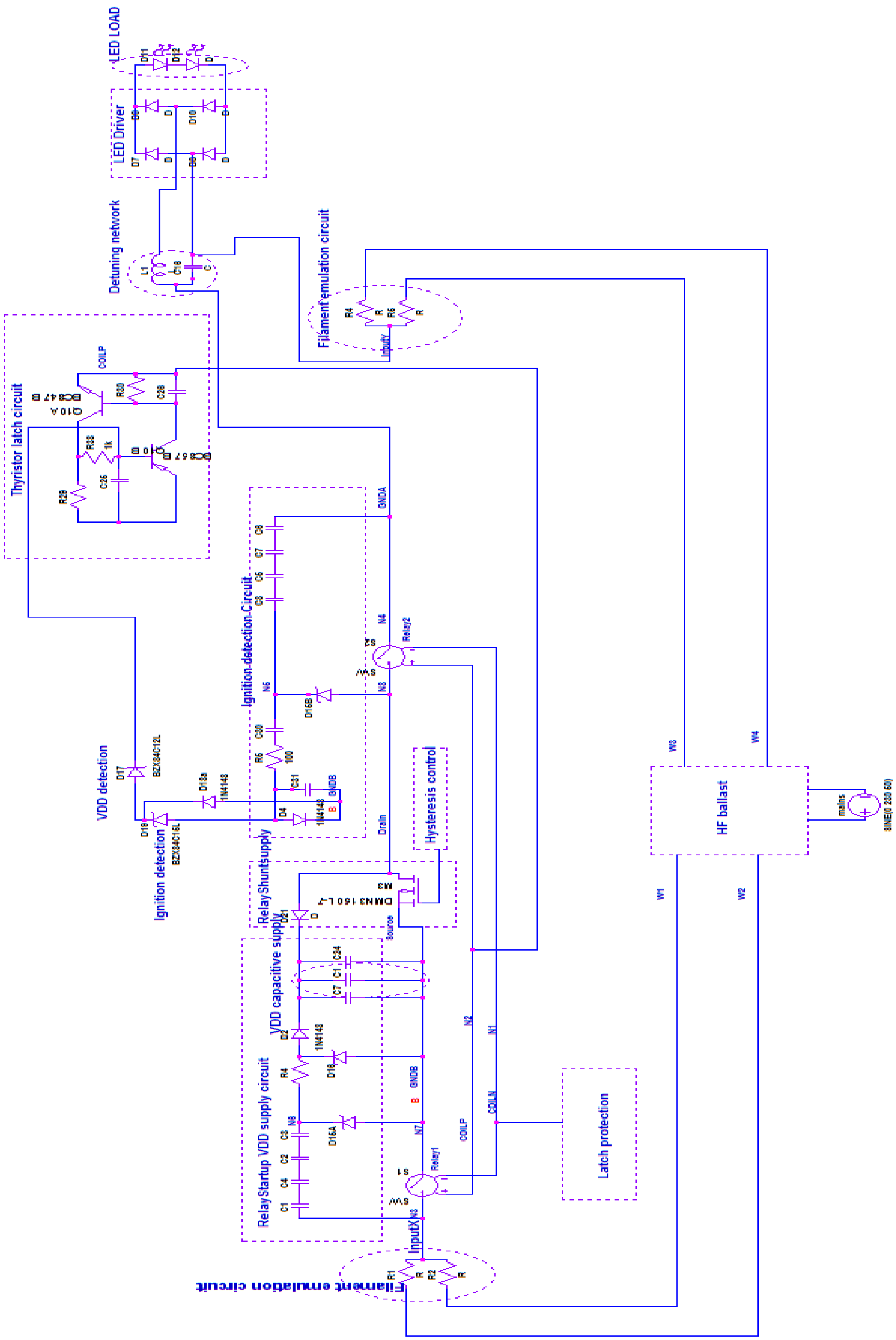


Figure 95: Present TLED Relay driver architecture

5.1.2 Redesigning of Daughter board and changes to Mother board, for integrating hybrid relay system to the TLED

After studying the present two electromechanical relay circuit architecture in detail, various methods of integrating hybrid safety relay system (EMR and TRIAC) are investigated: First possible way to integrate was just to replace the second electromechical relay (EMR) with the triac at the same location where second EMR is placed on daughter board. But after analyzing the basic creepage and clearance requirements of board, this way of integration was not possible. After few trials and analyzing the present relay board, the next best possible way to integrate hybrid relay system is to replace the daughter board with the redesigned architecture of electronics. Redesigned daughter board consisting of triac triggering circuit and relay start up circuit. For this new daughter board to be compatible with old mother board, few modifications to mother board are made. Below Figure 96 shows the newly redesigned daughter board.

The changes made in mother board are described below (refer to Figure 95):

- Latch protection is disabled by shoring a wire from N1 terminal to GNDB.
- N8 terminal is connected to N4 i.e drain of MOSFET is connected to GNDA.
- D15A, D15B are removed from the board, since both the ignition detection and VDD supply circuit are connected only across inputX -(relay) in redesigned daughter board rather than connecting VDD supply circuit across inputX and ignition detection across inputY.
- Power MOSFET N channel Switch M3-DMN3110S[V_{DS}=30V,V_{GS}=_+20V,$R_{DS(on)}$ =73mΩ@ V_{GS}=10V,I_{Dmax}=3A] is replaced with higher Drain-Source voltage MOSFET N Channel switch STD6NF10 [VDS=100V,VGS_{max}= -+20V;$R_{DS(on)}$=250mΩ@V_{GS}=10V,I_{Dmax}=6A). This is done because ,the relay VDD supply required is 24VDC ,Since relay which was used [EC2-NEC-series] has 24V coil voltage requirement[coil resistance 2.8K].
- Diode D21[PMEG3010BEA-Reverse voltage rating30V,Forward current rating 1A] is replaced with power diode PMEG6010BEA which has reverse voltage 60V,Forward current rating of 3A.
- Hysteresis loop control-Resistor R35 is changed from 10K to 1.5K to increase the VDD supply voltage.

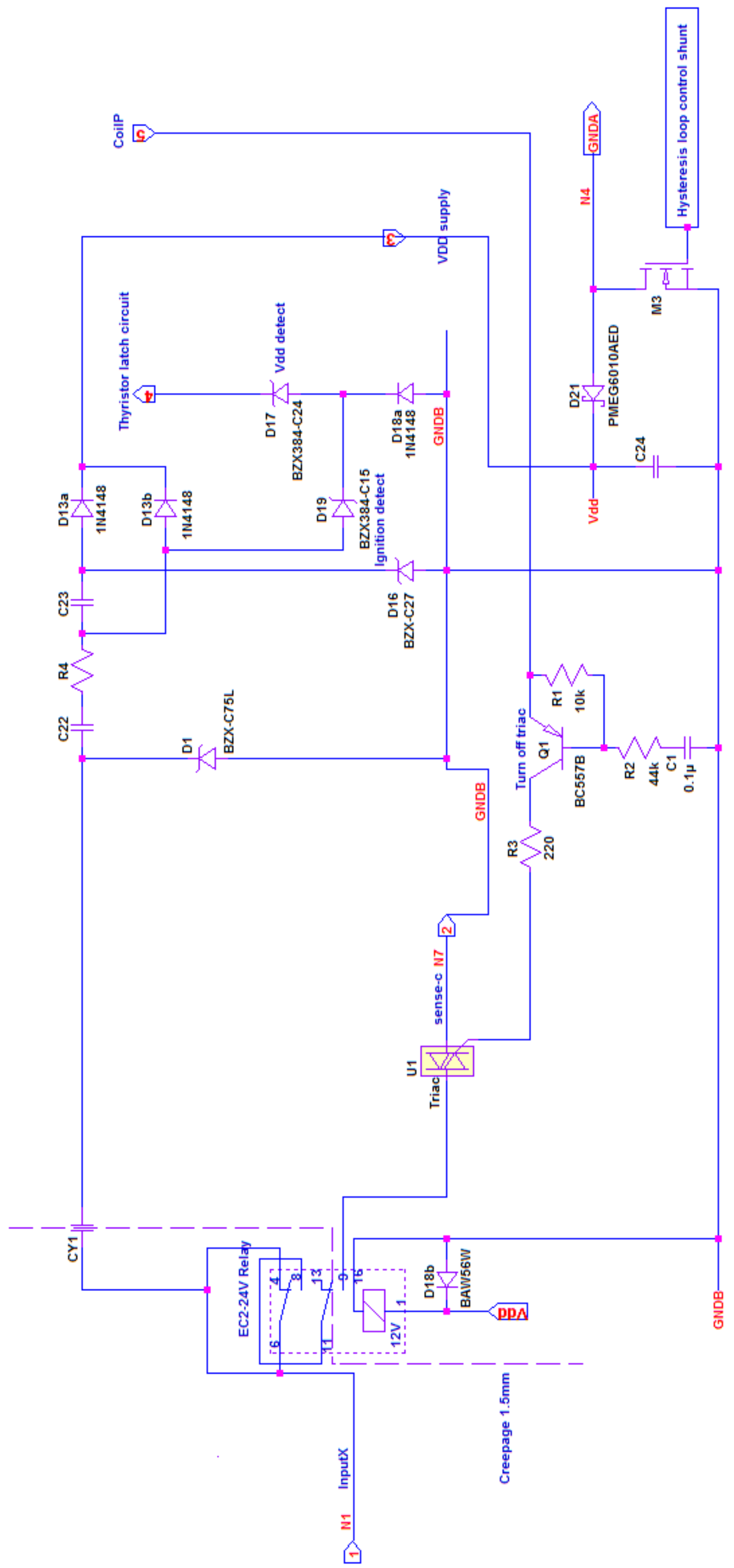


Figure 96: Redesigned daughterboard

5.1.2.1 Redesigned Daughter board circuit for hybrid relay system description

5.1.2.1.1 Startup Phase

The redesigned daughter board consists of various components, next will discuss about the use of each components in relay startup driver circuit (refer Figure 96).

