LED Driver with Feedback Control

A Thesis submitted to fulfilment the requirement for the degree of

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by

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Abstract

LEDs are gaining too much popularity in recent time. People are also eager to use it as much as possible wherever they find any hope of light. The reasons are many. LEDs have average burning hours of 30,000 hours. They possess average luminous efficacy of 70-100 lumens/watt. Besides, CRI of LED is 60-98. For domestic purposes, a 5W to 15W LED can provide these features. On the other hand, luxury areas, where decorative lights. LEDs are unable to regulate their own current, being essentially constant-voltage loads. LED light output is directly dependent on forward current. This means that LEDs require a current regulating driving circuit to support its working performance similar to that of a ballast for discharge lamps.

The objective of this thesis is to propose a new LED driver topology to improve the performance of valley switching by decreasing the MOSFET switching losses. The proposed topology is designed in a way that the MOSFET works at the significantly lower switching and conduction losses in compared with conventional LED drivers. With the wide applications of LEDs, many new technologies have been established. Whether we want to apply a driver or not in the field of applications, depends upon driver output. A smooth DC output is expected. Again, since LED driver consists of nonlinear elements like diodes, inductors, capacitors, MOSFET and other electronic elements, it incorporates harmonics to the input signals. As a result, when a large numbers of such drivers are in operating condition, it negatively affects the power system and other connected loads can face serious problems. Hence, keeping harmonics as minimum as possible is highly required. Apart from this, very low power loss across individual elements inside the LED driver is highly recommended to reduce power loss and increase driver efficiency.

MATLAB/SIMULINK software of version R2022a has been used to simulate the complete LED driver circuit. Simulation also shows the different output and input signals. The proposed topology mainly focuses on the benefits of implementation of valley switching. Finally, comparative study has been shown in order to elaborate its advantages.

Acronyms

LED	Light Emitting Diode
IP	Ingress Protection
RMS	Root Mean Square
CRI	Color Rendering Index
DC	Direct Current
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
THD	Total Harmonic Distortion
PFC	Power Factor Correction
ZVS	Zero Voltage Switching
ZCS	Zero Current Switching
AC	Alternating Current
PI	Proportional Integral
PWM	Pulse Width Modulation
OPAMP	Operational Amplifier
BJT	Bipolar Junction Transistor
FFT	Fast Fourier Transform

Nomenclature

W	Watt
V	Volt
A	Ampere
lm/W	Lumens/Watt
L	Buck Converter Inductance
$\mathbf{C}_p$	MOSFET Parasitic Output Capacitance
$\mathbf{I}_{max}$	Maximum Inductance Current
$\mathbf{V}_{in}$	Input AC Voltage Source
$\mathbf{C}_{in}$	Input Filter Capacitor
Q	MOSFET
$\mathbf{C}_{out}$	Output Filter Capacitor
$\mathbf{R}_L$	Load Resistance
K	Constant Block
$\mathbf{K}_s$	Subtract Block
$\mathbf{K}_{pi}$	PI Controller
$\mathbf{K}_g$	PWM Generator
Hz	Hertz
f	Fundamental Frequency

List of Figures

List of Tables

Table of Contents

Chapter 1

Introduction

1.1. Motivation of the Work:

Today incandescent and fluorescent lamps are replaced by LED lamps due to their long lifespan, non-mercury content, high efficiency, and simple control. These lamps need a driver to supply constant voltage or current. Although LED lamps have higher efficiency in compared with other lamps, power losses in LED drivers cause rising temperature which results in shortening their lifespan. These losses occures mainly due to losses in converter inductance, diodes, input bridge, and MOSFET switching and conduction losses [3]. Therefore, thermal management and preventing power loss in LED drivers are indispensable to control their temperature and improving LED's efficiency [4].

Valley switching method is a solution for these issues which uses the resonance between the converter inductance and parasitic output capacitance of the MOSFET. Thus, MOSFET gets turned on, only when its drain-source voltage is minimum. The motive of this work is to implement valley switching technique in LED driver so that the MOSFET switching losses minimized. Also, it shows that this topology decreases the conduction losses of the MOSFET in addition to switching losses.

1.2. Literature Review:

Appearing as practical electronic components in 1962, the earliest LEDs emitted low-intensity infrared (IR) light. Infrared LEDs are used in remote-control circuits, such as those used with a wide variety of consumer electronics. The first visible-light LEDs were of low intensity and limited to red. Early LEDs were often used as indicator lamps, replacing small incandescent bulbs, and in seven-segment displays. Later developments produced LEDs available in visible, ultraviolet (UV), and infrared wavelengths, with high, low, or intermediate light output, for instance white LEDs suitable for room and outdoor area lighting. LEDs have also given rise to new types of displays and sensors, while their high switching rates are useful in advanced communications technology with applications as diverse as aviation lighting, fairy lights, automotive headlamps, advertising, general lighting, traffic signals, camera flashes, lighted wallpaper, horticultural grow lights, and medical devices.

LEDs have many advantages over incandescent light sources, including lower power consumption, longer lifetime, improved physical robustness, smaller size, and faster switching. In exchange for these generally favorable attributes, disadvantages of LEDs include electrical limitations to low voltage and generally to DC (not AC) power, inability to provide steady illumination from a pulsing DC or an AC electrical supply source, and lesser maximum operating temperature and storage temperature. In contrast to LEDs, incandescent lamps can be made to intrinsically run at virtually any supply voltage, can utilize either AC or DC current interchangeably, and will provide steady illumination when powered by AC or pulsing DC even at a frequency as low as 50 Hz. LEDs usually need electronic support components to function, while an incandescent bulb can and usually does operate directly from an unregulated DC or AC power source.

Several researches investigated different aspects of LEDs to increase their efficiency, lifespan, and performance. Different converters such as buck, boost, buck-boost, flyback are used as LED driver. In these converters the output current has ripple and the lamp has flicker. In this view, some studies focused on mitigating the output current ripple and attenuating the flicker [5–7]. Some researches tried to eliminate the input bridge using new control method and novel LED driver [8, 9]. However, these drivers have shorter lifespan. Poor power factor is another problem of these lamps, which causes using power factor correction (PFC) converter for LED driver. But, using PFC converter increase the overall cost of LED lamp. Thus, some studies attempted to overcome this drawback by combining PFC converter and LED driver in a single converter [10–13].

In electronics, a driver is a circuit or component used to control another circuit or component, such as a high-power transistor, liquid crystal display (LCD), stepper motors, and numerous others. They are usually used to regulate current flowing through a circuit or to control other factors such as other components and some other devices in the circuit. The term is often used, for example, for a specialized integrated circuit that controls high-power switches in switched-mode power converters. An amplifier can also be considered a driver for loudspeakers, or a voltage regulator that keeps an attached component operating within a broad range of input voltages.

Typically the driver stage(s) of a circuit requires different characteristics to other circuit stages. For example, in a transistor power amplifier circuit, typically the driver circuit requires current gain, often the ability to discharge the following transistor bases rapidly, and low output impedance to avoid or minimize distortion.

Losses in LED drivers cause increasing temperature and shorten their lifespan. Therefore, improving the efficiency of LED drivers not only saves energy but also is indispensable to increase their lifespan. As discussed before, fundamental reason for these losses is MOSFET switching losses. Zero voltage switching (ZVS) and zero current switching (ZCS) are implemented using resonance phenomena in order to decrease switching losses and increase the efficiency [14–20]. However, extra circuit elements such as capacitors and inductors are required to implement the resonance which increases the size and overall cost issues. Valley switching is a solution for these issues, which uses resonance between the converter inductance and parasitic output capacitance of the MOSFET instead of extra circuit elements [21–24]. Again, minimum point of resonance voltage is not low enough to decrease the switching losses sufficiently in low output voltage and hence, using resonance in this condition is not efficient.

In this paper, a new topology has been proposed to minimize the valley point of resonance at the MOSFET output voltage to zero, so that the MOSFET switching losses minimized at this point. Also, it shows that the new topology decreases the conduction losses of the MOSFET in addition to switching losses. Besides decreasing MOSFET losses, the other elements' losses such as inductor and diode conduction losses and input bridge losses are decreased, significantly. In this proposed topology, implementation of valley switching without requiring a secondary winding makes an LED driver more efficient and cheaper in compared with other designs in which a secondary winding coupled by the converter inductance is required to detect the minimum point of the MOSFET output voltage [23].

Organization of the Thesis

This section presents an outline of the work carried by the author.

Chapter-1 contains the motivation behind the work along with the review of different literature available on the above-mentioned topic and their limitations. Various types of LED driver topology along with different valley switching is also represented.

Chapter-2 presents fundamentals of LED driver. It also shows the purposes of LED driver, types of LED driver, selection of LED driver and finally, parts of LED driver. There are two types of LED driver, viz. internal LED driver and external LED driver. A LED driver is basically use after the supply terminal in the household appliances, in order to regulate supply for those domestic devices.

Chapter-3 represents basics of buck converter. It elaborates the purpose for the use of it in LED drivers. Also here discussed, how the efficiency of LED drivers get affected by the switching topology adopted in the buck converters for triggering of MOSFET.

Chapter-4 depicts basic operation of valley switching. This is basically triggering of MOSFET used in DC-DC converters, during low drain-source voltage. The time of triggering the MOSFET is called resonance. Resonance is a very important concept to do valley switching. This section also states the problem regarding gate triggering in conventional approaches of valley switching.

Chapter-5 shows what is feedback control topology for switching of MOSFET in DC-DC converter. Graph analysis also given in order to make it clear when MOSFET is going to trigger.

Chapter-6 represents design of an input filter in order to eliminate input current waveform distortion. At first poor waveform distortion has been shown in case of conventional valley switching. After that proposed input filter has been shown an improvement in input current waveform is analysed with graphical figures. Also THD percentage evaluated in the circuit proposed in this paper found to be 1.13%, which is quite low.

Chapter-7 finally concludes our work regarding valley switching and a possible future scope of work in this area.

Chapter 2

Fundamentals of LED Driver

2.1. What is a LED Driver:

A light-emitting diode (LED) is a semiconductor device that emits light when current flows through it. Electrons in the semiconductor recombine with electron holes, releasing energy in the form of photons. The color of the light (corresponding to the energy of the photons) is determined by the energy required for electrons to cross the band gap of the semiconductor. White light is obtained by using multiple semiconductors or a layer of light-emitting phosphor on the semiconductor device. Light emitting diode (LED) is a low energy lighting device with a long lifespan and consumes low power. Hence, it requires specialized power supplies. Therefore, LED driver is a self contained power supply which regulates the power required for a LED or array of LEDs.

A LED driver is somewhat like cruise control in a car. The power level required for a LED, changes throughout the LED's temperature increases and decreases. Without the correct driver, LEDs would become too hot and unstable resulting in failure and bad performance. To ensure the LEDs are functioning perfectly the self contained LED driver is required to supply a maintained constant amount of power to the LED.

An LED Driver is an electronic device which regulates the power to an LED or a string (or strings) of LEDs. LEDs are solid state semiconductor devices impregnated, or doped, with layers to create a p-n junction. When the current flows across the doped layers, holes from the p-region and electrons from the n-region are injected into the p-n junction. They recombine to generate photons which we perceive as visible light. The conversion from current to light output is nearly linear, increasing the input current allows more electrons and holes recombining in the p-n junction and thus more photons are generated.

In contrast to conventional light sources that runs directly from an alternating current (AC) power supply, LEDs operate on DC input or modulated square wave input because the diodes have polarity. An input of the AC signal will cause an LED to only light up approximately half of the time when the AC signal is the correct polarity and immediately go out under negative bias. Hence, a constant supply of DC electrical current at a fixed output or a variable output within an allowed range must be applied to an LED array for stable, non-flickering lighting.

LED drivers provide an interface between the power supply (line) and the LED (load), converting the incoming 50 Hz or 60 Hz AC line power at voltages such as 120 Volts, 220 Volts, 240 Volts, 277 Volts or 480 Volts to the regulated DC output current. There are drivers designed to accept other types of power sources as well, e.g., DC power from DC micro-grids or Power over Ethernet (PoE). An LED driver circuit should have immunity against voltage spikes and other noise on the AC line within a predetermined design range while also filtering out harmonics in the output current to prevent them from affecting the output quality of the LED light source. The driver is not merely a power converter. Some types of LED drivers have additional electronics to enable precise control of the light output or to support smart lighting.

2.1.1. Constant current LED drivers:

Constant current LED drivers provide a constant current (e.g., 50mA, 100mA, 175mA, 350mA, 525mA, 700mA, or 1A), regardless of the voltage load, to an LED module within a specific voltage range. The driver may power a single module with LEDs connected in series or multiple LED modules connected in parallel. Series connection is preferred in CC circuit architectures because it ensures all the LEDs have the same current flowing across their semiconductor junctions and the light output is uniform across the LEDs. Driving multiple LED modules in parallel requires a resistor in each LED module, which leads to lower efficiency and poor current matching. Most CC drivers can be programmed to operate over an output current range for precise pairing between the driver and a specific LED module. Constant current LED drivers are used when light output should be independent of the input voltage fluctuation. They are found in many types of general lighting products, such as downlights, troffers, table/floor lamps, street lights and high bay lights, for which high current quality and precise output control are the priority. CC drivers support both pulse-width modulation (PWM) and constant-current reduction (CCR) dimming. Operating a power supply in a CC mode usually requires overvoltage protection just in case an excessive load resistance is encountered or when the load is disconnected.