The main principle behind the integration of hybrid relay system to TLED is that; relay (electromechanical relay) is switched on first, even before the ignition phase in HF ballast has started. After the relay has been switched on, then triac is switched on (triggered) after ignition detection. This principle used in hybrid relay system integration, where relay(EMR) is switched on first before TRIAC is switched on is to make sure that whole hybrid relay system comply with the safety rules and regulations laid by IEC regarding isolation ,clearance and creepage requirements. In the present TLED safety relay solution, VDD relay coil supply voltage circuit was designed to place across the first relay – i.e near the inpuX, whereas ignition detection circuit was designed to place across the second relay-i.e near the inputY. But in the redesigned board for hybrid safety relay solution, both the VDD supply circuit and ignition detection was placed across the electromechanical relay i.e inputX and not across TRIAC as shown in above Figure 96**.**

Capacitor CY1 is ceramic cap, which is used as a startup capacitor to build the startup voltage supply for relay coil. This capacitor is also serves another purpose as a safety capacitor as previously discussed about the present relay driving circuit. In this circuit, EC2 NEC relay type is used for testing. This relay is non-latch type, 24V rated coil voltage, coil resistance of 2.8KΩ and nominal power consumption is 200mW (for more details data sheet of this relay).The reason for choosing this relay type is, it has high coil resistance and hence consumes less energy compared to 12V FTR C1 relay type which has coil resistance of 514Ω, 12V rated coil voltage and nominal power consumption of 280mW (refer to data sheet of FTR-C1 relay type).Refer to Table 10 below for comparison between these two rely types.

Table 10: Comparison between two relay types

Relay type	Nominal coil voltage(V)	Coil resistance(Ω)	Nominal operating power(mW)
FTR-C1	12	514	280
EC2-NEC	24	2800	200

Zener diodes D1(75V) and D16(27V) are used to limit the voltage across the startup circuit for safety reasons and also during steady state , these diodes conduct a positive current and hence ultimately make sure that in steady state all the ballast current passes through the relay and triac combination but not in to the startup cap(CY1). The combination of diodes [D13a,D13b] which conduct positive current, capacitors[C22,C23]and resistor R4 are used to to supply charge to VDD supply capacitor(C24).This VDD supply capacitor after its charged to 24V ,supplies power to relay coil to switch on the relay during startup even before ignition is detected from the ballast. Zener diode D19 (15V) is used as an ignition detection element to detect scaled voltage of -15V.Zener diode D17(24V) is used as VDD supply voltage detection, which will conduct only when voltage across it reaches -24V. When both D19 and D17 diodes conduct a negative current, then the thyristor latch circuit gets triggered and this in turn supply the gate signal current to the triac. Hence triac is triggered and conducts ballast current after ignition. Since triac once triggered, doesn't require any gate signal to keep it on continuously, a RC circuit(R2,C1) has been designed to turn off the TRIAC gate pulse circuit ,when the anode to cathode current reaches above the rated latching current(I_L).

5.1.2.1.2 Steady state Phase

In steady state, both the relay and triac are in ON state and ballast current passes through them as shown in figure 8.The MOSFET gate signal is synchronized with ballast output frequency in steady state. The basic principle of operation is explained below from Figure 97:

- When VDD supply capacitor (C24) voltage is higher than the threshold level voltage (as discussed in hysteresis control), MOSFET is switched ON, such that it bypasses the ballast current so that it doesn't charge capacitor anymore. Then the capacitor C24 discharges to supply power to relay coil at this moment. Ballast current flows from inputX(pin N3) to Relay ,Relay to TRIAC,TRIAC to Pin N7(Sense-C) and then to GNDB, from GNDB to [Source –Drain] MOSFET. Finally from MOSFET drain terminal to GNDA. The current path for this mode of operation is shown in orange color in the Figure 97.Also refer LTspice simulation model(Figure 100

- When VDD supply capacitor (C24) voltage is lower than the threshold voltage level, MOSFET is switched OFF. Then the current from ballast enters the circuit via inputY making the diode D21 conduct positive current and hence charge the VDD capacitor to sufficient voltage. The current path for this mode of operation is shown with green color in the Figure 97.

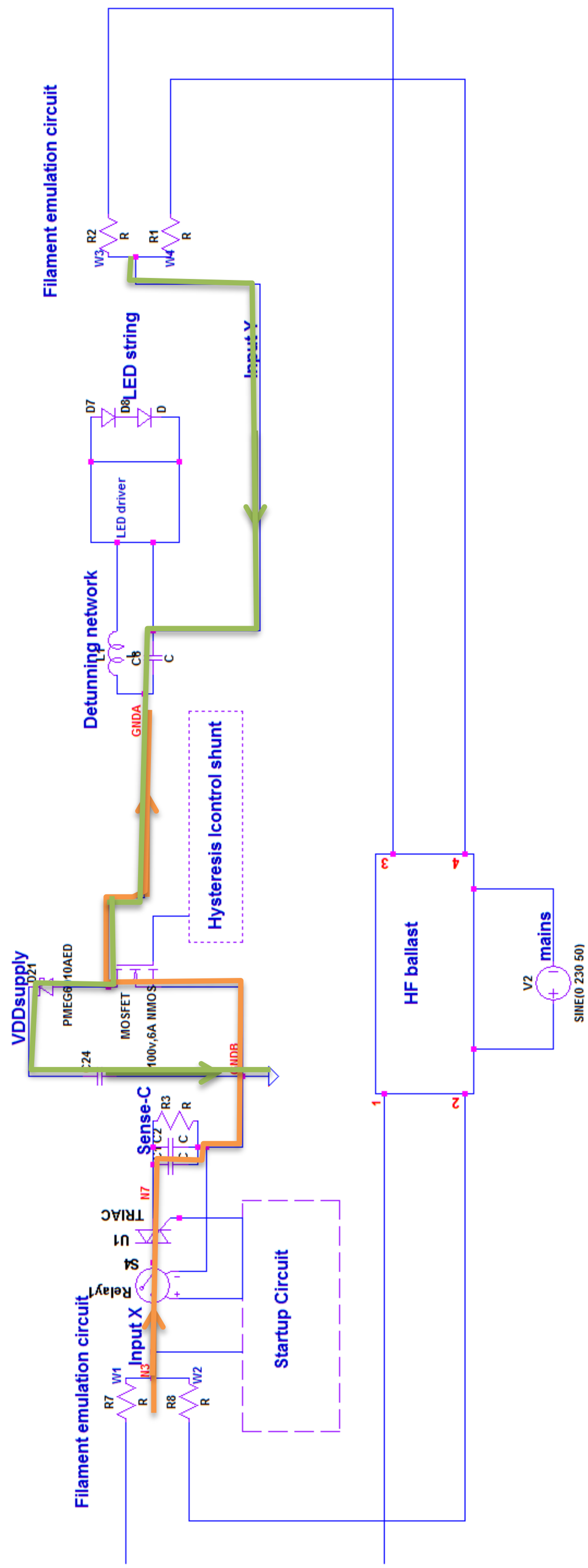


Figure 97: Working of hybrid relay system in steady state (Orange-MOSFET ON; Green-MOSFET OFF)

5.1.2.2 LTspice simulations of integrated hybrid relay system with driver board

Before building a hardware model for integrating hybrid relay system with TLED relay board, LTspice simulation model was designed and simulated (refer Figure 100). The waveforms of various signals are shown below in Figure 98 Figure 99, Figure 101,Figure 102:

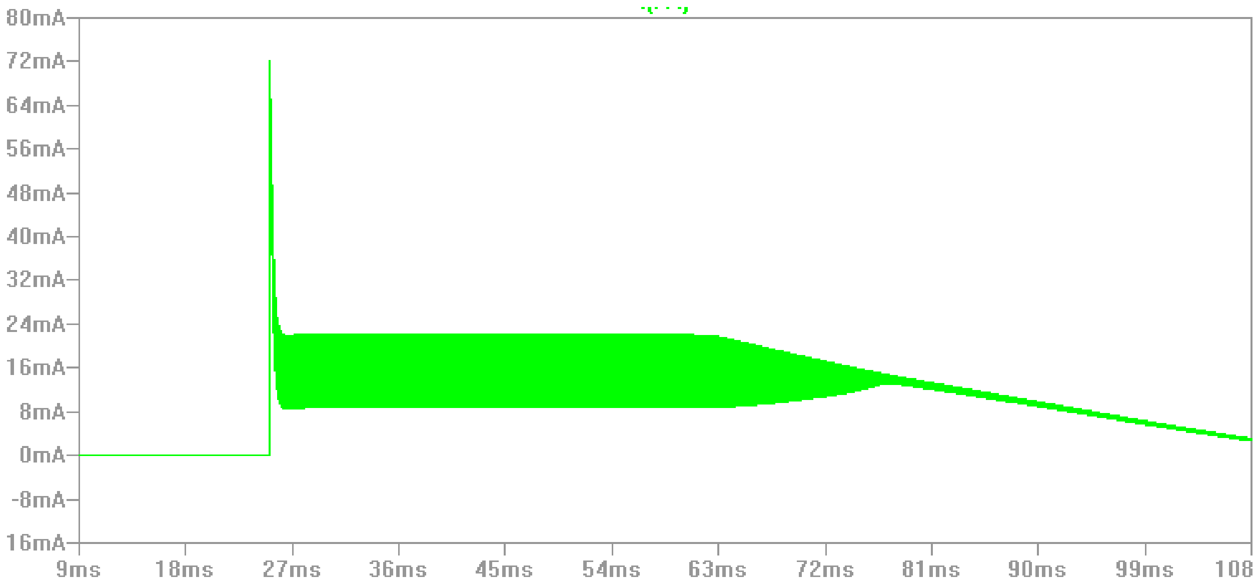


Figure 98: Triggering pulse to TRIAC

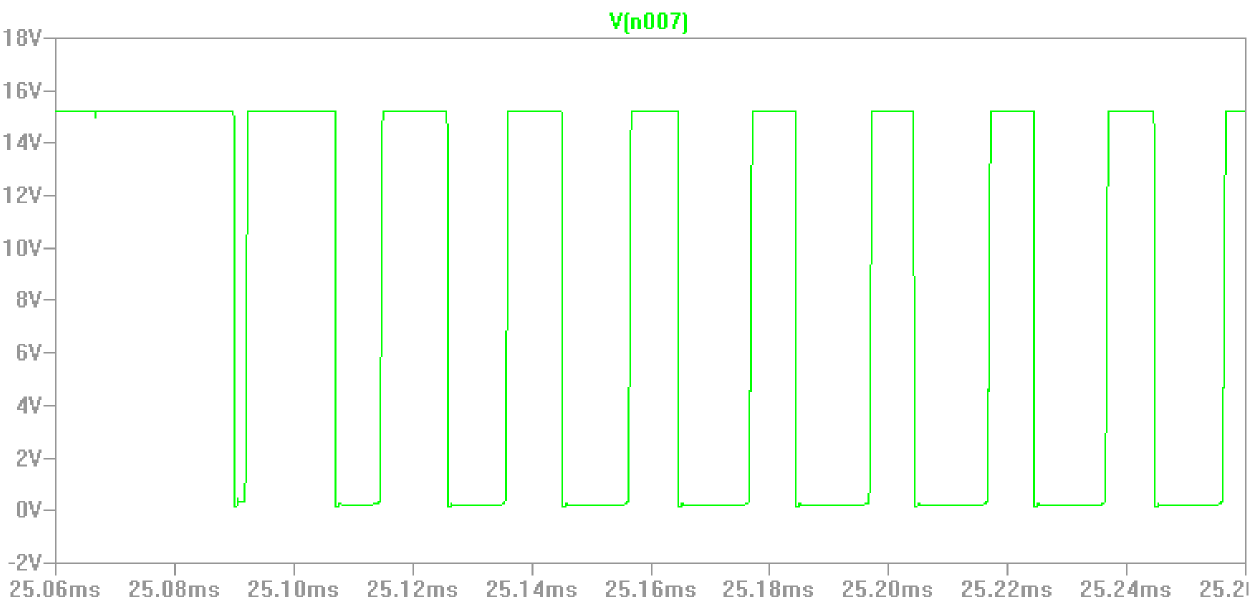


Figure 99: MOSFET (M3) gate signal

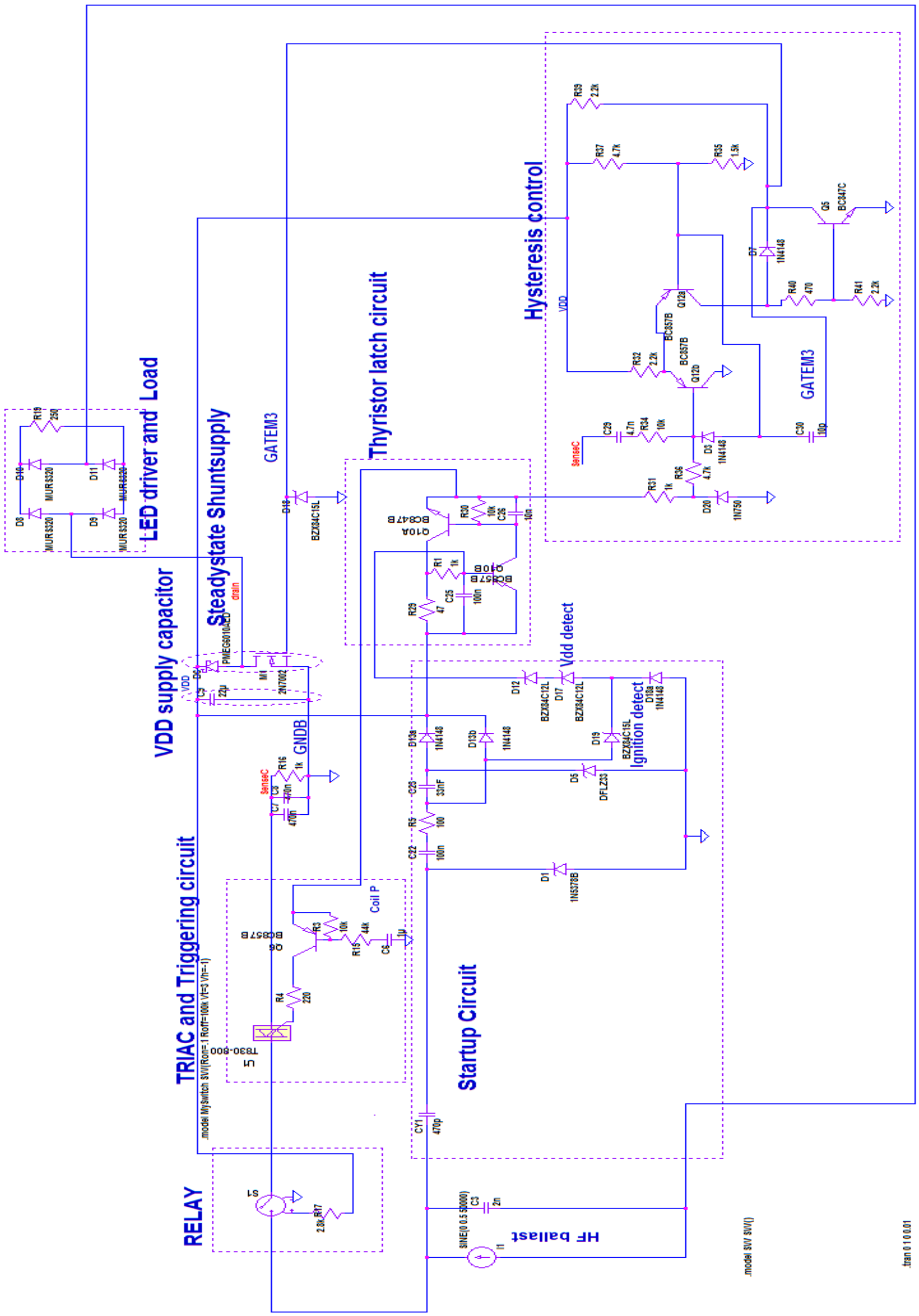


Figure 100: LTspice simulation of system after integrating hybrid safety relay system to TLED relay board