2.1.2. Constant voltage LED drivers:

Constant voltage LED drivers are designed to operate LED modules at a fixed voltage, typically 12V or 24V. Each LED module has its own linear or switching current regulator to limit the current in order to maintain a constant output. It is generally preferred to provide a constant voltage supply to multiple LED modules or fixtures connected in parallel. The maximum number of LEDs or LED modules and the forward voltages across them must not exceed the DC electrical energy power supply. The CV circuit must tolerate the power dissipation when the load goes short circuit. The current limiters typically have thermal shutdown to protect the circuit when a voltage higher than the maximum allowable voltage is placed across the current limiter. CV drivers are often used in low voltage LED lighting applications that demand ease of group connection in parallel control, e.g., driving LED strip lights, LED sign modules for lightboxes. Constant voltage drivers can only be PWM dimmed.

2.2. Purposes of LED Driver:

- Individual LED bulbs operate at voltages, ranging from about 1.5 to 3.5 volts and currents of up to a maximum of 30 milliamperes. The domestic bulbs may consist of several bulbs in series and parallel combinations, which require a total voltage of between 12V to 24V DC. The LED driver rectifies the AC and lowers the level to suit the requirements. This means converting the high AC mains voltage which ranges from 120 Volts to 277 Volts, to the required low DC voltage.
- The LED drivers provide protection to the LED bulbs against current and voltage fluctuations. The drivers ensure that the voltage and current to the LED bulbs remains within the operating range of the LEDs, regardless of fluctuations in the mains supply. The protection avoids providing too much voltage and current that would degrade the LEDs or too low current that would reduce the light output.

2.3. Types of LED Driver:

The LED drivers can either be used as internally or externally within the LED bulb assembly.

2.3.1. Internal LED Driver:

These are commonly used in domestic LED bulbs to make it easy when replacing the bulbs. The internal drivers are usually housed in the same case as the LEDs.

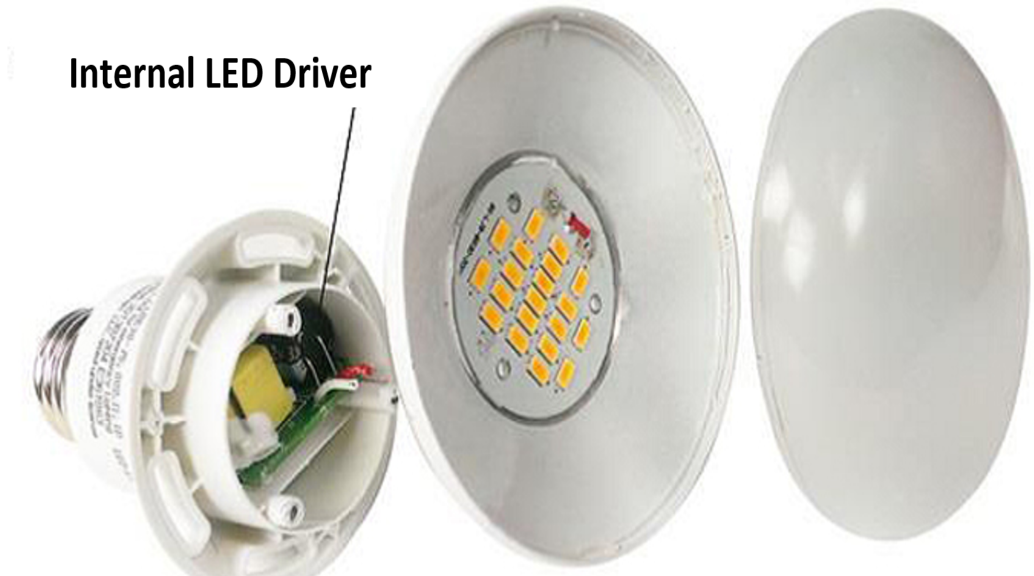

Figure 1: Internal LED Driver in a LED Bulb [1]

2.3.2. External LED Driver:

The external drivers are housed separately from the LEDs and usually used for applications such as outdoor, commercial, roadways lighting. These types of lights require separate drivers which are easier and cheaper to replace. In most of these applications the manufacturer specifies the type of the LED driver to use for particular light assembly.
Most of the LED bulb failures are due to the failure in the driver, and it is easier to replace or repair the external driver compared to the internal driver.

2.4. Selecting a LED Driver:

LED drivers either can provide constant current or constant voltage.

- The constant current drivers provide a fixed output current and may have a wide range of output voltages. An example of a constant current driver is one with 700mA output current and with an output voltage range of 4V to 13 V DC drivers.
- The constant voltage LED drivers provides a fixed output voltage and a maximum regulated output current. These are sued to power LED systems that require a stable voltage of say 12 Volts or 24 Volts DC. A typical driver may provide 24V and a maximum output current of 1.04A.

Physical size also needed to be ensured, so that the LED fits in the area it is to be fixed.

IP rating of the casing gives an indication of the environmental protection provided by the outer casing of the driver against ingress of moisture, dust and other objects or liquids.

Other factors considered include the power factor, maximum wattage, dimming ability and the compliance with international regulatory standards such as the UL1310 in regard to safety.

2.5. Parts of LED Driver:

LED drivers can be remote mounted or co-located within lamp or luminaire housings. In co-located, non-DOB systems, the driver must be thermally isolated from LEDs which generate a huge amount of heat. Driver maintenance should be taken into consideration when designing a luminaire housing. In remote-mounted systems, PWM drivers can experience performance losses over a long distance. As such, CCR is the preferred dimming technique for remote-mounted systems. Any LED driver consists of three individual parts. These are AC to DC rectifier, DC to DC buck converter and finally output harmonics filter.

LED drivers for roadway, street, exterior and landscape lighting applications must be sealed to protect against ingress of dust, moisture, water and other objects that may

Figure 2: External LED Driver in a LED Bulb [2]

pass through into the products. A high degree of ingress protection (IP) for LED drivers is critical for indoor applications such as carwashes, cleanrooms, bottling and canning plants, food processing facilities, pharmaceutical plants or any industrial application requiring exposure to daily high-pressure wash downs. Self-contained LED drivers for wet locations are usually potted in silicone to enhance enclosure integrity while also facilitating electrical insulation and thermal management. These drivers typically come with IP65, IP66 or IP67 level ingress protection.
LED is a diode. We know diode works in DC. Since our supply is AC quantity, hence the first objective of a LED driver is to convert AC supply voltage into DC output voltage. Therefore, an AC to DC rectifier stage is required first. Assuming standard AC supply voltage for domestic sector to be 220V to 230V RMS in India, rectified DC output voltage will be approximately 310V.

As discussed earlier, a LED supply voltage can be on an average of 20V to 30V DC. That is why, the rectified DC voltage is needed to be chopped. Voltage regulator or, voltage divider circuit using series resistance can be used, but they are power consuming. So the best way to chop the DC voltage is to use a buck converter, which incorporates MOSFET switching at high frequency of several kHz. In this case, it is 25kHz.

In order to minimize the fluctuations in converter output DC voltage and current, simple LC filter has been used. Random fluctuations in DC can cause a LED lamp failure, increase lamp temperature, variable lamp output lumen and thus a constant DC as much as possible is preferable.

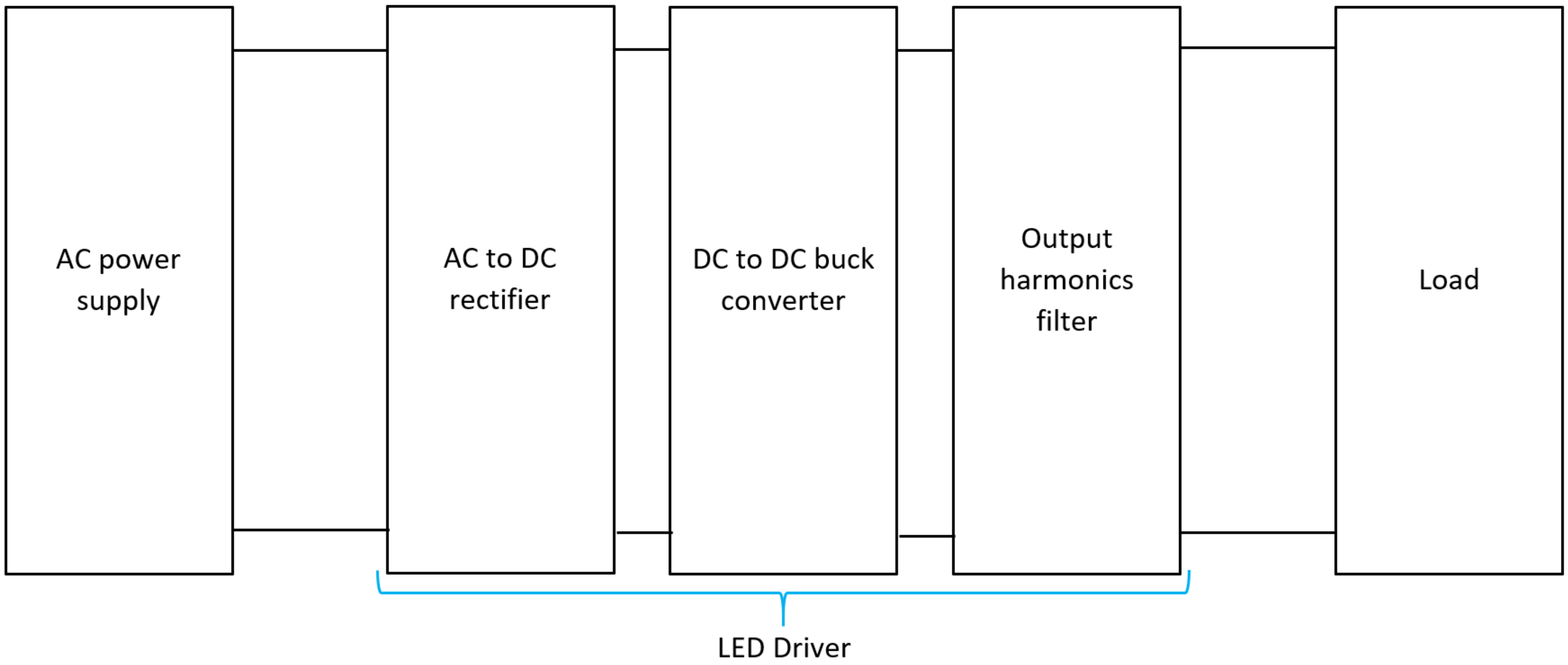

Figure 3: Parts of LED Driver

Chapter 3

Buck Converter

3.1. What is buck converter:

A buck converter (step-down converter) is a DC-DC power converter which steps down voltage, while stepping up current from its input supply to its output load. It is a class of switched-mode power supply (SMPS) typically containing at least two semiconductors: a diode and a transistor, although modern buck converters frequently replace the diode with a second transistor used for synchronous rectification and at least one energy storage element, a capacitor, inductor, or the two in combination. To reduce voltage ripple, filters made of capacitors (sometimes in combination with inductors) are normally added to such a converter's output (load-side filter) and input (supply-side filter). Its name derives from the inductor that "bucks" or opposes the supply voltage.

Buck converters provide much greater power efficiency as DC-DC converters than linear regulators, which are simpler circuits that lower voltages by dissipating power as heat, but do not step up output current.

The efficiency of buck converters can be very high, often over 90%, making them useful for tasks such as converting a computer's main supply voltage, which is usually 12 V, down to lower voltages needed by USB, DRAM and the CPU, which are usually 5, 3.3 or 1.8 V.

Buck converters typically operate with a switching frequency of 50-100 kHz so that the size of inductors and capacitors are relatively small.

3.2. Theory of operations:

The basic operation of the buck converter has the current in an inductor controlled by two switches (usually a transistor and a diode). In Figure 4, the transistor is shown as a simple switch.

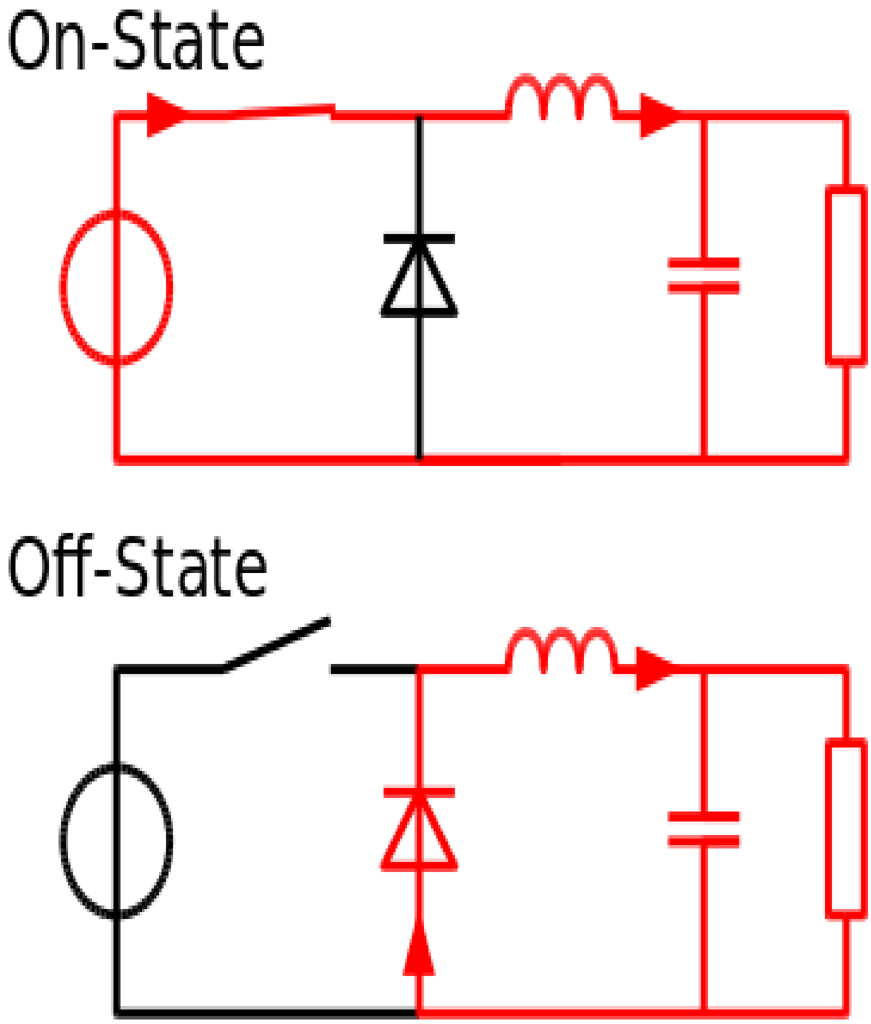

Figure 4: The two circuit configurations of a buck converter: on-state, when the switch is closed; and off-state, when the switch is open (arrows indicate current according to the direction conventional current model)

To simplify the explanation an idealised converter is assumed: i.e. certain real world factors are ignored (in the same way that explaining a car engine may ignore friction in the bearings, say). The assumptions here,

- All the components are considered to be perfect. Specifically, the switch and the diode have zero voltage drop when on and zero current flow when off, and the inductor has zero series resistance.
- the input and output voltages do not change over the course of a cycle, which would imply the output capacitance as being infinite.

Given those assumptions, the conceptual model of the buck converter is best understood in terms of the relation between current and voltage of the inductor. Beginning with the switch open (off-state), the current in the circuit is zero. When the switch

is first closed (on-state), the current will begin to increase, and the inductor will produce an opposing voltage across its terminals in response to the changing current. This voltage drop counteracts the voltage of the source and therefore reduces the net voltage across the load. Over time, the rate of change of current decreases, and the voltage across the inductor also then decreases, increasing the voltage at the load. During this time, the inductor stores energy in the form of a magnetic field.
If the switch is opened while the current is still changing, then there will always be a voltage drop across the inductor, so the net voltage at the load will always be less than the input voltage source. When the switch is opened again (off-state), the voltage source will be removed from the circuit, and the current will decrease. The decreasing current will produce a voltage drop across the inductor (opposite to the drop at on-state), and now the inductor becomes a current source. The stored energy in the inductor's magnetic field supports the current flow through the load. This current, flowing while the input voltage source is disconnected, when appended to the current flowing during on-state, totals to current greater than the average input current (being zero during off-state).
The "increase" in average current makes up for the reduction in voltage, and ideally preserves the power provided to the load. During the off-state, the inductor is discharging its stored energy into the rest of the circuit. If the switch is closed again before the inductor fully discharges (on-state), the voltage at the load will always be greater than zero.

In switching operation, there are two modes, a discontinuous mode and a continuous mode. The operation item for comparison is the waveform of the currents flowing in the primary windings and secondary windings of the transformer. In discontinuous mode, there is a period in which the inductor current is interrupted, hence the name, discontinuous mode. In contrast, in continuous mode there is no period in which the inductor current is zero.

3.3. Efficiency Factors:

There are two main phenomenon impacting the efficiency: conduction losses and switching losses.

Conduction losses happen when current is flowing through the components and thus depend on the load. They are caused by Joule effect in the resistance when the transistor or MOSFET switch is conducting, the inductor winding resistance, and the capacitor equivalent series resistance. Losses are proportional to the square of the current in this case. Conduction losses are also generated by the diode forward voltage drop (usually 0.7 V or 0.4 V for schottky diode), and are proportional to the current in this case.

Switching losses happen in the transistor and diode when the voltage and the current overlap during the transitions between closed and open states. A schottky diode can be used to minimize the switching losses caused by the reverse recovery of a regular PN diode.[11] The switching losses are proportionnal to the switching frequency.

In a complete real-world buck converter, there is also a command circuit to regulate the output voltage or the inductor current. This circuit and the MOSFET gate controller have a power consumption, impacting the overall efficiency of the converter.

Chapter 4

Valley Switching

4.1. Definition:

Conventional converter uses pulse width modulation (PWM) technique to control the output current and voltage; as a result, the output current has ripple and the lamp has flicker. In this view, some studies focused on mitigating the output current ripple and attenuating the flicker. Most of converters use a diode bridge and an electrolytic capacitor to supply the LED lamp. Some researches tried to eliminate the input bridge using new control method and novel LED driver. However, using electrolytic capacitors at the input of these converter shorten their lifespan; therefore, some researches tried to improve the lifespan of LED lamp by eliminating these bulk capacitor. Poor power factor is another problem of these lamps, which causes using power factor correction (PFC) converter, for LED driver. However, using PFC converter increase the overall cost of LED lamp. Thus, some studies attempted to overcome this drawback by combining PFC converter and LED driver in a single converter. Although LED lamps have higher efficiency in compared with other lamps, power losses in LED drivers cause rising temperature which results in shortening their lifespan. Therefore, thermal management and preventing power loss in LED drivers are indispensable to control their temperature and improving LED's efficiency. These losses are mainly included losses in converter inductance, diodes, input bridge, and losses in the MOSFET switching and conduction. Zero voltage switching (ZVS) and zero current switching (ZCS) are implemented using resonance phenomena to decrease the switching losses and increase the efficiency. However, extra circuit elements such as capacitors and inductors are required to implement the resonance which increases the size and overall cost issues. Valley switching method is a solution for these issues which uses the resonance between the converter inductance and parasitic output capacitance of the MOSFET instead of extra circuit elements. However, the minimum point of resonance voltage is not low enough to decrease the switching losses sufficiently in low output voltage; therefore, using resonance in this condition is not efficient.

In this paper, a new topology is proposed to minimize the valley point of resonance at the MOSFET output voltage to zero, so that the MOSFET switching losses minimized at this point. Also, it shows that the new topology decreases the conduction losses of the MOSFET in addition to switching losses. Besides decreasing the MOSFET losses, the other elements' losses such as inductor and diode conduction losses and input bridge losses are decreased, significantly. In this proposed topology, the implementation of valley switching without requiring a secondary winding makes an LED driver more efficient and cheaper in compared with other designs in which a secondary winding coupled by the converter inductance is required to detect the minimum point of the MOSFET output voltageValley switching is a soft-switching technique that improves system efficiency of AC-DC and DC-DC converters. Significant efficiency improvements are achieved with valley switching mainly under low-load conditions where efficiency standards are difficult to meet.

Figure 5 shows a Simulink model of a conventional buck converter. Valley switching is a method, which uses resonance between converter inductance (L) and parasitic output capacitance of MOSFET (C_p) to decrease the switching losses. The converter inductance and the MOSFET output capacitance are shown in red color to emphasis the main resonance elements.

Figure 5 shows the Simulink model of figure 4 with gate triggering. In a gate pulse generator, pulses are generated in response to the gate command signal and forward voltage signal. They and are converted into the light signals which in turn are transmitted to the converter, whether or not the forward voltage signal exists when the gate command signal is generated is detected and when the forward voltage signal is generated prior to the generation of the gate command signal, the pulse duration is narrowed to a minimum required for firing. When the forward voltage signal is generated during the time interval in which the gate command signal continues, the differences in time point when the forward voltage signals are generated due to the storage carrier differences, there are taken into consideration so that the pulse duration is increased. Therefore, from the standpoint of the frequency of occurrence, gate can be triggered in response to the pulse signal with a narrow pulse duration in almost all cases. Simple gate triggering of following parameters has been used, which are shown in following table.