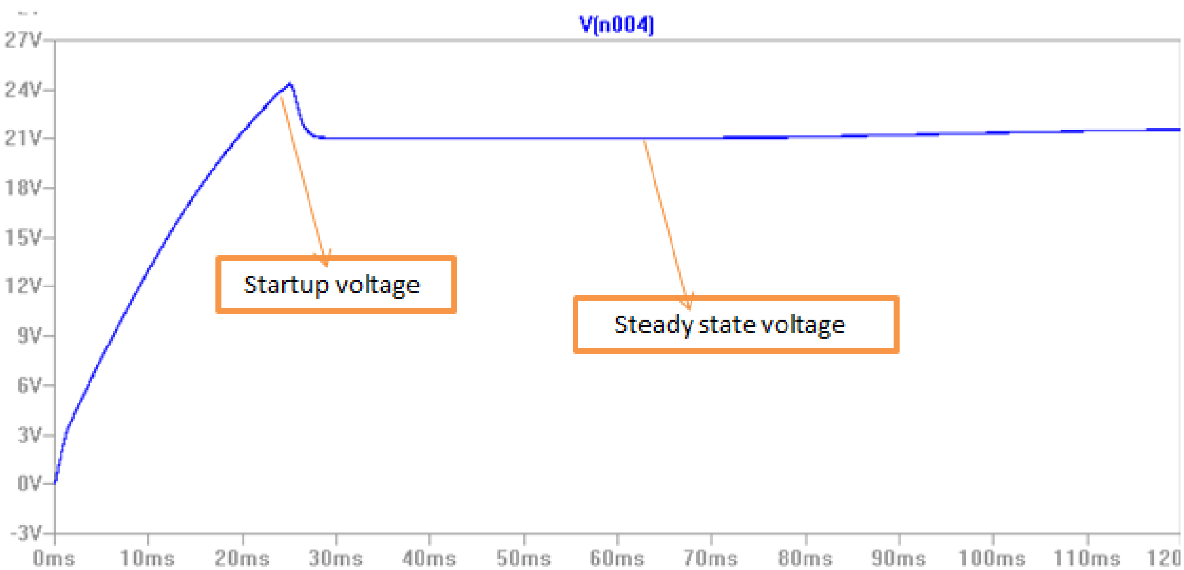


Figure 101: Voltage on VDD supply capacitor

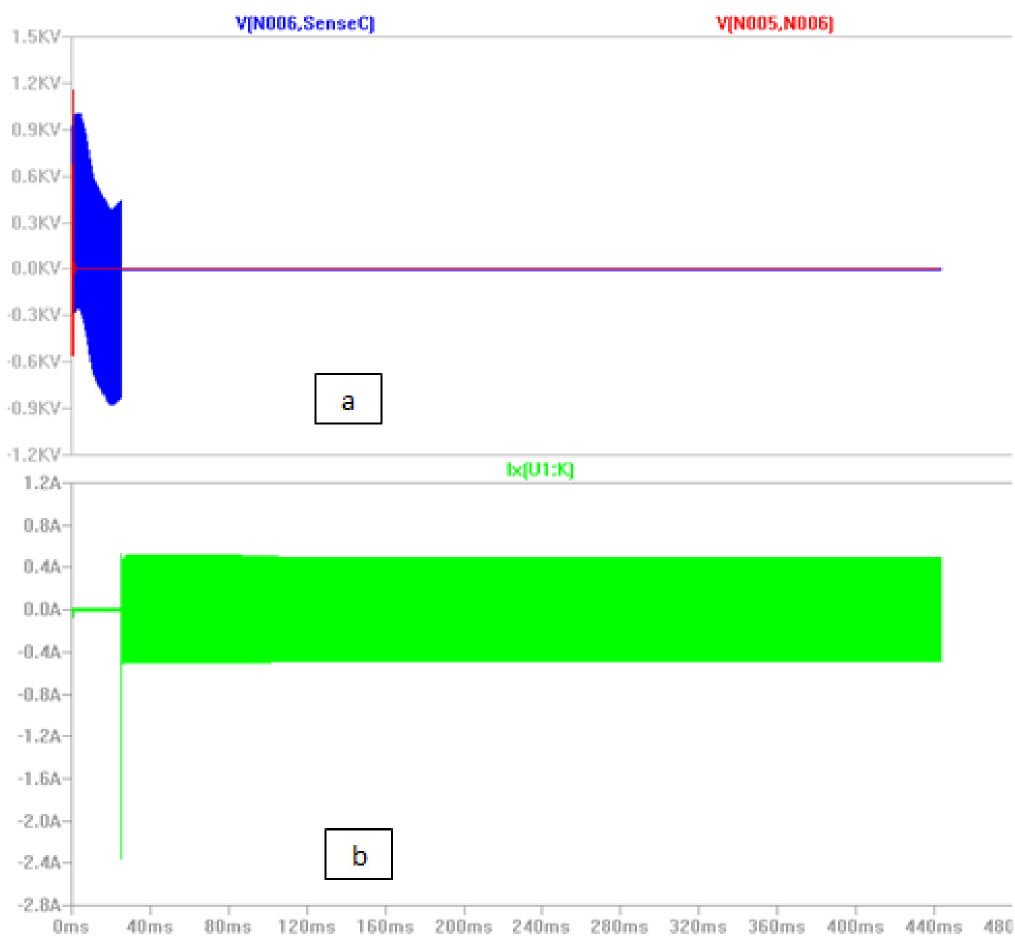


Figure 102: (a)blue color- Voltage on the triac, red color- voltage on relay (b)) current flowing through the relay and triac combination.

We can see from the Figure 102, first relay is switched on and then only triac is switched on by triggering pulse, hence simulation model shows the intended functionality of components and control circuit correctly.

5.1.2.3 Hardware test setup and results for integrating hybrid relay system with TLED

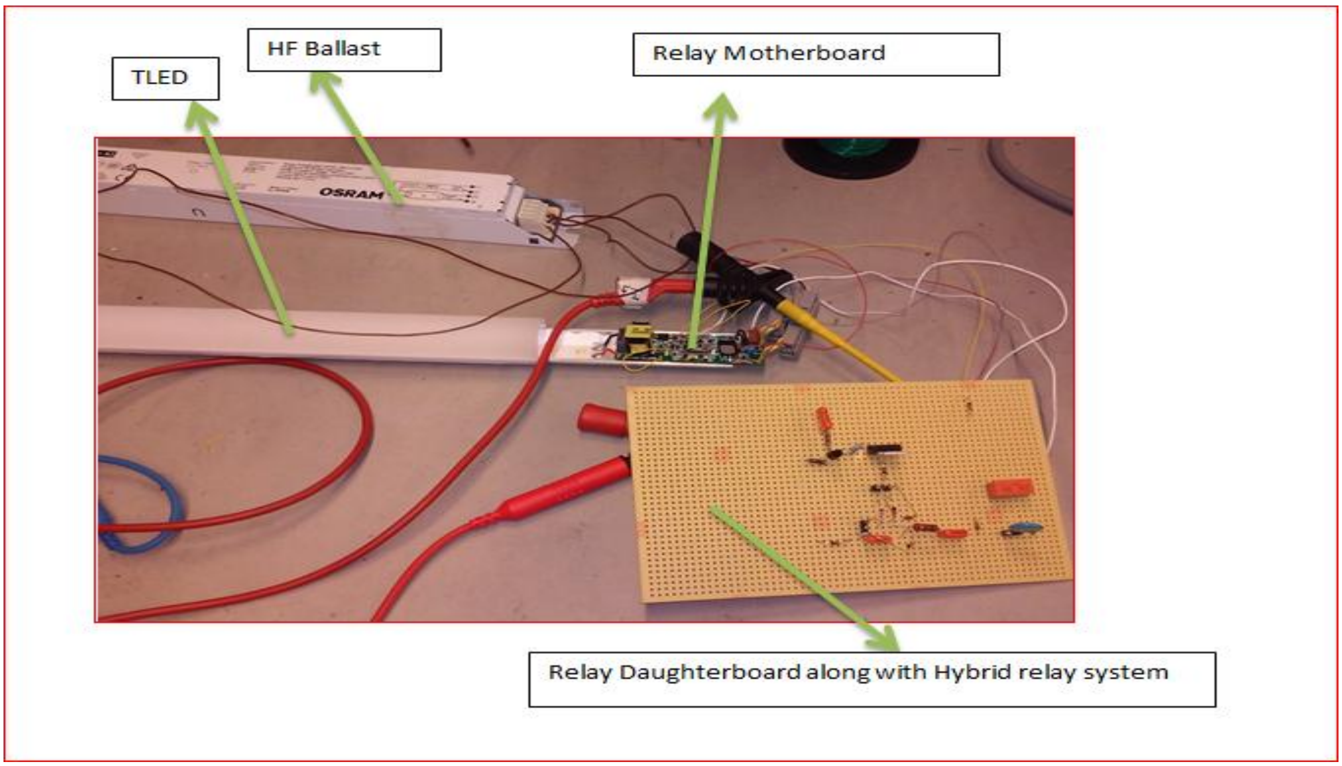


Figure 103: Hardware setup for integrating hybrid relay system with TLED

Figure 103 shows the hardware model test circuit designed in lab for integrating hybrid relay system with TLED.

The voltage and current waveforms captured in oscilloscope shown in Figure 104,Figure 105,Figure 106 during hardware testing: EC2-NEC relay 24V type and QTP8 1*58 ballast is used.

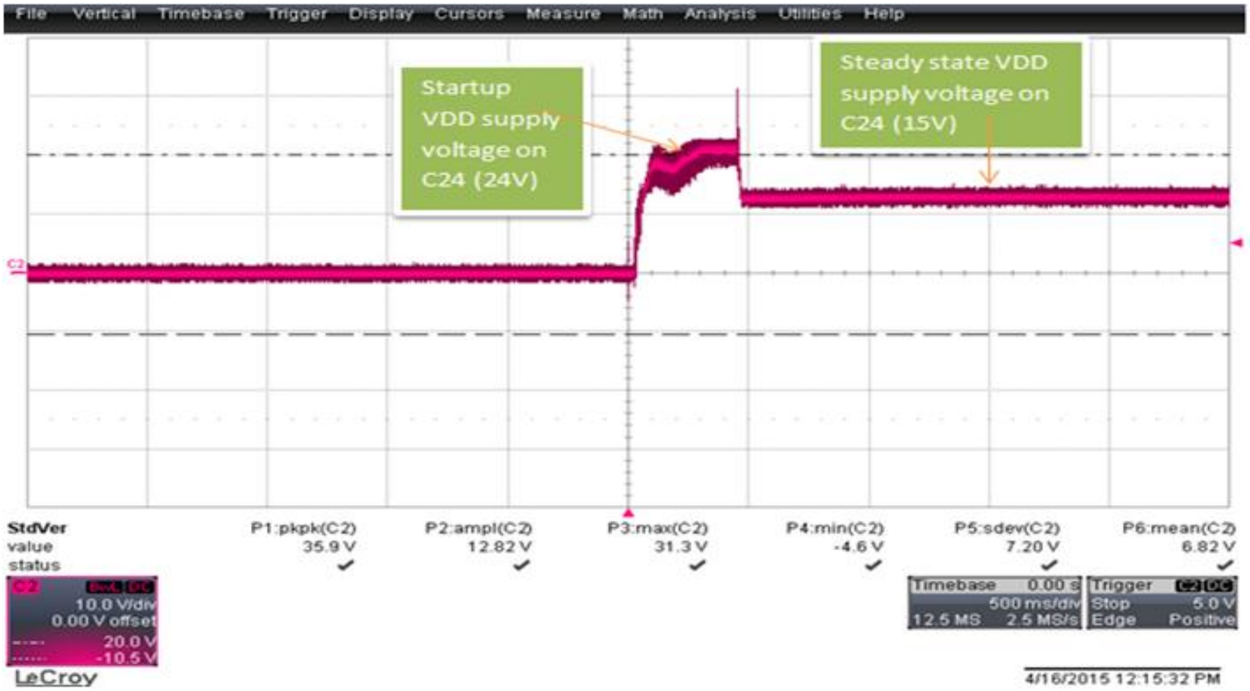


Figure 104: VDD supply voltage capacitor C24

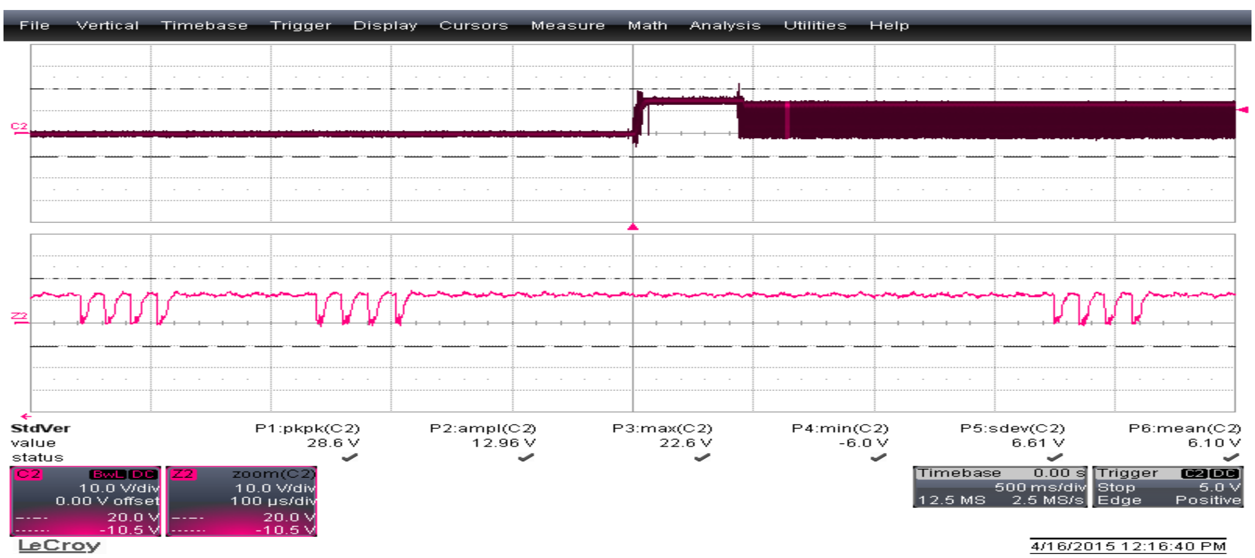


Figure 105: MOSFET (M3) gate signal

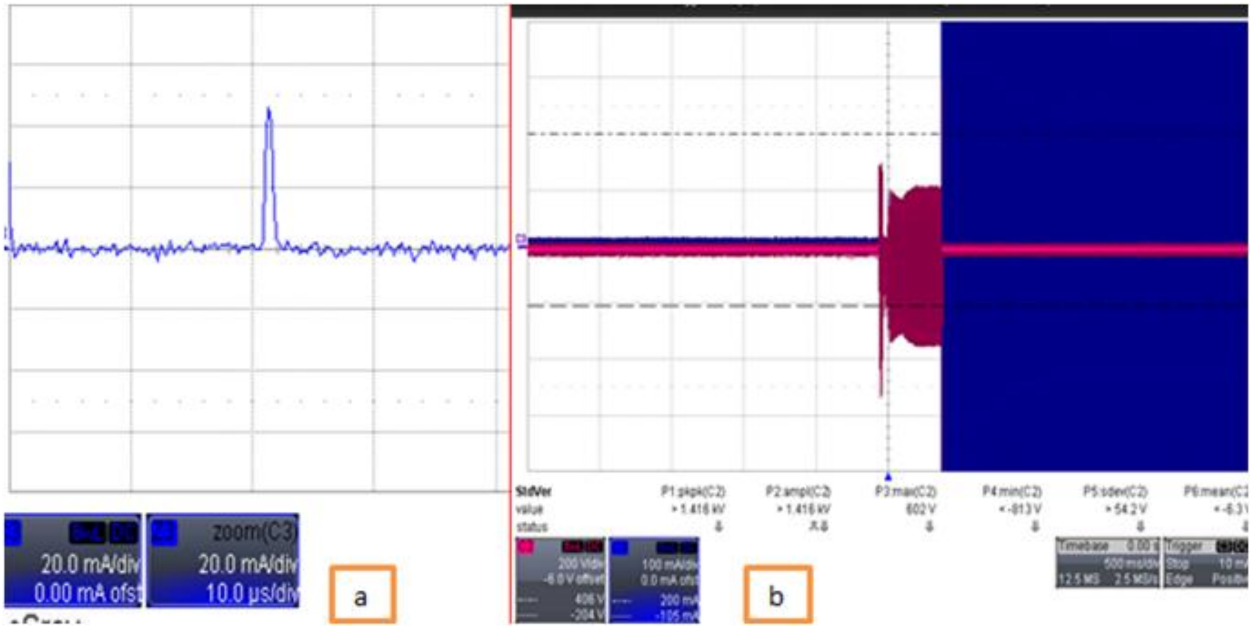


Figure 106: (a) Triac gate pulse (b) pink color- Voltage on triac, blue color-current flowing through triac(anode-cathode)

5.1.2.3.1 Hardware results observations and conclusion

After analyzing the results from hardware test setup, the following conclusions and observations can be made:

- The VDD supply voltage on capacitor in steady state is 15V and during startup it is 24V .This results exactly match with simulation results.
- The trigger pulse to triac is designed to give a peak pulse magnitude of 60mA, but in hardware it is only 45 mA. The reason can be attributed to tolerance values of components used.
- The relay is switched ON first and then triac is switched ON after ignition voltage is detected from ballast, hence control circuit functions exactly as per design.
- MOSFET gate signal shows a deviation in steady state phase, as MOSFET is not switched in every cycle of ballast frequency .After analyzing carefully, the main reason for this deviation was found. The reason is that the hybrid safety relay system consumes very less energy from VDD capacitor; hence gate signal of MOSFET is always ON and only few times switches OFF-which mean mains current is shunted for long time. Hence the new hybrid safety relay hardware prototype is very energy efficient compared to older TLED safety solution. However to prove that it consumes less energy, a resistor of 1kohm is connected parallel to relay coil resistance. By adding a 1kohm resistor parallel to coil resistance, the net resistance of coil is reduced so that relay coil consumes more power. The change in MOSFET signal behavior during this experiment is captured and shown in Figure 107, from this figure one can observe that MOSFET gate signal switches OFF number of times higher than without 1kohm resistor connected across coil. This

proves that by reducing coil resistance of relay, energy consumed by hybrid relay system is more compared to original design without 1kohm resistor across coil.

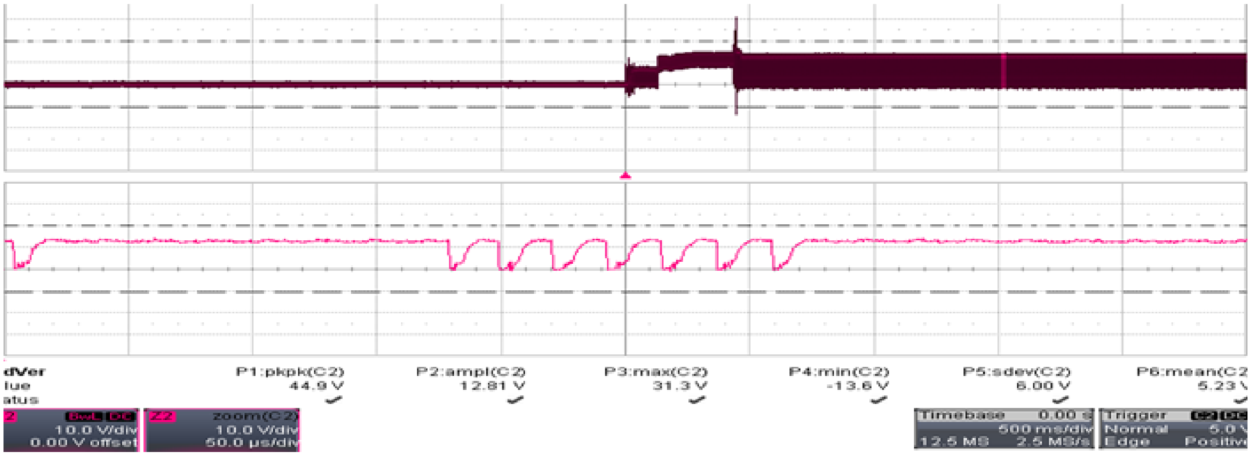


Figure 107: MOSFET (M3) gate signal after 1kohm resistor is added parallel to relay coil.

- Similar experimental tests are perfumed with few other warm start ballasts like HF- Perfomer-II(HF-P158),QT-FIT8,HF-S-158 and lamp is able to start and functioned as expected. But with some ballasts like QTP8 1*36 the lamp is unable to start due to insufficient voltage during startup on relay coil. The VDD supply voltage waveform is shown in Figure 108.The main reason for this behavior is attributed to the fact that each ballast has preheat frequency which was designed by manufacturers, hence different preheat frequency influences the startup capacitor impedance to current flow according to equation given below, and this in turn influences the startup VDD supply voltage circuit and hence not enough voltage is generated during startup.

$$X_C = \frac{1}{2 * \pi * f} \tag{13}$$

Since preheat frequency of ballast is never specified on datasheet, it is very hard and time consuming to find out preheat frequency of each ballast in lab and design the startup voltage supply components accordingly. Hence lot of fine tuning of the startup circuit is needed for making this system work for all kind of warm start ballasts, keeping time constraint this work is recommended for future research. This experiment also proves that the designed hybrid safety relay system has influence on other components of TLED like LED driver, which are not well taken into consideration while designing.

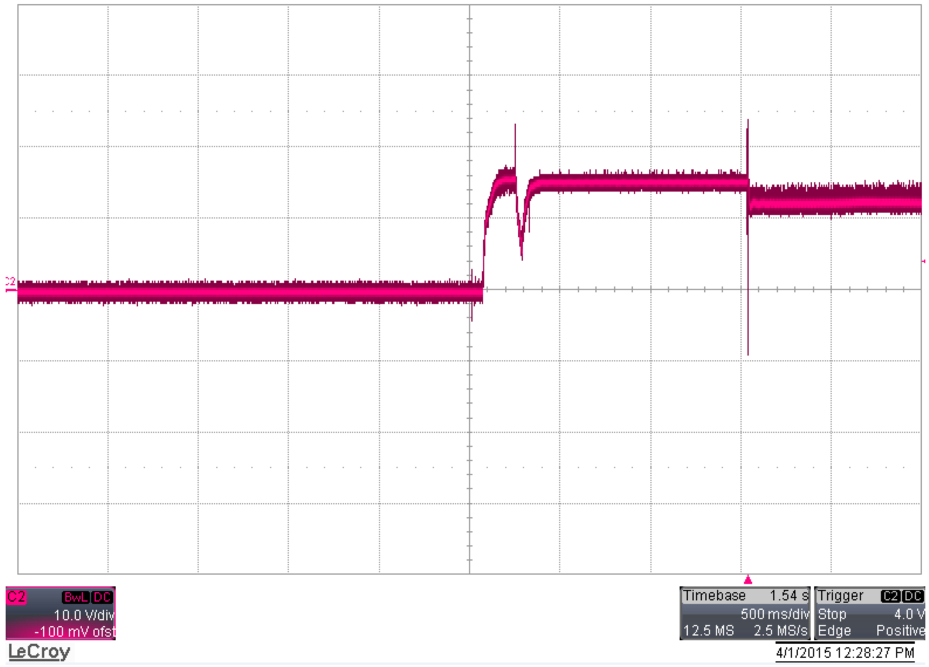


Figure 108: VDD supply voltage on capacitor C24 when QTP-OSRAM(1*36) ballast is used

Thus successfully hybrid safety relay system with one triac and one electromechanical relay is integrated to TLED relay board and lamp is tested with this integrated circuit. This system can block few warm start ballasts. Thus final goal of this project is achieved with some design trades off like fine tuning recommended for future research.