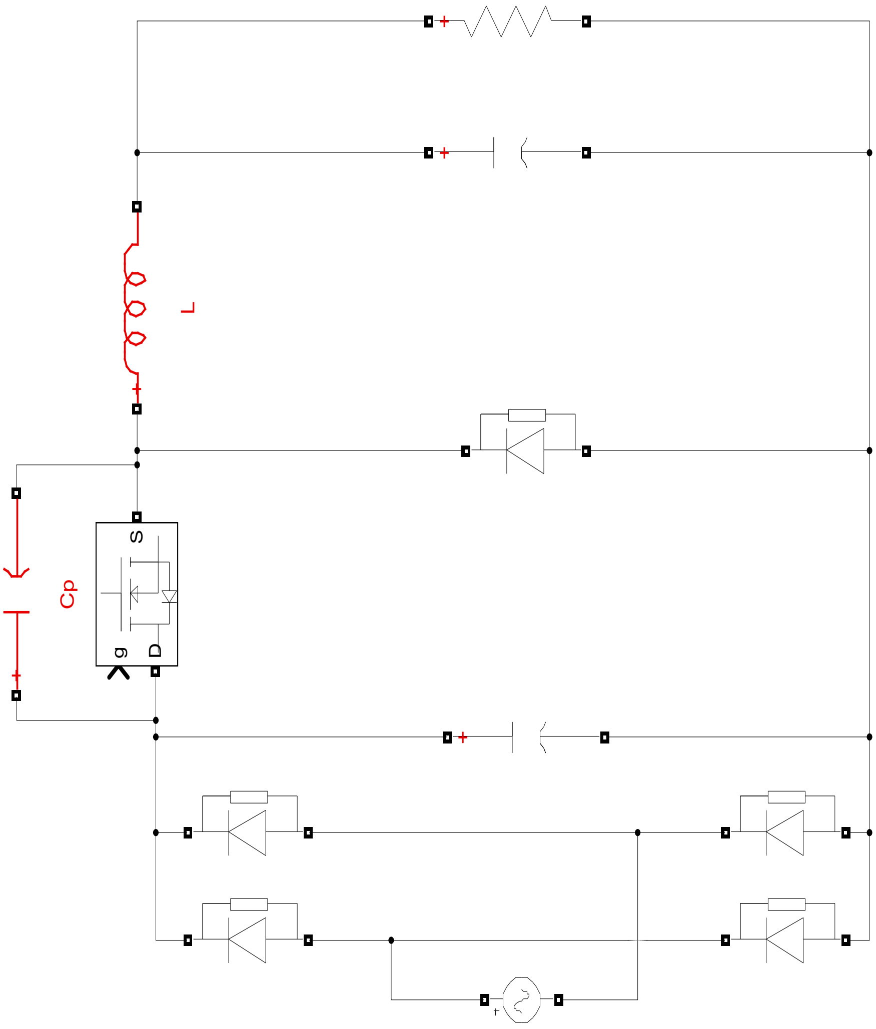

Figure 5: Conventional Buck LED Driver

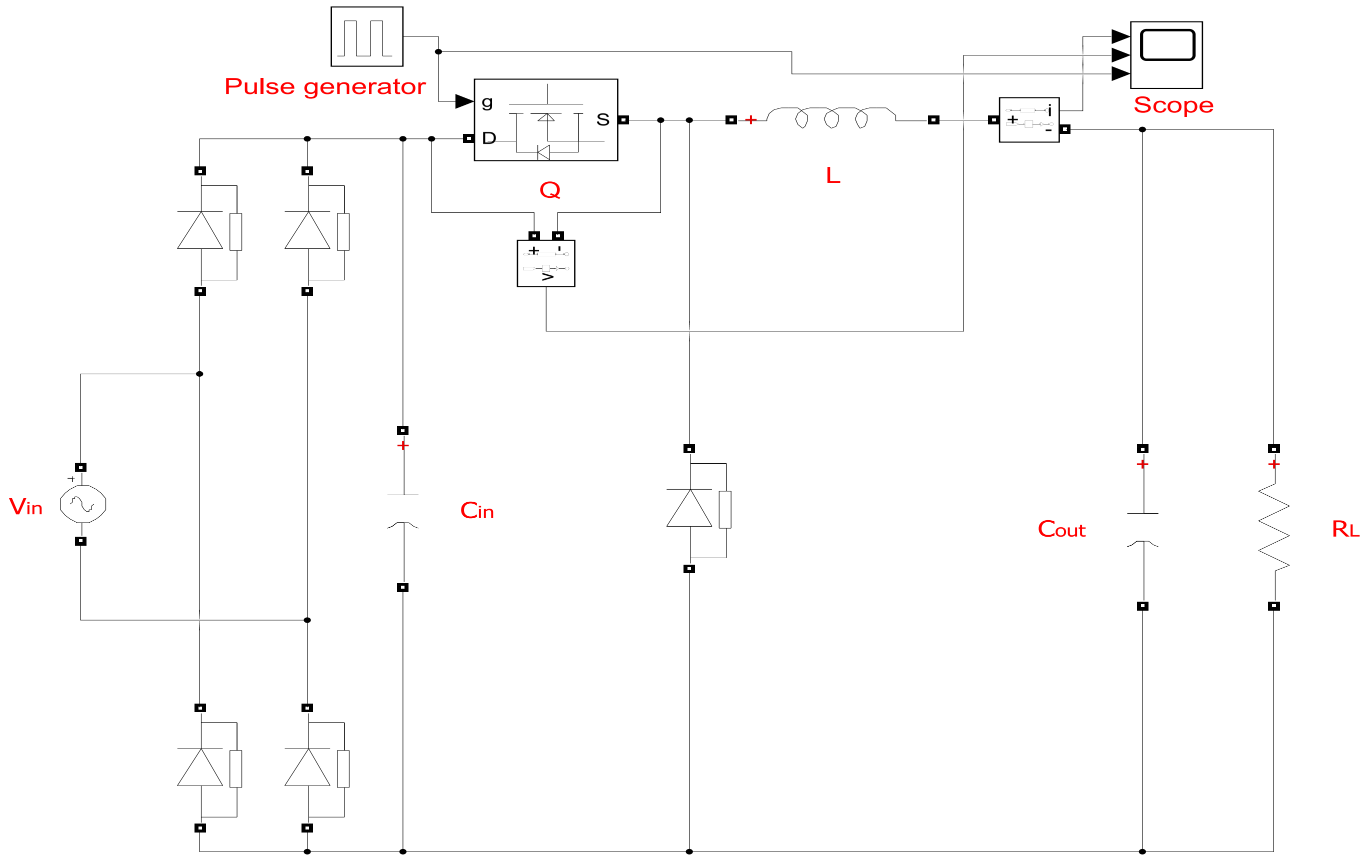

Figure 6: Conventional Buck LED Driver with Pulse Generator

Parameter	Description	Value
V_{in}	Input AC voltage source	Peak value = 310V 50Hz
C_{in}	Input filter capacitor	68μF
Q	MOSFET	N-channel enhancement
L	Buck inductor	0.82mH
C_{out}	Output filter capacitor	68μF
R_L	Load resistance	72Ω
Pulse generator	Gate triggering	Amplitude = 15 Time period = 80μs Pulse width = 25% of time period

Table 1: System Parameters of Figure 2

4.2. Importance of Resonance:

A MOSFET is said to be turned on, when its drain-source voltage is maximum and is said to be turned off, when its drain-source voltage starts to fall. Figure 6 shows the scope output graphs of the simulink model in figure 5. From figure 6, the inductance current rises to maximum reference current (I_{max}) when the MOSFET turns on at point a. Then, inductance current starts decreasing and falls to zero at point b. After that, MOSFET turns off at point c. A resonance is occurred at this moment at point c, between the converter inductance and parasitic output capacitance of the MOSFET. MOSFET drain-source voltage becomes zero at point c and inductance current starts to increase again. When resonance has been occured at point c, MOSFET gate has been triggered until drain-source voltage starts to rise again.

Figure 9 also shows the scope output graphs of the simulink model in figure 5. We can define that inductance current is equal to MOSFET source current, since they are connected in series. From figure 7, it is clear that, gate has been triggered from point c to point d. The time period b-d can be subdivided into two parts, viz. b-c and c-d. If we observe carefully, from point b to point c, MOSFET source current is zero and MOSFET drain-source voltage is non-zero. Again, point c to point d, MOSFET source current is non-zero, while MOSFET drain-source voltage is zero. Therefore, it can be said that, from point b to point d, power consumed by the MOSFET is zero. This is the reason to turn on the MOSFET at the time of resonance to reduce its switching loss.

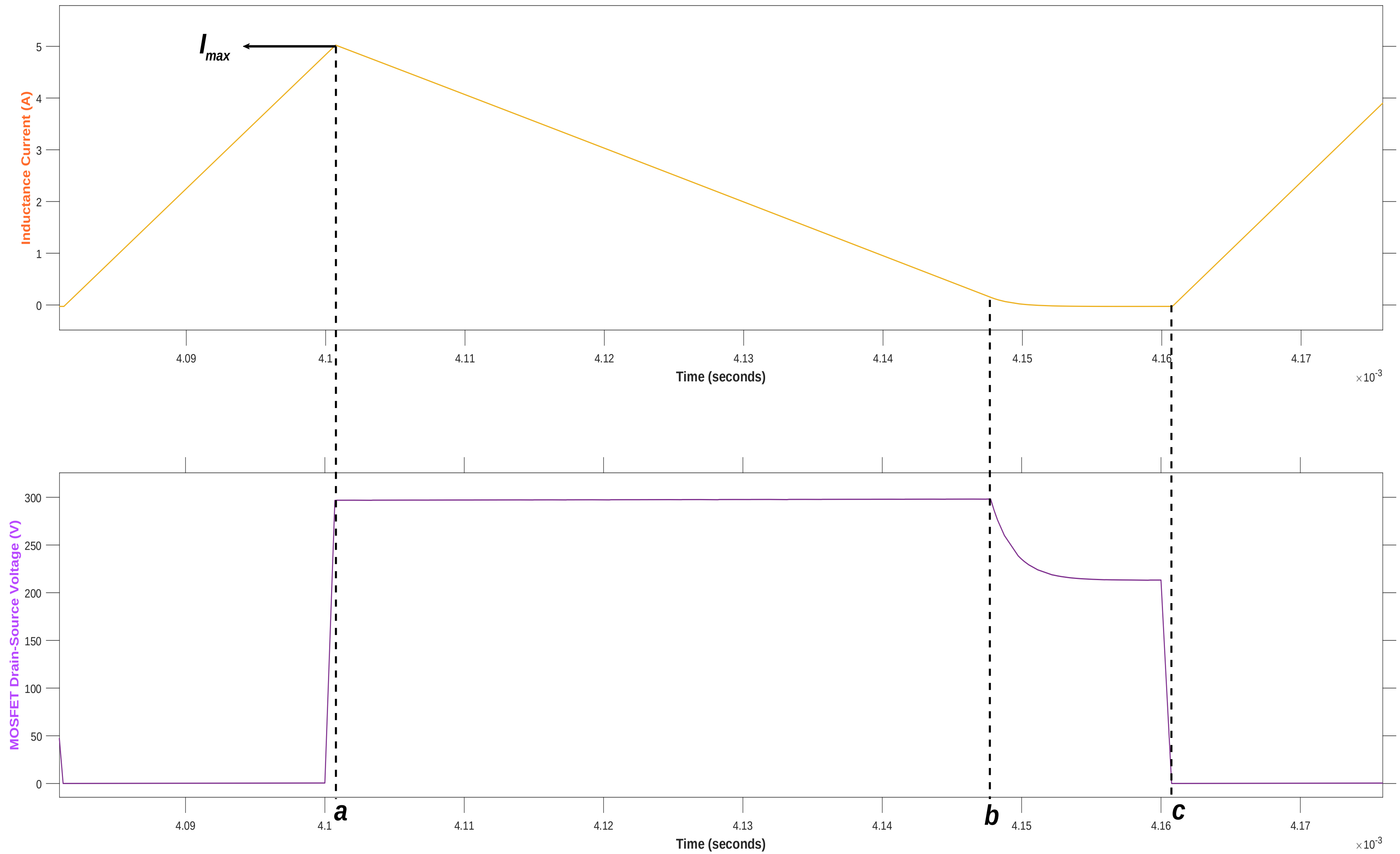

Figure 7: Inductance Current and MOSFET Output Voltage of Conventional Driver

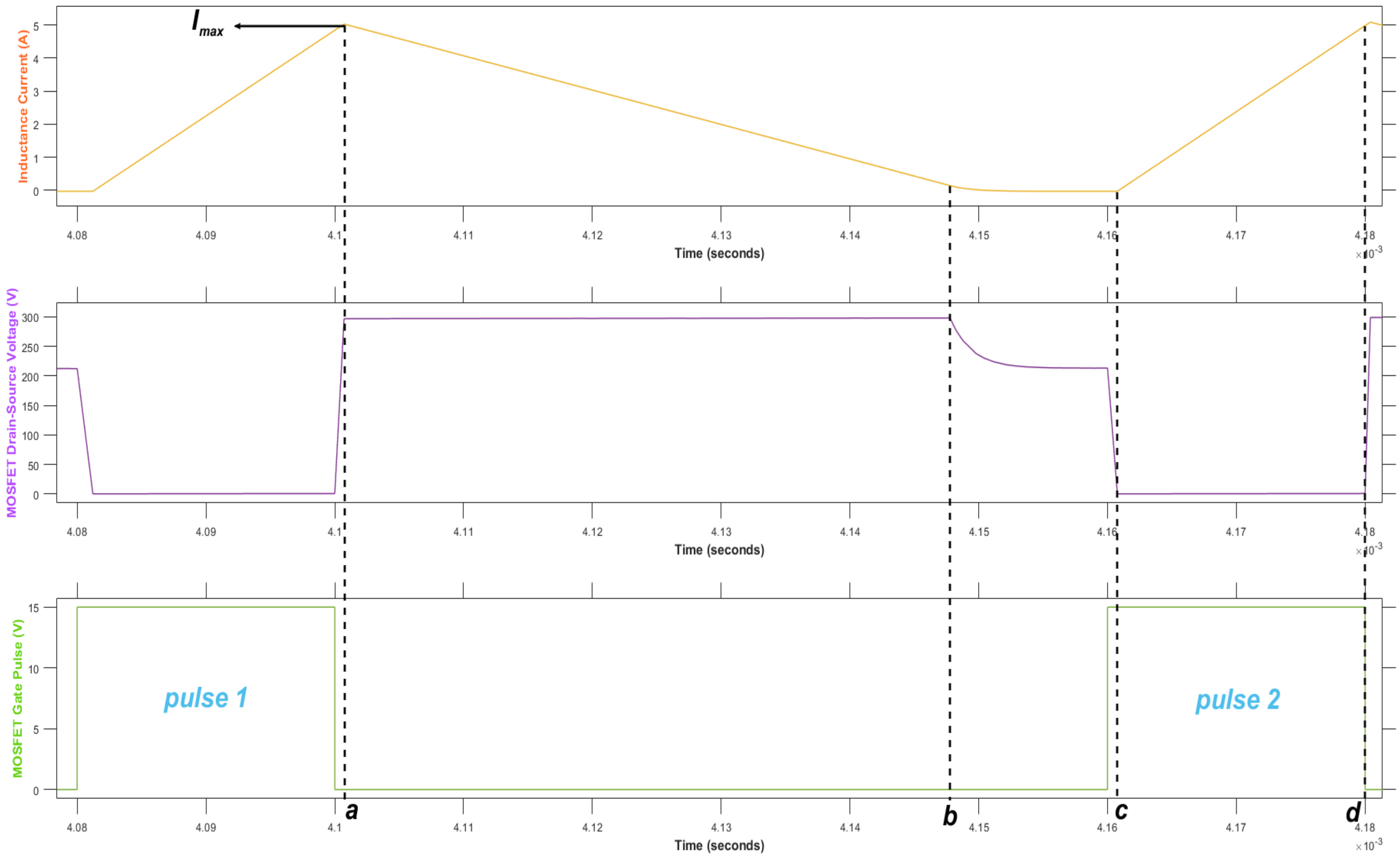

Figure 8: Inductance Current, MOSFET Output Voltage and Gate Pulse of Conventional Driver

Figure 9 again shows the scope output graphs of the simulink model in figure 5 for ease of comparison of different signals.

4.3. Problems in Gate Triggering:

It is now clear that, MOSFET gate terminal should be triggered from point c to point d. In figure 7, two gate pulses are shown as pulse 1 and pulse 2. Lets take pulse 2 for our discussion. Some issues regarding this gate triggering are as follows.

- It should be triggered at point c, but it has been triggered before point c. This is occurring because, in this case we can observe from figure 8 that, MOSFET drain-source voltage takes too much time to fall to minimum value at point c.
- As the time instances of gate triggering do not match with that of resonance of the circuit, unwanted power loss will reduce overall system efficiency. It incorporates poor power factor, which causes using power factor correction (PFC) converter, for LED driver. However, using PFC converter increase the overall cost of LED lamp. Thus, some studies attempted to overcome this drawback by combining PFC converter and LED driver in a single converter.
- Although LED lamps have higher efficiency in compared with other lamps, power losses in LED drivers cause rising temperature which results in shortening their lifespan. Therefore, thermal management and preventing power loss in LED drivers are indispensable to control their temperature and improving LED's efficiency.
- These losses are mainly included losses in converter inductance, diodes, input bridge, and losses in the MOSFET switching and conduction. Zero voltage switching (ZVS) and zero current switching (ZCS) are implemented using resonance phenomena to decrease the switching losses and increase the efficiency. However, extra circuit elements such as capacitors and inductors are required to implement the resonance which increases the size and overall cost issues.
- An LED driver is configured to convert the AC line voltage into DC output as efficiently as possible, and any energy lost in the conversion process will be converted into heat. This means an LED driver with 90% efficiency requires an input power of 100W/0.9 = 111 W to drive a 100W load. Among the input power 11W is the power loss that escapes in the form of heat. This places a high thermal stress on the LED driver circuit. When the driver is co-located within the luminaire housing, the thermal load from the LEDs will end up in additional increase in the driver temperature. In addition to utilizing components that are rated for high temperatures, the driver has to be designed to pull heat away from thermally-sensitive components. Excess heat buildup will cause reliability issues with components, including electrolytic capacitors which will dry out when exposed to heat. Therefore the temperature at which an LED driver is running is fundamentally important in defining its lifetime. To facilitate heat dissipation, LED drivers for high wattage LED luminaires use aluminum enclosures which can come with high density fins and thermally conductive potting.

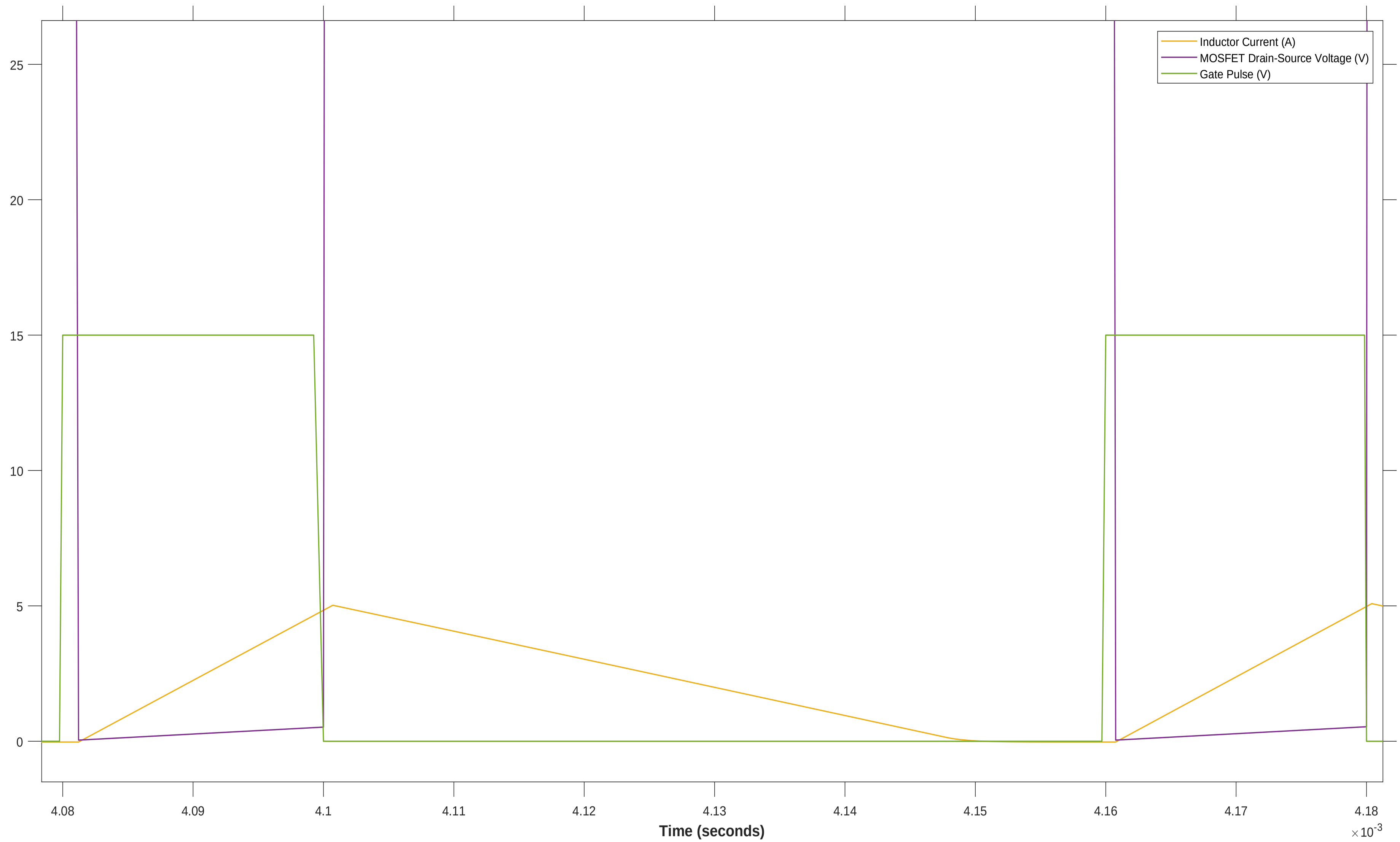

Figure 9: Inductance Current, MOSFET Output Voltage and Gate Pulse of Conventional Driver

Chapter 5

Feedback Control

As we discussed earlier, valley switching method is a solution for previously stated issues which uses the resonance between the converter inductance and parasitic output capacitance of the MOSFET instead of extra circuit elements. However, the minimum point of resonance voltage is not low enough to decrease the switching losses sufficiently in low output voltage; therefore, using resonance in this condition is not efficient. In this chapter we are proposing a new method of valley switching by using a closed loop control system.

5.1. Introduction:

So far we have seen that, conventional gate triggering for LED driver leads poor MOSFET switching and hence performs at lower efficiency. Proposed LED driver overcomes the problems of gate triggering stated before and yields a much better performance. In this topology, MOSFET output voltage takes significantly lesser amount of time to turn off. Besides, gate has been able to trigger at more exact time of resonance. Also, at the time of resonance, MOSFET output current completely falls to its minimum value or zero. Therefore, MOSFET switching loss has been reduced compared to the conventional method of switching.

5.2. Methodology:

The proposed topology for gate triggering is to use a feedback path, which will detect present driver output and compare it with desired driver output to generate MOSFET gate pulse. Figure 9 shows the simulink model of the LED driver of this topology. Instead of using simple pulse generator for gate triggering, four blocks from simulink library have been used. These are, constant block, subtract block, one PI controller and a PWM generator. Following is a description and physical significance of these blocks.

A constant block is the output, which is desired. In simulink model in figure 9, it has been shown as 'K'. The numeric value inside the block indicates the desired output of the LED driver. In this thesis, a 310V to 33V dc-dc LED driver has been proposed. This means, our desired output is 33V dc. In simulink model, it has been shown as a simple square block, but in practice, it designates a dc supply. This DC supply can be obtained from supply 'V_{in}'. After 'V_{in}' is rectified and filtered through capacitor, a voltage regulator IC can be connected to generate that 33V DC.

Subtract block represents a comparator circuit comprises with opamp and resistors. In figure 9 it has been shown by 'K_s'. Details of comparator circuit has not been included in this thesis, but is redirected to reference [25]. For the sake of discussion of the proposed LED driver, we can say that a comparator is a simple electronic circuit, which compares two signals and generates an error signal. Among the two comparing signals, one signal is the desired output, which is 33V DC in this case and the other signal is the present driver output, i.e. output across 'R_L'.

Then comes the PI controller. The block has been named as 'K_{pi}' in figure 9. The purpose of this block is to modify the error signal into a convenient signal for MOSFET gate triggering. This is because, depending upon the total non-linearity of the circuit, input and output may have harmonics. Simultaneously, the error signal comprises of harmonics too. If such signals with harmonics have been introduced to electronic component like MOSFET, their life expectancy will decay. Hence, only for a single component a whole LED driver needs to be dismantled. The proportional and integral gain of the PI controller has been set to 1 and 7 respectively. Zero-crossing detection has also been disabled to get better output graphs.

Finally, the PWM generator, which converts the signal from PI controller into the MOSFET switching signal at desired frequency. In this case, our switching frequency is 25,000 Hz. In figure 9, it has been shown as 'K_g'.

Following table presents all the simulink blocks connected in the feedback path of figure 9 and also shows the necessary data for those blocks.

Parameter	**Description**	**Value**
K	Constant block	Constant value = 33
K_s	Subtract block	-
K_{pi}	PI controller	Proportional gain = 1 Integral gain = 7
K_g	PWM generator	Switching frequency = 25kHz

Table 2: System Parameters of Figure 9

5.3. Graph Analysis:

In conventional valley switching in chapter 3, we have seen there are some problems regarding MOSFET gate triggering. So, we are now interested to look into the output graphs of proposed circuit, shown in figure 9. Similar to figure 7, inductance current, MOSFET drain-source voltage and MOSFET gate pulse have been shown

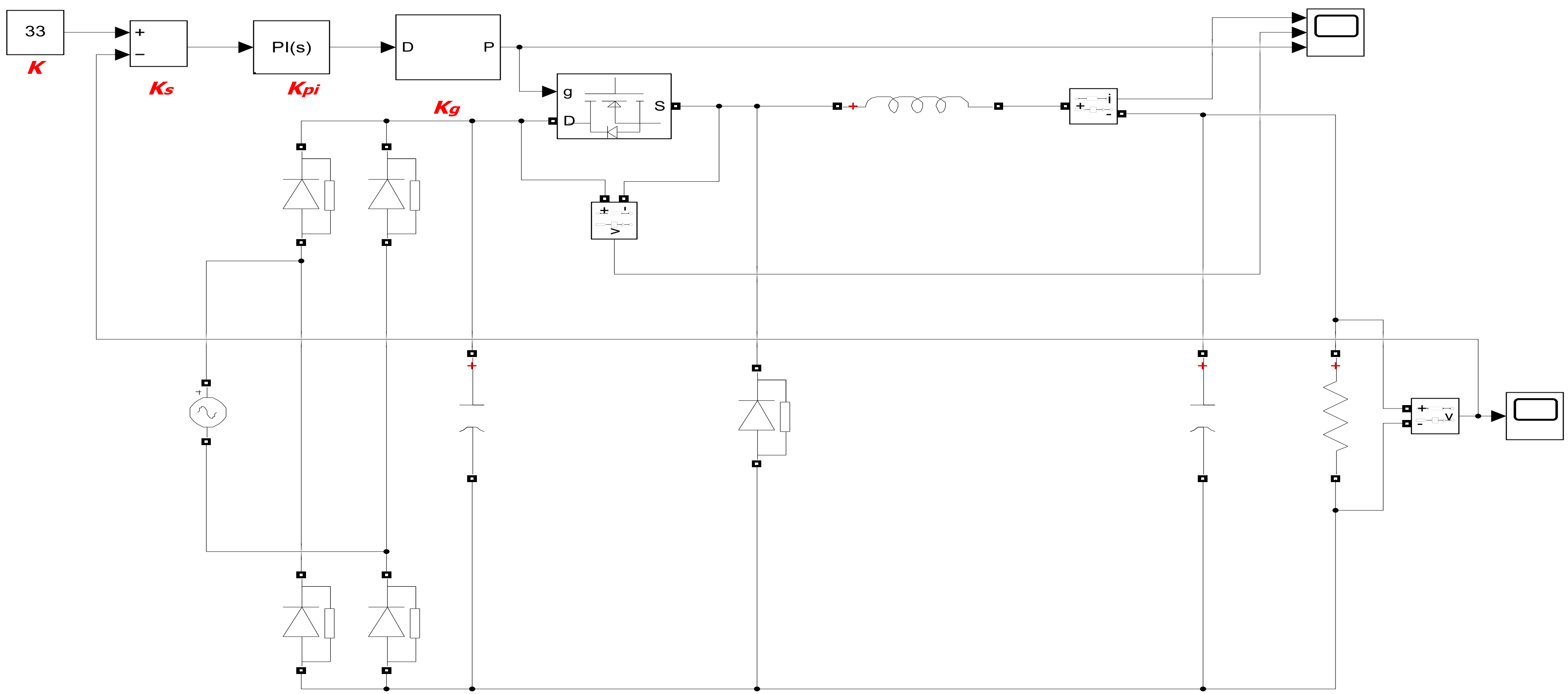

Figure 10: Buck LED Driver with Feedback Control

in figure 10. Hence, comparison between conventional circuit and proposed circuit can be done by comparing between figure 8 and figure 11.
It has been depicted previously about problems of gate triggering of conventional LED driver by analysing the graphs in figure 7. Now, observing figure 10, it is evident that, at point c', MOSFET drain to source voltage fall to its minimum value within a shorter time interval than figure 7. Moreover, MOSFET output voltage drops almost instantly to its minimum value. This enhances the time instant for the MOSFET gate to be turned on. Specifically, more accurate gate triggering can be performed as below.

MOSFET gate has also been triggered at point c', means exactly at the time of resonance. Comparing with figure 7, where gate was triggering prior to the instant of resonance, it can be stated that gate triggering has been improved. Simultaneously, unwanted power loss can also be diminished and overall system efficiency can be improved.

By observing figure 7 and figure 10, we can also comment that, nature of the respective graphs are same. No other characteristics of MOSFET, converter inductance and other elements in the circuit have been kept unaltered. Therefore, no other additional power losses are occurring in proposed LED driver circuit in figure 9.