Chapter 6: Conclusion and recommendations for future research

6 Chapter 6: Conclusion and recommendation for future research

The hybrid safety relay system was designed and tested for its functionality as discussed in previous chapter. In this chapter the conclusions from the study and work performed in thesis at Philips light labs are discussed along with the future recommendations for research.

6.1 Conclusion

The major objective of this thesis project was to design a hybrid safety relay system for TLED based on one electromechanical relay and one semiconductor switch combination so as to implement safety relay system for TLED with low cost, low energy consumption and also eliminate the bouncing and arcing effects associated with using two electromechanical relays.

In order to achieve this goal, the project was divided in to several research questions. Some major conclusions are drawn below:

1. The optimum high voltage semiconductor switch that is best suitable for blocking high voltage and high frequency signal from high frequency (HF) ballast is found be TRIAC device. This conclusion is made after analyzing the properties of various high voltage devices like MOSFET/BJT/IGBT/TRIAC that fulfils the essential requirements for acting as a safety switch (relay) in TLED.

- After series of experiments on main characteristic of TRIAC - Static dV/dt , it is found that single TRIAC switch is able to block high dV/dt from only few warm start ballasts. Hence to solve this problem, a system with two TRIACs in series was proposed to block high voltage and frequency from most of the warm and cold start ballasts.
- The proposed system with two TRIACs in series has an advantage of not requiring snubbers. Since using snubbers will improve TRIAC behavior but also it imposes considerable stress on TRIAC that can limit the use of it and also snubbers add cost to the system.
- The proposed two TRIACs in series system was tested for its static dV/dt and found to be blocking all clod and warm start ballasts without being much effected by miller effect. The measured leakage current was less than 30mA.

2. The proposed hybrid relay system with two TRIACs in series was simulated in LTspice after exploring ways to drive two TRIACs in series with minimum components and driving them with low energy and low cost. After analyzing the results from simulation, a hardware prototype was built and tested for its functionality.

- After analyzing the essential requirements of TLED, timing control and drive circuit was designed and simulated with minimum components and low energy consumption.
- The tests results proved that the prototype performs the intended functionality as per the design and consumed less energy when TRIACs were triggered in 3rd quadrant.

3. After carefully analyzing the present relay board architecture, it was found that integrating two TRIAC solutions with TLED driver board is very complex requiring lot of time and skills concerning PCB design and fulfilling creepage and clearance requirements laid by safety standards such as IEC. Hence decided with go for integrating only single TRIAC solution for few of the warm start ballasts instead of all warm and cold start ballasts.

- The ways of integrating the TRIAC and triggering circuit was explored and best possible way was found to redesign the present relay board for making it to be compatible for hybrid safety relay system.
- The redesigning process required a lot of understanding and analyzing the present safety solution and accordingly all the startup and steady state voltage circuits for VDD supply redesigned. A simulation was made on proposed design and compared with the hardware prototype.
- The results were analyzed and found most of the waveforms obtained are comparable to the simulation results and hence the hardware prototype performs the intended functionality, but only MOSFET gate signal showed deviation from its expected behavior. The reason for this behavior was analyzed and tested. Hence by this experiment it is proved the energy consumed by the designed hardware model is less than the simulation model. This tells us that hybrid relay system has influence on other parts of TLED like driver and other parameters, which are not exactly represented in simulation.
- When tested with different HF warm start ballasts, most of them are able to start the lamp and give similar results, but with few types of ballast the lamp is not able to start due to insufficient voltage build on VDD supply capacitor. However the reason for this behavior of few ballast is analyzed and found that it is connected with preheat frequency of different ballasts, which influences the startup capacitor impedance to the current flow and hence the startup supply circuits for relay and triac behave differently with different ballasts.

6.2 Recommendations for future research

Since thesis is carried in a limited period of time, all the steps for testing the hybrid safety system was not performed. Hence further study and design is still needed:

- The single TRIAC system along with triggering circuits was integrated to TLED relay board for only few warm start ballast applications. However further analysis is needed to integrate hybrid safety relay system that can block all warm and cold start ballasts which consisting of two TRIACs in series operation with one electromechanical relay. More analysis should be done focusing on creepage and clearance requirements of TLED and driving two TRIACs in series with less energy consumption from startup supply.
- The designed hybrid safety relay system works with few of the warm start ballasts but with few types of ballast like QTP8 1*36, lamp is unable to start due to insufficient voltage on VDD supply capacitor during startup. Hence to make the designed system work for all warm start ballasts, future research has to be carried out for fine tuning various components involved in startup voltage supply considering different HF ballasts preheat frequency as an important parameter.
- More research has to be done to reduce the leakage current through TRIACs in order to ensure safety during abnormal condition i.e one end connected to mains and other end is open.
- Switching tests have to be performed to test the reliability of designed hybrid safety relay system.

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8 Appendix

Appendix A

This section deals with more details of 555 timer and basic calculations:

In this project LM555 timer manufactured from "TEXAS INSTRUMENTS "is used, the Figure 109 shows the basic schematic of LM555 timer, showing the 8 pins and their functions.

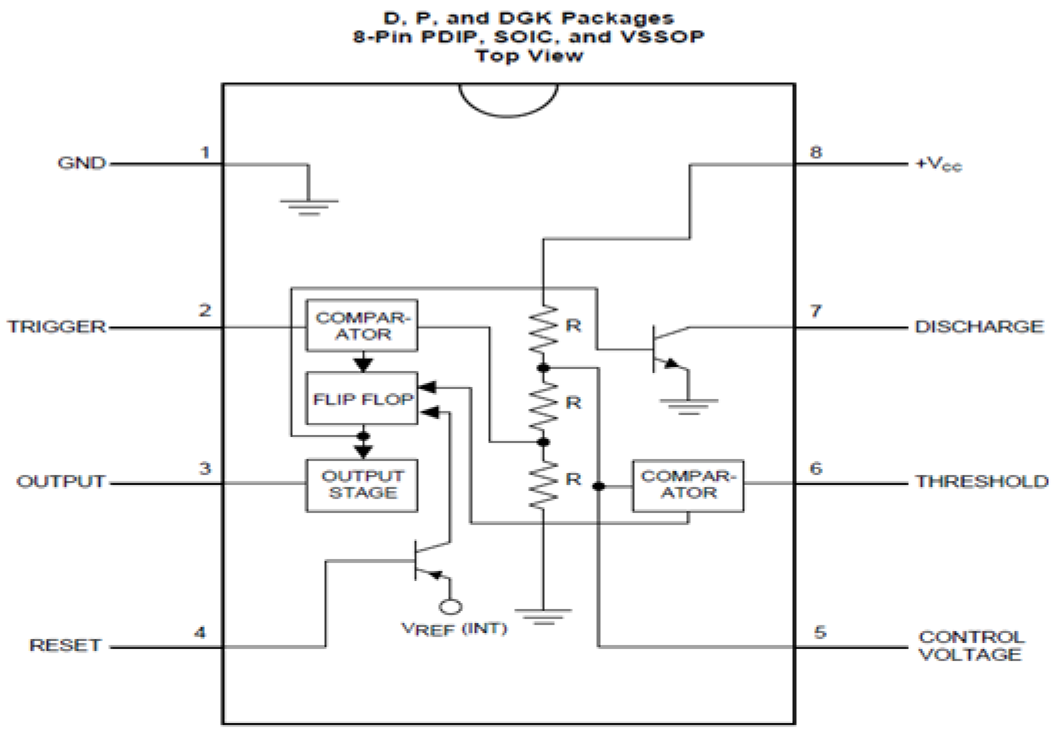

Figure 109: Basic LM555 Timer schematic showing 8 pins and their intended functionality [29]

The basic calculations for operating 555 timer in astable mode is given below:

Charging time t1 is given by:

$$t1 = 0.693(R1 + R2)C1 \tag{14}$$

Discharging time t2 is given by:

$$t2 = 0.693(R2)C1 \tag{15}$$

Total duration of one full cycle is T:

$$T = t1 + t2 = 0.693(R1 + 2R2)C1 \tag{16}$$

The frequency of operating cycle is F=$\frac{1}{T}$, hence

$$F = \frac{1.44}{(R1 + 2R2)C1} \tag{17}$$

Duty cycle D is given by:

$$D = \frac{Ton}{Ton+Toff} = \frac{R1+R2}{R1+2R2}\% \tag{18}$$

Using the above equations, the frequency of oscillation, duty cycle is calculated for this project. After trying out this parameters in simulation, the best frequency of operation was chosen >110 kHz. High frequency of oscillation is necessary to reduce the inductance required by primary winding of the gate drive (isolation) transformer according to basic equation $V_L = L * \frac{dI}{dt}$. After basic calculations, R1, R2 and C1 values were estimated, given below:

R1=820Ω,

R2=1.5KΩ,

C1=0.0033µF,

Ton=5.306µs,

Toff=3.430µs,

D=60.73%,

F=114 KHz

The duty cycle D is tuned in such a way that, $V_{ON}*t_{ON}=V_{OFF}*t_{OFF}$. Where V_{ON} is voltage on primary winding of gate drive transformer during high pulse from 555timer output (9V), whereas V_{OFF} is the voltage on primary winding of transformer during low pulse from 555timer(-15V due to resetting flux network). Thus volt time product during high pulse and low pulse should be equal so that, transformer doesn't go in to saturation and high oscillating voltage (AC) pulse results on primary side of transformer without a DC component in it. The DC component in oscillating signal leads to power loss, since DC power cannot be transferred across secondary's of gate drive transformers.