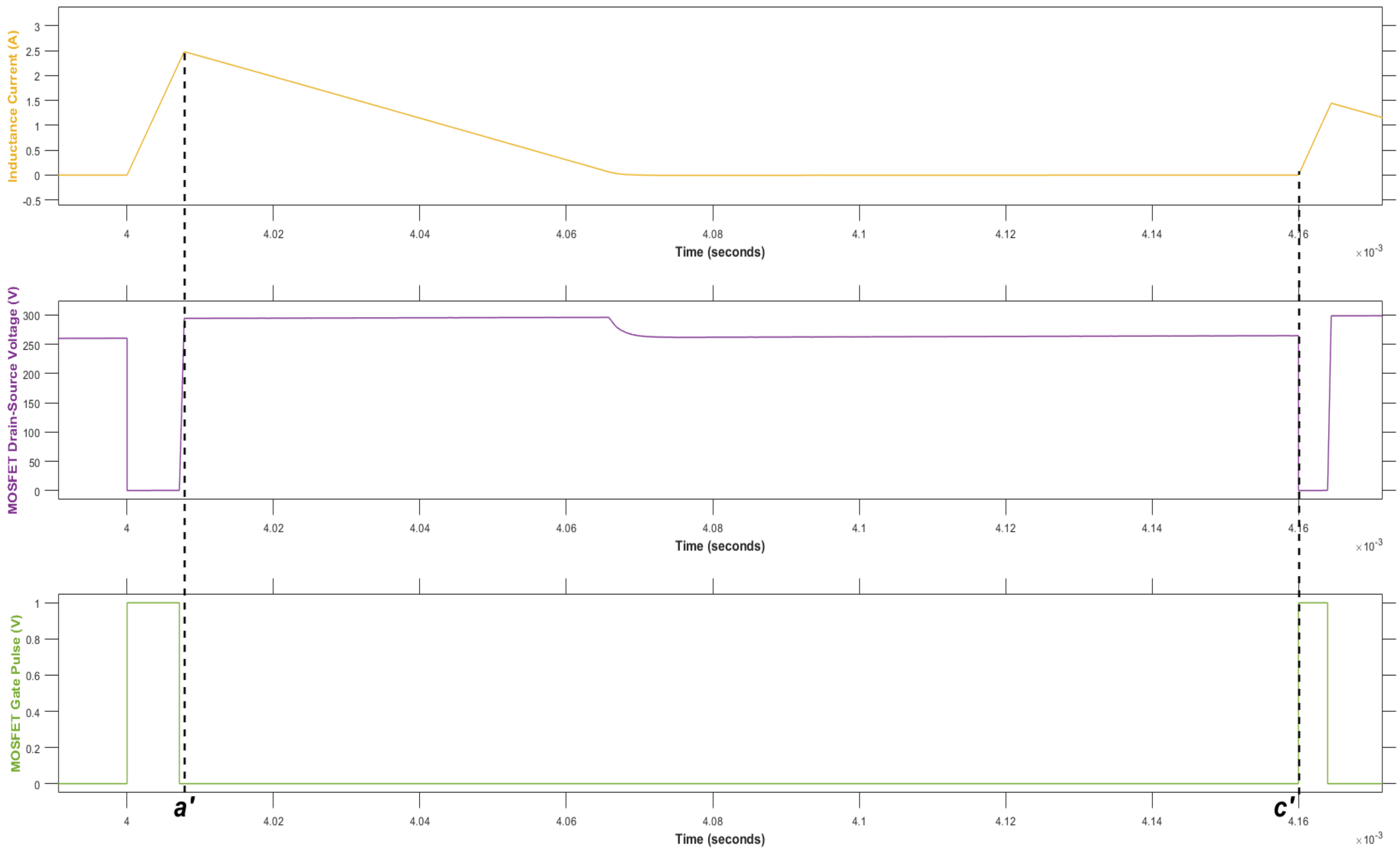

Figure 11: Inductance Current, MOSFET Output Voltage and Gate Pulse of Proposed Driver

Chapter 6

Input Filter Design

6.1. Distortion of Supply Current:

Output voltage or current from a wall socket is sinusoidal in nature. This voltage or current is also the input of the loads we use for our purposes. These loads comprises of many nonlinear elements like diodes, BJT, MOSFET, inductor, capacitor and other electronic elements. These elements distort the nature of supply current waveform.

Flicker is amplitude modulation of the light output that can be induced by voltage fluctuations in AC mains, residual ripples in the output current provided to the LED load, or incompatible interaction between the dimming circuits and LED power supplies. Flicker can cause other temporal light artifacts (TLAs) which include stroboscopic effect (the misperception of motion) and phantom array (pattern appears when eyes move). TLAs come in both visible and invisible forms. Flicker that occurs at frequencies of 80 Hz and lower is directly visible to the eye, and invisible flicker is the temporal variations occurring at frequencies of 100 Hz or higher. The stroboscopic effect and phantom array will typically occur within a frequency range of between 80 Hz and 2 kHz, their visibility varies in populations. While invisible TLAs is not perceptible to the human eye they can still have a number of negative consequences.

Flicker and other TLAs are undesired temporal patterns of light output that can cause eye strain, blurred vision, visual discomfort, reduced visual performance and, in some cases, even migraines and photosensitive epileptic seizures. Therefore they're one of the key considerations in light quality assessment. The intended use of artificial lighting plays a role. Different lighting scenarios may tolerate different level of temporal light artifacts. TLAs may be less of a concern for roadway, parking lot, and outdoor architectural lighting, or other applications where the duration of exposure to artificial light is limited. Artificial light with a high percentage of flicker should not use for both ambient lighting and task lighting in homes, offices, classrooms, hotels, laboratories and industrial spaces. Flicker-free lighting is not only critical for visual tasks that demand precise positioning of the eyes and environments where susceptible populations spend considerable time, it's high desired for HDTV broadcasting, digital photography and slow-motion recording in studios, stadiums and gymnasiums. Video cameras can pick up TLAs the way like the human eye detects these effects.

The key to mitigating flicker lies in the LED driver which is designed to rectify commercial AC power into DC power and filter out any undesirable current ripple. Sufficiently large ripples, which typically occurs at twice the frequency of the AC mains voltage, in the DC current provided to the LED load result in flicker and other visual anomalies at a frequency of 100/120 Hz. Thus the allowed level of ripple current in the LEDs, such as ±15% ripple (a total of 30%), must be defined in LED drivers for various applications where flicker matters. The ripples may be smoothed out by using a filter capacitor. One of the major challenges in driver design is to filter out ripples and harmonics without using bulky, short-lived high voltage electrolytic capacitor on primary side. AC LED engines are inherently susceptible to the flicker phenomenon because the LEDs in fact run from what is essentially the intermediary DC voltage that would be in an SMPS-based LED lighting system. Rapid alteration in polarity gives rise to a flicker in the intensity at a frequency twice the AC sinusoidal frequency. Despite the simplicity in circuit design, additional circuitry is required to effectively reduce the temporal variation in the power supply.

Standards for limiting flicker for different applications are yet to be established. Two metrics were established by IES to quantify flicker. Percent flicker measures the relative change in the light modulation (the depth of modulation). Flicker index is a metric that characterizes the intensity variation over the entire periodic waveform (or duty cycle, for square waveforms). Percent flicker is better known to general consumers. In general, 10 percent flicker or less at 120 Hz or 8 percent flicker or less at 100 Hz is tolerable for most people except for the at-risk populations, 4 percent flicker or less at 120 Hz or 3 percent flicker or less at 100 Hz is considered safe for all populations and highly desired in visually intensive applications. Unfortunately, a large number of LED lamps and luminaires currently supplied on the market have a high flicker percentage. AC LED lights, in particular, come with flicker typically higher than 30 percent at 120 Hz.

Electromagnetic interference (EMI), also referred to as radio frequency interference (RFI), affects other electrical circuit as a consequence of either electromagnetic conduction or electromagnetic radiation emitted by electronics such as those in LED drivers, CB radios and cell phones. Any LED driver connected to AC mains supply has to meet the radiated emissions standards such as defined in IEC 61000-6-3. In an LED driving circuit, MOSFET switching is usually the main source of EMI. A PCB layout with paths for the switching currents kept short and compact is also important to limit EMI. In some applications an input filter is required to reduce high frequency harmonics and the design of this circuit is critical to maintain a low EMI. The ground plane on the circuit board must remain continuous so as to avoid creating a current loop that causes high levels of EMI to be emitted. A metal screen may be mounted over the switching area to provide an enclosure that stops EMI radiation.

Electromagnetic compatibility (EMC) is the ability of a device or system to operate in its electromagnetic environment without yielding EMI that disturbs neighboring equipment or being disturbed by the EMI radiated by neighboring equipment. The EMC performance of the LED driver is often automatically assured by a good EMI design. However, electrostatic discharge (ESD) and surge immunity which are not taken into account in EMI practices also affects the EMC performance.

6.1.1. Waveform Analysis:

Nature of the waveform of the supply current has no longer been sinusoidal. Original waveform incorporates several sinusoidal waveforms of other frequencies. Suppose, the supply frequency is 'f' Hz, then it incorporates sinusoidal waveforms of $2f$, $3f$, $4f$ and so on frequencies. Among these other frequencies, only those frequencies having odd multiplier of fundamental frequency, are responsible to distort the original waveform. Frequencies of even multiplier of fundamental frequency get cancelled out each other by Fourier Transform. Figure 11 and figure 12 shows original supply voltage, current and distorted supply voltage, current respectively.
It can be observed that, only supply current waveform gets distorted. Whereas, supply voltage waveform remains same. Therefore, it is the prime objective to minimize the distortions in supply current waveform.

6.1.2. FFT Analysis:

A fast Fourier transform (FFT) is a highly optimized implementation of the discrete Fourier transform (DFT), which convert discrete signals from the time domain to the frequency domain. FFT computations provide information about the frequency content, phase, and other properties of the signal. Popular FFT algorithms include the Cooley-Tukey algorithm, prime factor FFT algorithm, and Rader's FFT algorithm. The most commonly used FFT algorithm is the Cooley-Tukey algorithm, which reduces a large DFT into smaller DFTs to increase computation speed and reduce complexity. FFT has applications in many fields.

FFT analysis of supply current has also been shown in figure 13 to check the original current waveform distortion in terms of percentage of THD.
Fundamental waveform is of course supply current, frequency of which is 50Hz. 2 consecutive cycles of fundamental waveform have been taken into account for THD calculation and maximum distortion frequency allowed for this calculation is set to 150Hz. This is because, from fourier transform, the frequency responsible for harmonics inclusion is the third order harmonics of the fundamental frequency. From these set points, THD calculated is 255.17% from figure 13, which is quite large and not permissible value for practical implementations.

6.2. Purpose of Input Filter:

It is not expected from a load, that it will distort the nature of the graph of supply parameters. This is because, there are several other interconnected loads in that same power system from which that power supply belongs. If any of the loads alters the nature of the supply parameters, then the performance of these other interconnected loads will hamper and if we consider a large amount of loads altering the supply nature, then other loads may cause malfunctioning also.

6.2.1. Circuit of Input Filter:

It is hence required for any load that it should not distort the supply waveform. This is the reason for the requirement of filter circuit for any load comprises of nonlinear elements. The filter circuit used here is shown in figure 15.

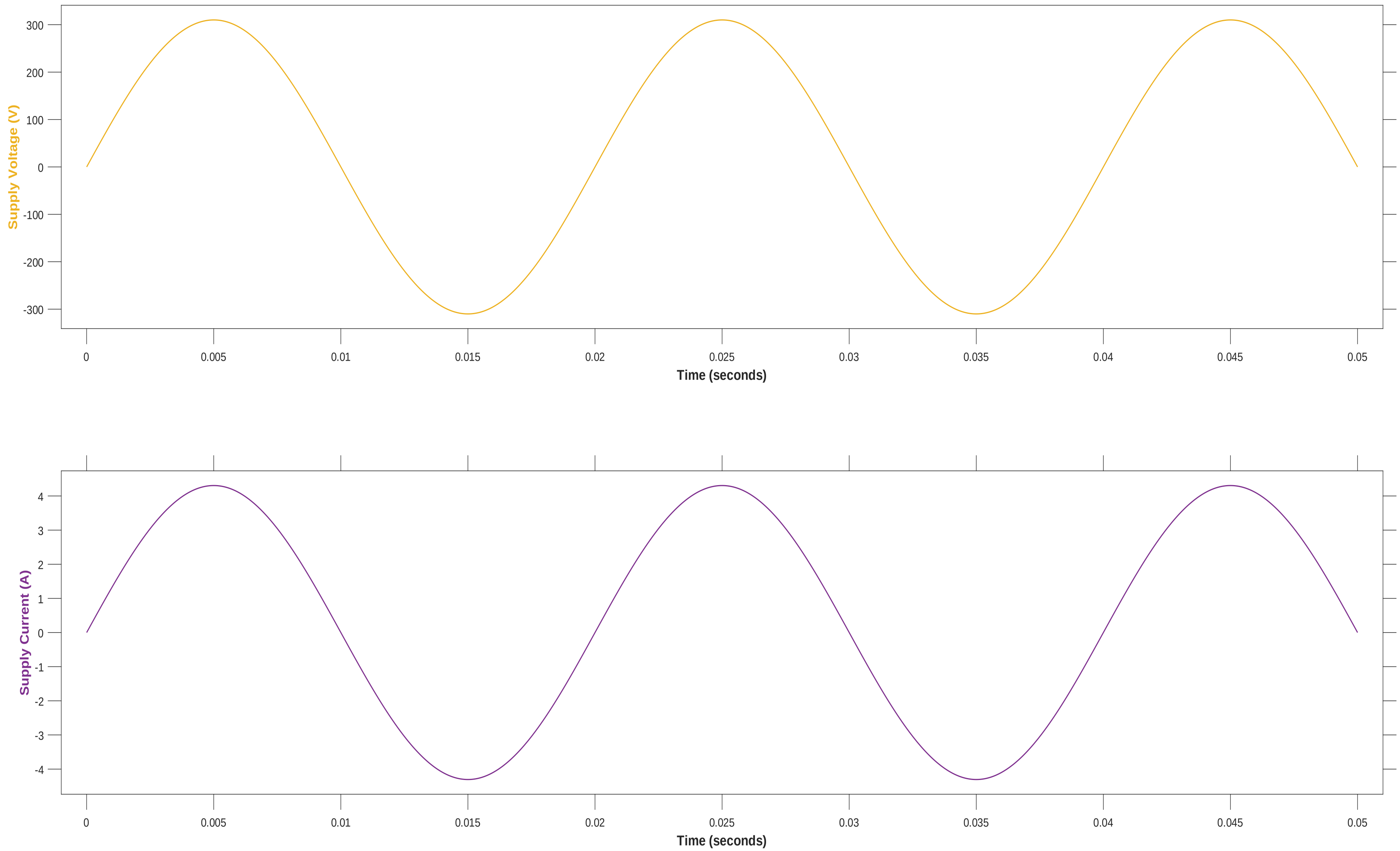

Figure 12: Original Nature of Supply Voltage and Current

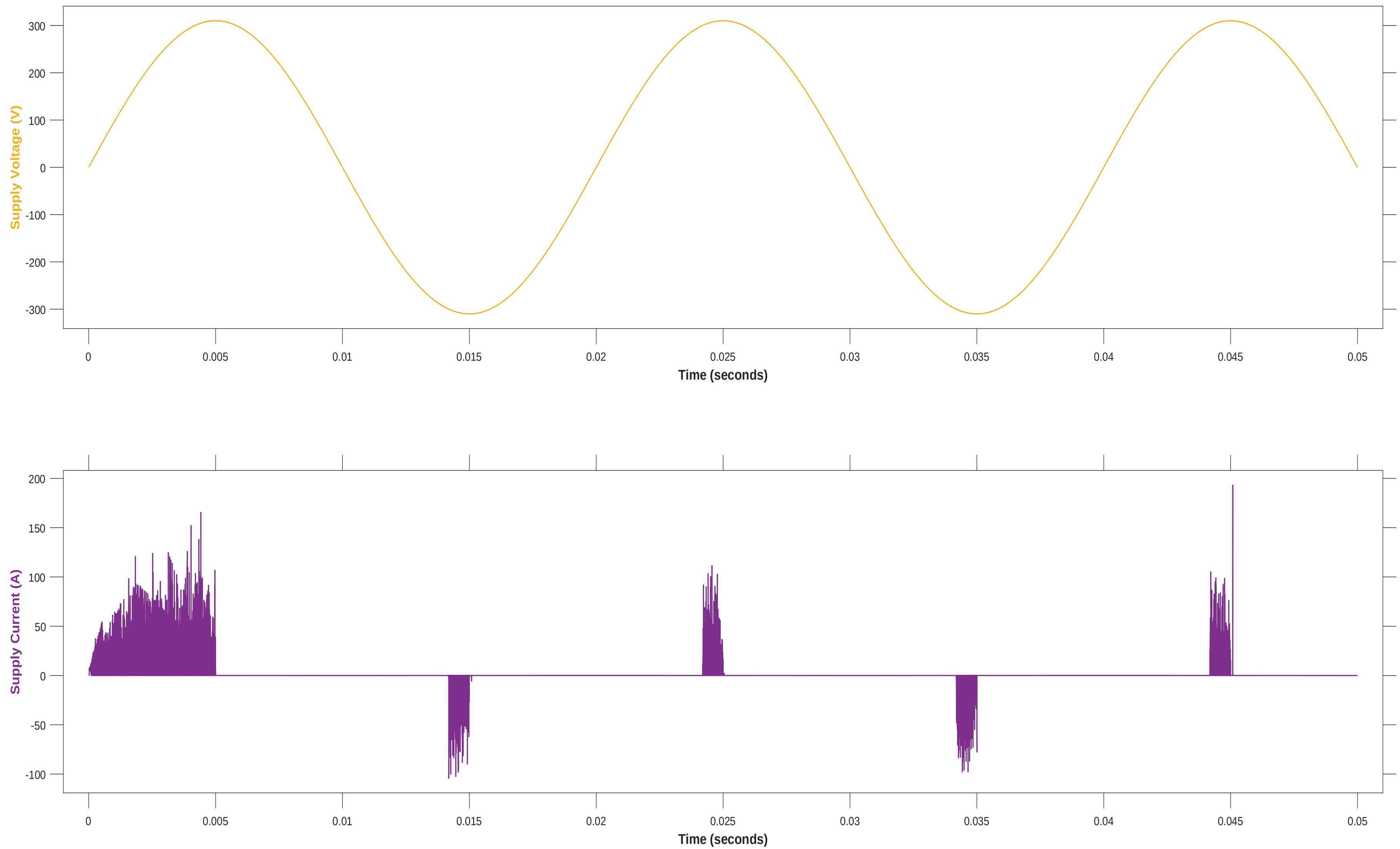

Figure 13: Distorted Nature of Supply Voltage and Current

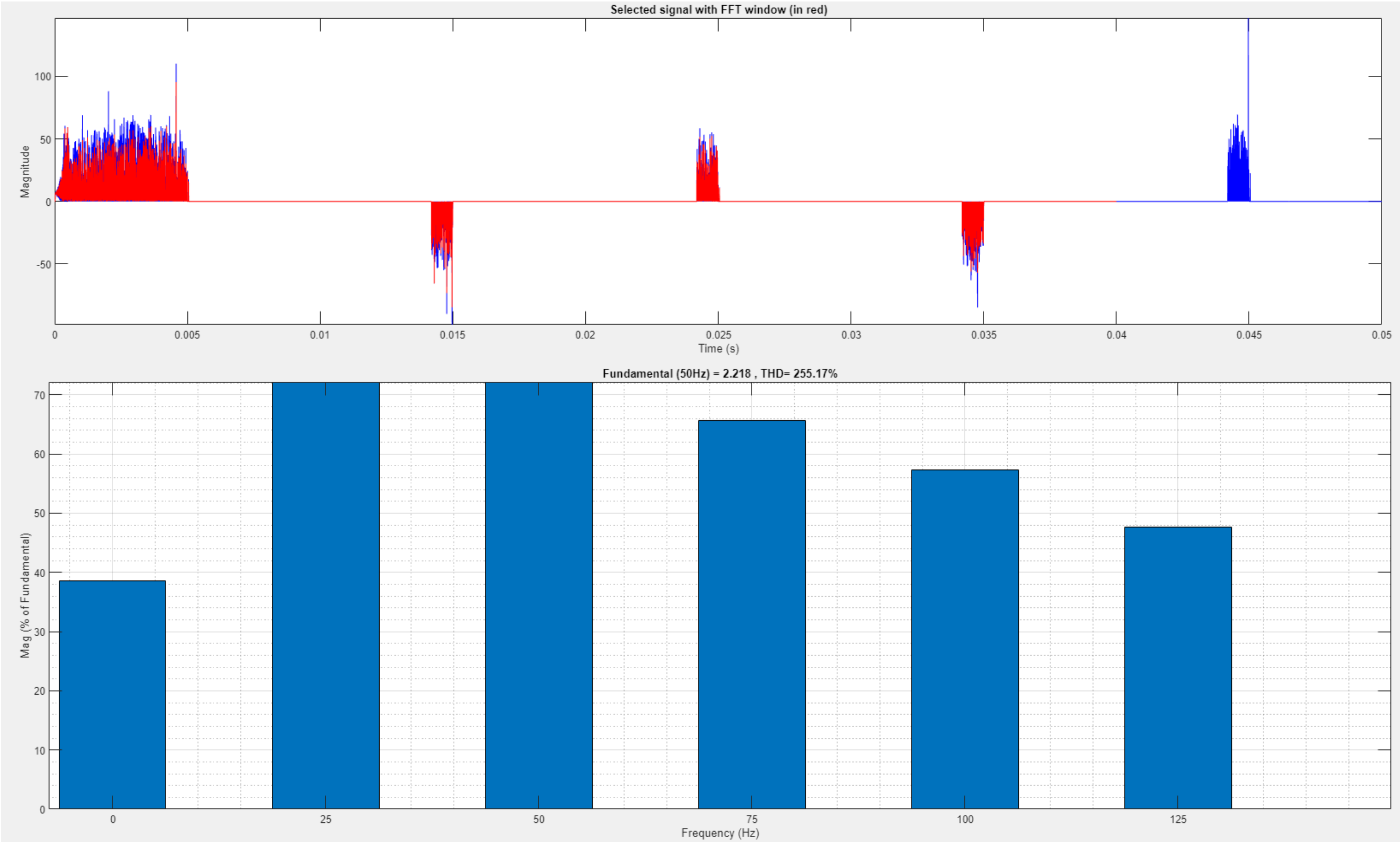

Figure 14: FFT Analysis of Distorted Supply Voltage and Current

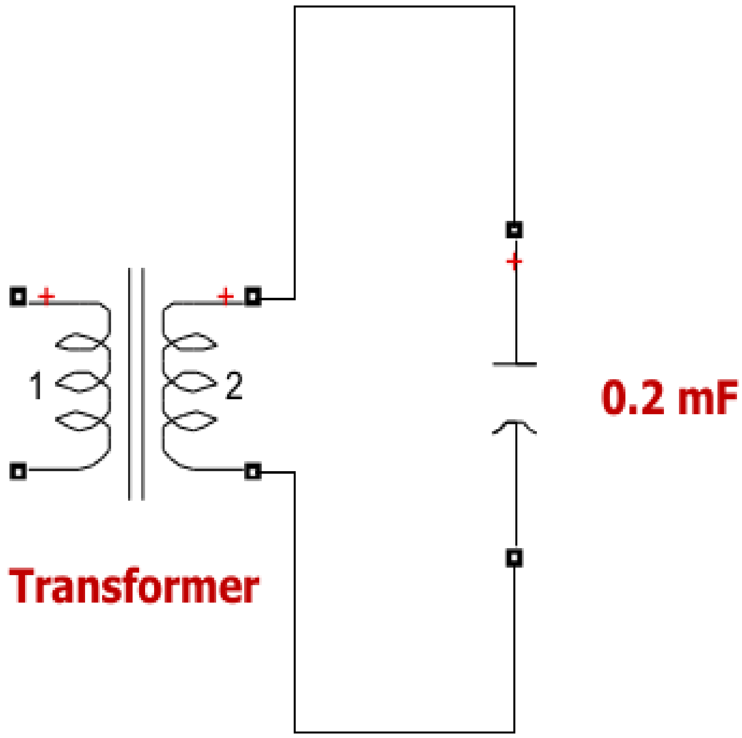

Figure 15: Input Filter Circuit

Generally, any filter circuit can be designed by different combinations of inductor and capacitor. Inductor reduce current harmonics and capacitor reduce voltage harmonics. But here a different approach has been adapted.

This filter circuit comprises of a transformer and a capacitor. Transformer has been used in order to step down the input voltage first. If we step down the input voltage, we can do MOSFET switching at higher duty cycle. This will reduce incorporation of harmonics in the supply side. Though voltage waveform gets a very little distortion, but for safety purpose a capacitor has been included.

After doing multiple trial and error, values of different parameters of the transformer and capacitor has been selected. It has been seen that these values incorporate very little harmonics, which has been discussed below. Units of transformer have been taken in SI.

Parameter	Description	Value
P_n(VA)	Nominal Power	25
f_n(Hz)	Nominal frequency	50
V1(V_{rms})	Winding 1 voltage	220
R1(ohm)	Winding 1 resistance	4.3218
L1(H)	Winding 1 inductance	0.45856
V2(V_{rms})	Winding 2 voltage	70
R2(ohm)	Winding 2 resistance	0.7938
L2(H)	Winding 2 inductance	0.084225

Table 3: System Parameters of Figure 15

6.2.2. Waveform Analysis:

In this study, a new buck LED driver is introduced to improve its efficiency. By elaborating the proposed driver configuration and analyzing power losses of main elements (i.e. the MOSFET, inductors, and diodes) it is shown that at the same operating conditions, the proposed LED driver has much more higher efficiency than the conventional one. The reason is based on two principles. Firstly, the minimum point of output resonant voltage of the MOSFET is near zero in the proposed LED driver, therefore the switching loss of the MOSFET decreases dramatically using valley switching method. This result is more prominent when the output voltage value is very lower than the input voltage value. Secondely, is the current waveform of the proposed LED driver is changed in a way that the other main losses consist of the MOSFET, inductance, and diode conduction losses are reduces strongly. Also, a new valley switching method is introduced according to the new converter which does not require the coupling winding. Therefore, the cost and dimension of the proposed converter is much less than the conventional driver. After the inclusion of filter circuit, the final total circuit has been shown in figure 17.