Appendix B

This section deals with more details of isolation transformer and basic calculations:

Figure 110 shows the two winding transformer model,with both currents i_1 and i_2 entering the positive terminal of winding 1 and winding 2 respectively. The volatges of the two windings can be defined as :

$$\boldsymbol{V_1 = L_{11}\left(\frac{di_1}{dt}\right) + L_{12}(\frac{di_2}{dt})} \tag{19}$$

$$\boldsymbol{V_2 = L_{21}\left(\frac{di_1}{dt}\right) + L_{22}(\frac{di_2}{dt})} \tag{20}$$

Where,

L_{11} = self-inductance of winding 1

L_{22}= self- inductance of winding 2

i_1 = current in winding 1

i_2= current in winding 2

L_{12}= mutual inductance in winding 1 due to winding 2

L_{21}= mutual inductance in winding 2 due to winding 1

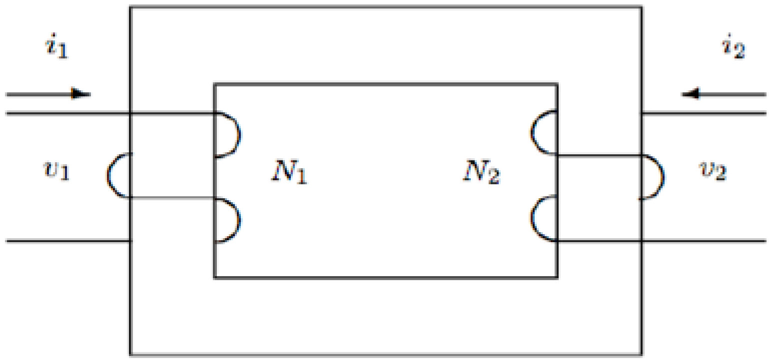

Figure 110: A two winding transformer model [32]

From [34] it is seen that, inductances L_{12} and L_{21} are equal, and hence can be replace by symbol M. The value of M is dependent on the coupling of the two windings, determined by the core material. It is defined by the coupling coefficient *k* as [32]:

$$\boldsymbol{K = \frac{M}{\sqrt{(L_{11}L_{22})}} \qquad -1 \leq K \leq 1} \tag{21}$$

K is in general is near to the value of 0.998 in iron core transformers. Higher the value of K, higher the coupling of the windings and this results in lesser leakage inductance and hence finally contributes to higher efficiency of pulse power transfer from primary to secondary. For defining the similar concepts for 3 winding transformer, this 2 winding transformer model can be extended to include the effects of additional winding. The modified equations are shown below:

$$\boldsymbol{V_1 = L_{11}\left(\frac{di_1}{dt}\right) + L_{12}\left(\frac{di_2}{dt}\right) + L_{13}\left(\frac{di_3}{dt}\right)} \tag{22}$$

$$\boldsymbol{V_2 = L_{21}\left(\frac{di_1}{dt}\right) + L_{22}\left(\frac{di_2}{dt}\right) + L_{23}\left(\frac{di_3}{dt}\right)} \tag{23}$$

$$\boldsymbol{V_3 = L_{31}\left(\frac{di_1}{dt}\right) + L_{32}\left(\frac{di_2}{dt}\right) + L_{33}\left(\frac{di_3}{dt}\right)} \tag{24}$$

From the above equations it is very clear that each winding will have effect on all other windings. And thus we can define approximate voltage equations for any n winding transformer using same principles.

In general, modeling of 2 winding transformer is very common in engineering practice and many literatures are available to describe the equivalent circuit models. However, modeling 3 winding or n winding gate drive transformer is very rarely found in literatures. Hence in few literatures [31] to define the n winding or 3 winding transformer model, an extended cantilever model and Nport model was used for approximate analysis. Figure 111 shows the normal n winding transformer model, its extended cantilever model and N-port model.

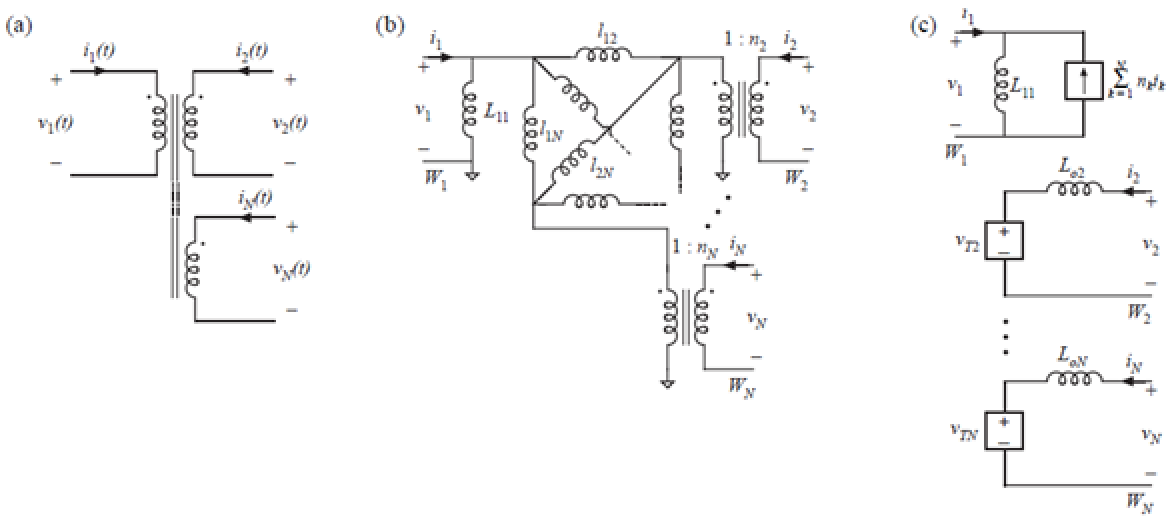

Figure 111: a) N winding transformer (b) extended cantilever model (c) N-port model [31]

For understanding the coupling between windings of gate drive transformer, leakage inductance effects and other related magnetic effects, a detailed study was made using the reference [35].However discussion on this study is beyond the scope of this thesis and not discussed in this document.

Designing a gate drive transformer:

Table 11: Transformer core material selection with respective frequency range of operation [20]

Vendors	Frequency range(10-200)kHz	Frequency range(200-500)kHz	Frequency range(500-1000)kHz
Ferroxcube	3C90	3F3	3F35
Epcos	N67, N87	N49	N49
ACME	P4	P5	P51
Mag Inc.	P	R	K
Nicera	NC-2H	2M	5M
TDK	PC40	PC50	PC50

Table 12: Choosing right primary inductance value versus operating frequency [20]

Operating Frequency (kHz)	Primary Inductance (mH)
50 to 100	2 to 4
100 to 300	0.5 to 2
300 to 500	0.05 to 0.5

Appendix C

This section gives more waveforms of simulation and hardware test results during designing hybrid safety relay system with 75VDC.

LTspice simulation results:

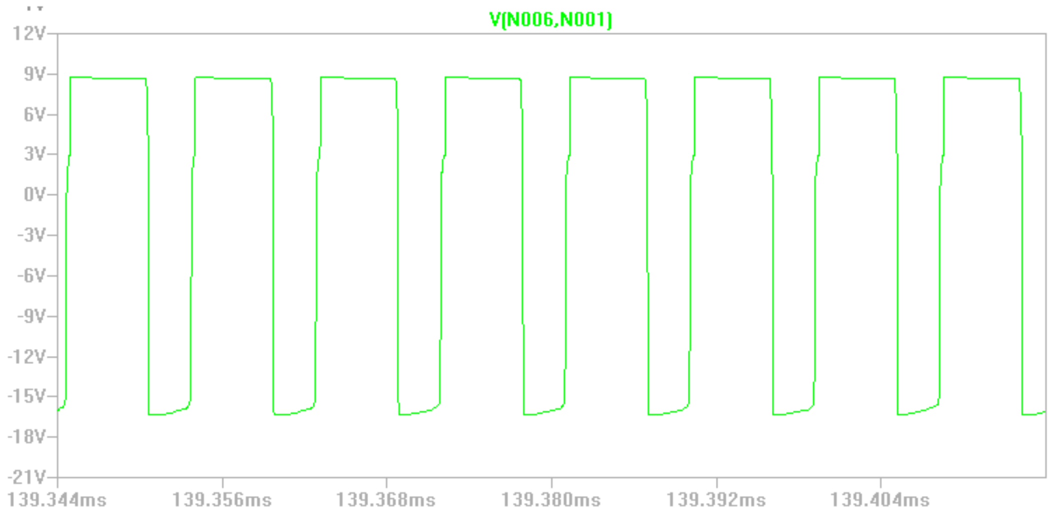

Figure 112: Primary winding voltage

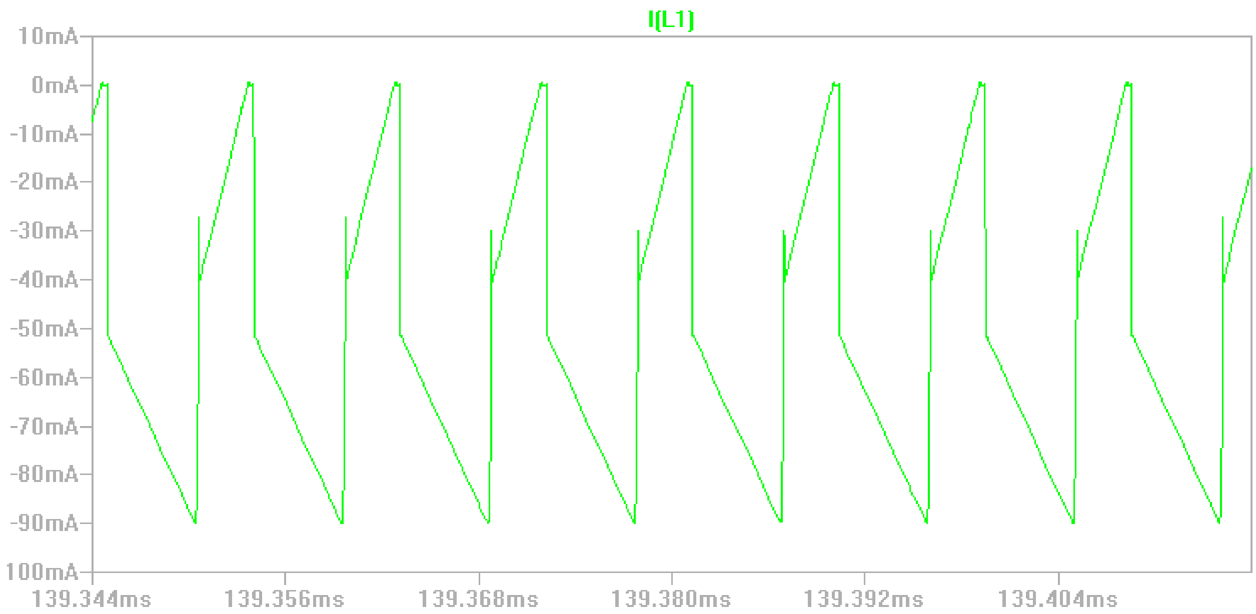

Figure 113: Primary winding current

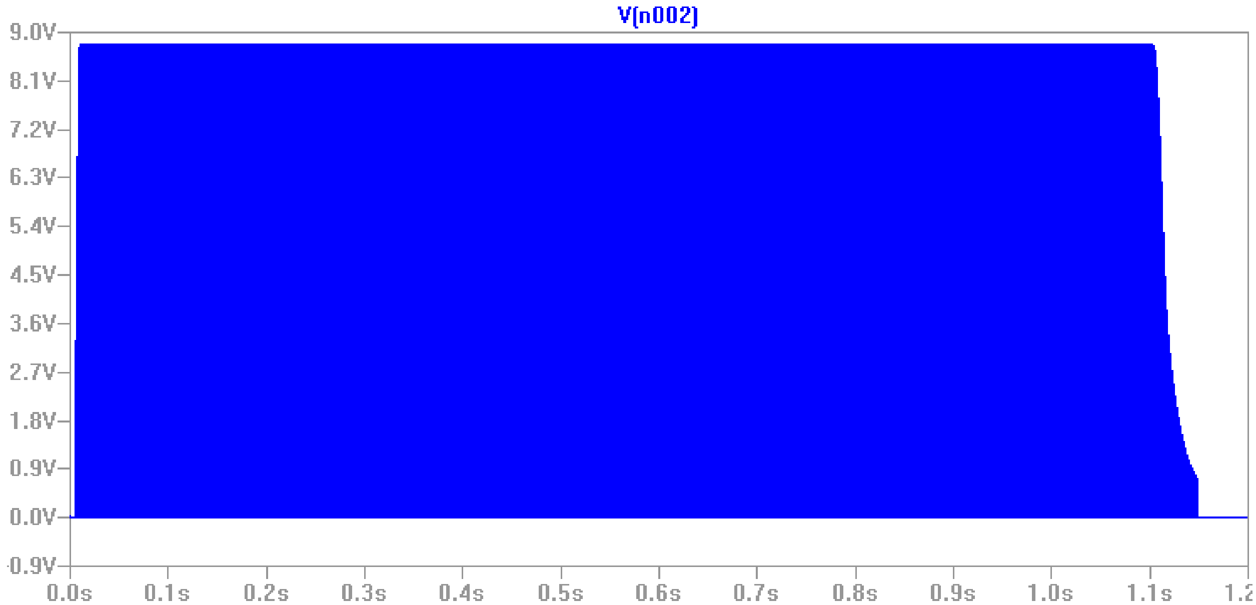

Figure 114: Zoom out version of 555 timer output voltage oscillating at 114 kHz, showing signal stops after 1s as designed.

Appendix D

This section details more about different HF ballasts tested and results of testing with single triac and two triacs in series.

Table 13 shows the different HF ballasts and their specifications. Table 14 shows the test results for blocking capability of triacs with different HF ballasts.

Table 13: Different HF ballasts types and their specifications

Ballast type	Output voltage(V)	Input current(A)	Power(W)	Type of starting method
HF-R 158 TLD(9137001116)	350	0.27-0.25	58	Warm
HF-S 158 TLD-II(9137130322)	380	0.27-0.24	58	Warm
HF-S 158	300	0.27-0.24	58	Warm
HF-P 158 TL-D III IDC(9137130318)	320	0.31-0.2	58	Warm
HF-P 158 TLD EII(9137001912)	< 300	0.25-0.24	58	Warm
HF-Pxt 158 TLE EII(9137006179)	300	0.25-0.24	58	Warm
HF-E 158 TL-D(9137130389)	380	0.24	58	Warm
HF-S158TL-D	380	0.29-0.20	58	Warm

II(9137130322)				
BCS58.1SR-011	250	0.25	58	Warm
BCS58.1FX-111	250	0.25	58	Warm
TRIDONIC(1*58 T8 PRO lp)	400	0.24	58	Cold
VS(VOSSLOH SCHWABE)-ELXE-258.222	330	0.26-0.23	58	Cold
HF-BASIC-II(HF-B 158 TLD EII 220-240)	350	0.25-0.24	58	Cold
HF-BASIC-II(HF-B 258 TLD EII 220-240	350	0.24	58	Cold
HELVAR EL1*58	250	0.26-0.23	58	Warm
HELVAR EL1*58ngn	250	0.26-0.23	58	Warm
QT-FIT81*58-70	430	0.25	58	Warm
QTP81*58	380	0.24	58	Warm
QTP-OPTIMAL	330	0.25	58	Warm
TRIDONIC(1*58 T8)	250	0.25	58	Warm
VS(VOSSLOH SCHWABE)-ELXC-158.201	330	0.26	58	Warm
VS(VOSSLOH SCHWABE)-ELXC-158.209	250	0.26-0.23	58	Warm
VS(VOSSLOH SCHWABE)-ELXC-158.218	250	0.27-0.23	58	Warm
HF-R 158 TLD EII(9137006094)	350	0.27-0.25	58	Warm
HF-P 158TLD EII (9137001911)	< 300	0.25-0.24	58	Warm

Table 14: Test for blocking ability of triacs with different HF ballasts.

Ballast type	Blocking ability of BTA204-800C	Blocking ability of ACTT2X-800E	Blocking ability of ACST830-8FP	Blocking ability of two BTA204-800C operated in series	Blocking ability of two ACTT2X-800E operated in series	Blocking ability of two ACST830-8FP operated in series
HF-R 158 TLD(9137001116)	✗	✗	✗	✓	✓	✓
HF-S 158 TLD-II(9137130322)	✓	✓	✓	✓	✓	✓
HF-S 158	✗	✗	✗	✓	✓	✓
HF-P 158 TL-D III IDC(9137130318)	✗	✗	✗	✓	✓	✓
HF-P 158 TLD EII(9137001912)	✗	✗	✗	✓	✓	✓
HF-Pxt 158 TLE EII(9137006179)	✗	✗	✗	✓	✓	✓
HF-E 158 TL-D(9137130389)	✗	✗	✓	✓	✓	✓

HF-S158TL-D II(9137130322)	✗	✗	✗	✓	✓	✓
BCS58.1SR-011	✗	✗	✗	✓	✓	✓
BCS58.1FX-111	✓	✓	✓	✓	✓	✓
TRIDONIC(1*58 T8 PRO lp)	✗	✗	✗	✓	✓	✓
VS(VOSSLOH SCHWABE)-ELXE-258.222	✗	✗	✗	✓	✓	✓
HF-BASIC-II(HF-B 158 TLD EII 220-240)	✗	✗	✗	✓	✓	✓
HF-BASIC-II(HF-B 258 TLD EII 220-240	✗	✗	✗	✓	✓	✓
HELVAR EL1*58	✓	✓	✓	✓	✓	✓
HELVAR EL1*58ngn	✗	✗	✗	✓	✓	✓
QT-FIT81*58-70	✓	✓	✓	✓	✓	✓
QTP81*58	✓	✓	✓	✓	✓	✓
QTP-OPTIMAL	✓	✗	✓	✓	✓	✓
TRIDONIC(1*58 T8)	✗	✗	✗	✓	✓	✓
VS(VOSSLOH SCHWABE)-ELXC-158.201	✗	✗	✗	✓	✓	✓
VS(VOSSLOH SCHWABE)-ELXC-158.209	✗	✗	✓	✓	✓	✓
VS(VOSSLOH SCHWABE)-ELXC-158.218	✗	✗	✓	✓	✓	✓
HF-R 158 TLD EII(9137006094)	✗	✗	✓	✓	✓	✓
HF-P 158TLD EII (9137001911)	✓	✗	✓	✓	✓	✓

Where ✓ indicates that triac is able to block the signal from HF ballast and ✗ indicates that triac is unable to block the signal from HF due to false turn on effect (miller effect).