After inclusion of input filter circuit, waveforms of input voltage and current has been shown in figure 17.
From the above two waveforms, we can conclude the following observations. There is no problem with input voltage. It was perfectly sinusoidal before the inclusion of input filter as well as after inclusion of input filter. But, the major change comes with the waveform of supply current. It was very poorly distorted and we saw that it contained 255.17% of harmonics. But now, from the graphical representation, it is obvious that current waveform gets improved. Talking about its THD percentage, it has been shown below.

6.2.3. FFT Analysis:

FFT analysis of supply current has also been shown in figure 17 to check the original current waveform distortion in terms of percentage of THD.
Fundamental waveform is of course supply current, frequency of which is 50Hz. 2 consecutive cycles of fundamental waveform have been taken into account for THD calculation and maximum distortion frequency allowed for this calculation is set to 150Hz. This is because, from Fourier transform, the frequency responsible for harmonics inclusion is the third order harmonics of the fundamental frequency. From these set points, THD calculated is 1.13% from figure 17, which is within the permissible value for practical implementations.

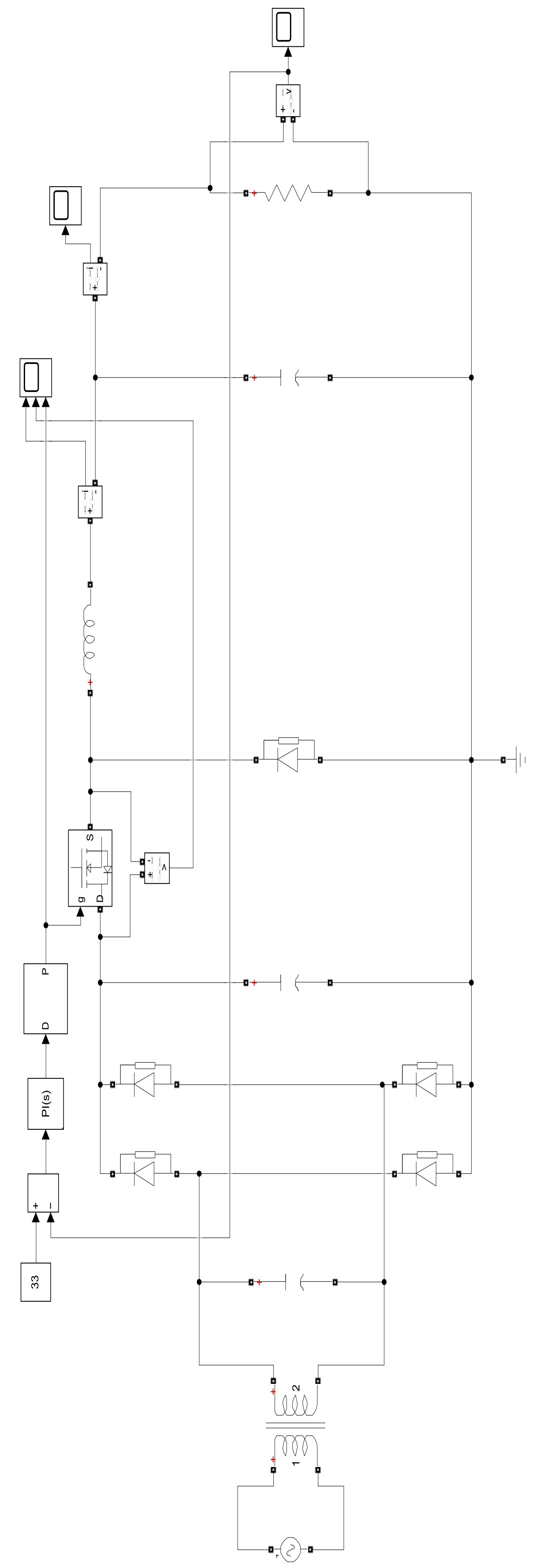

Figure 16: Proposed Circuit After Inclusion of Filter Circuit

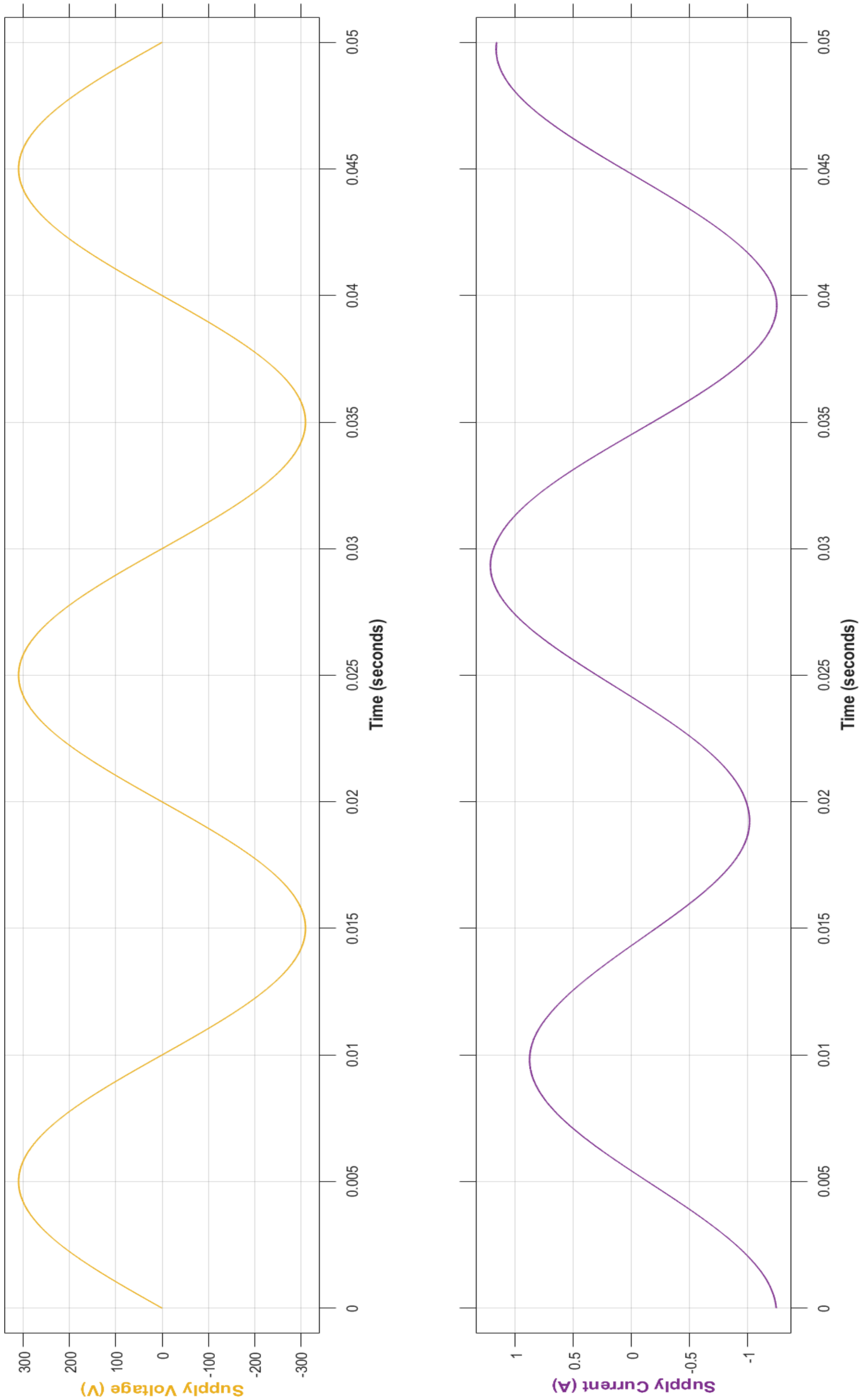

Figure 17: Input Voltage and Current

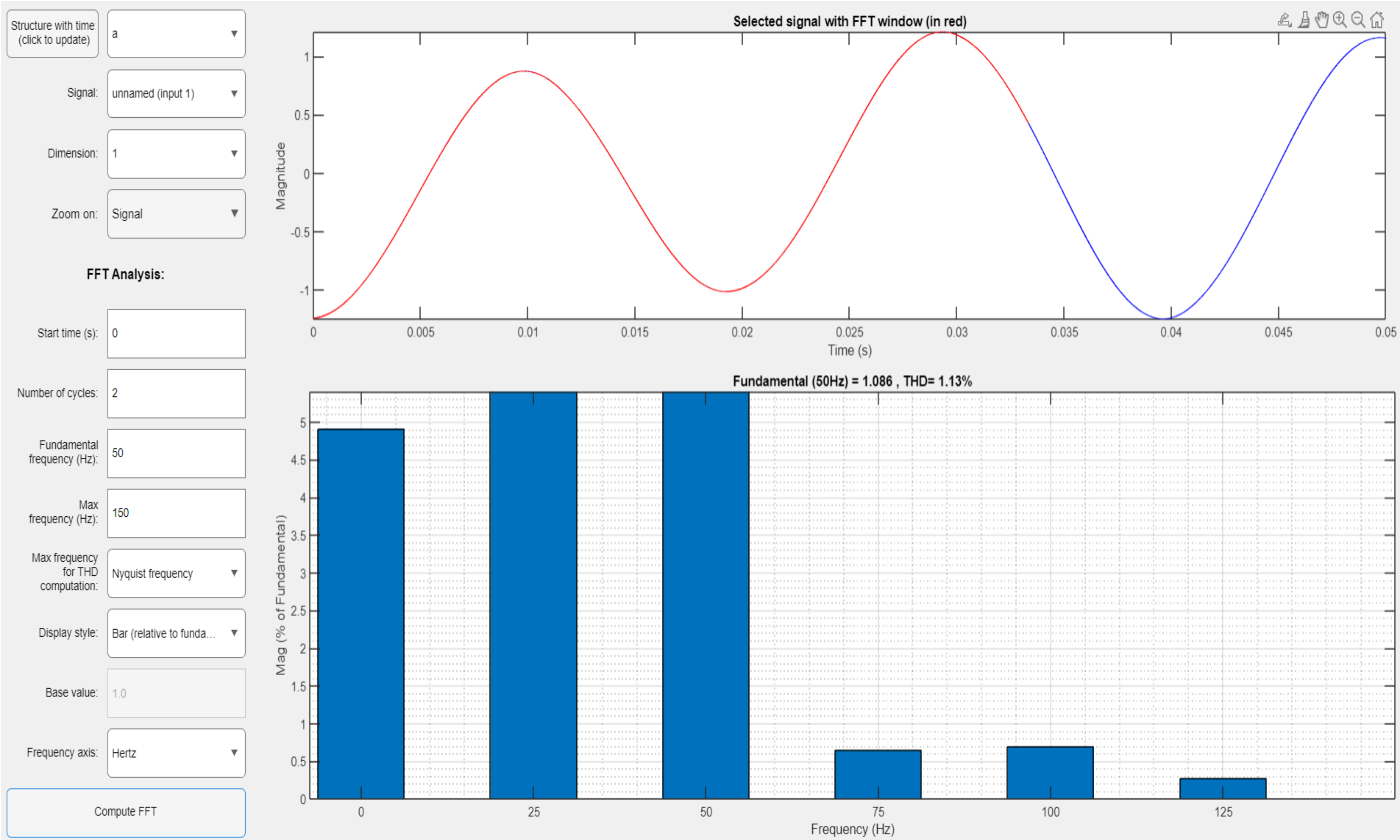

Figure 18: FFT Analysis of Supply Voltage and Current, After Inclusion of Input Filter

Chapter 7

Conclusion and Future Work

7.1. Conclusion from the Thesis:

We have consider valley switching as our fundamental area of study. Besides our final circuit has been shown in figure 16. This topology focuses on the improvement of feedback control of valley switching.

We have used a simple buck converter. Simultaneously, we trigger that MOSFET only when voltage across drain to source of the MOSFET is zero. Hence, when MOSFET gets turned on, power loss across the MOSFET is zero. Secondly, we have applied a simple control circuit using feedback control with the help of PI controller and PWM. Finally, we have incorporated a simple input filter circuit and able to achieve considerable reduction in harmonics.

The control circuit of the proposed circuit in this paper contains a comparator circuit, a PI controller and a PWM. So, the stated control topology is simple and comprises of less electronic components.

7.2. Future Scope of Work:

- A transformer is a power consuming device. Use of a more efficient transformer can definitely improve system efficiency in the topology depicted in this paper.
- There is much scope to work regarding improving power factor of this circuit.
- Efficiency can definitely be improved with other methods of valley switching. There is not so much calculation shown regarding system efficiency and performance due to lack of opportunities and infrastructure available. Hence, it can be discover further.

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