Studies on Single-Inductor-Multiple-Output (SIMO) Buck Drivers for Multicolour LED Lamp System

A Thesis submitted towards partial fulfilment of the requirements for the Degree of

Master of Technology in Illumination Technology & Design
submitted by

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All information in this document has been obtained and presented in accordance with academic rules and ethical conduct.

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Introduction

A light-emitting diode (LED) is a semiconductor light source that emits light when current flows through it. Electrons in the semiconductor recombine with holes, releasing energy in the form of photons and light produces. Since light is generated within the solid semiconductor material, LEDs are described as solid-state devices. Inside the semiconductor material of the LED, the electrons and holes are contained within energy bands. The separation of the bands, called Bandgap, determines the energy of the photons emitted by the LED. The photon energy determines the wavelength of the emitted light and its colour. Different semiconductor materials with different bandgaps produce different colours of light.

LEDs are increasingly gaining acceptance in the lighting industry with a growing list of applications. There are some major factors for this popularity -

- Long lifetime
- Environmental friendly
- High luminous efficiency
- Flexibility to perform colour mixing and dimming control [1]

According to the **RGB colour model** [2] red, green, and blue are primary colours of light, which are added together in various ways to reproduce a broad array of colours. This model is nothing but an additive colour model. To form a colour with RGB, three light beams must be superimposed. Each of the three beams is called a component of that colour, and each of them can have an arbitrary intensity, from fully off to fully on, in the mixture. Zero intensity for each component gives the darkest colour, considered black and full intensity of each gives a white.
When one of the components has the strongest intensity, the colour is a hue near this primary colour (red-ish, green-ish, or blue-ish), and when two components have the same strongest intensity, then the colour is a hue of a secondary colour (a shade of cyan, magenta or yellow). A secondary color is formed by the sum of two primary colours of equal intensity: cyan is green+blue, magenta is blue+red, and yellow is red+green. Every secondary colour is the complement of one primary colour: cyan complements red, magenta complements green, and yellow complements blue.

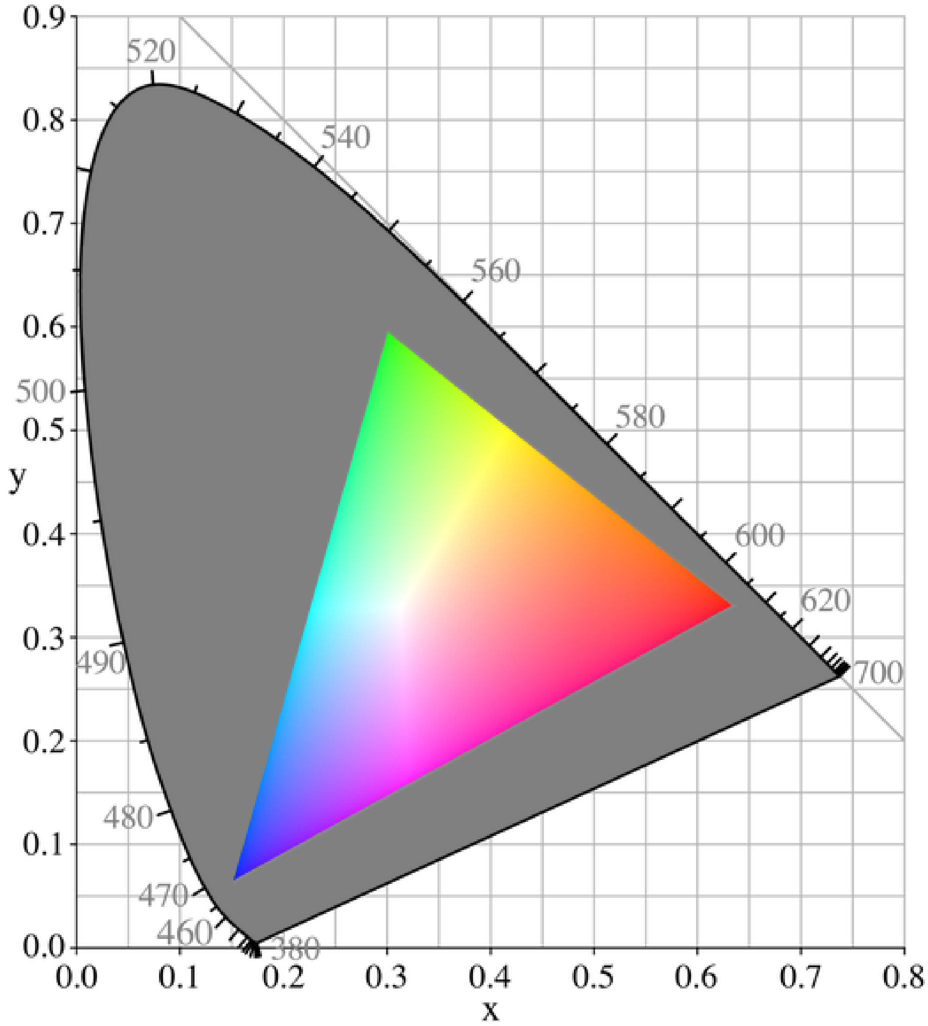


Figure 1: Colour Triangle
[3]

A set of primary colours, define a **colour triangle** [3] ; only colours within this triangle can be reproduced by mixing the primary colours. Colours outside the colour triangle are therefore shown here as grey. The use of the three primary colours is not sufficient to reproduce all colours; only colours within the colour triangle defined by the chromaticities of the primaries can be reproduced by additive mixing of nonnegative amounts of those colours of light. Colour is expressed as an RGB triplet (r,g,b), each component of which can vary from 0 to 1.

An LED driver is a self-contained power supply which regulates the power required for an LED or array of LEDs. LEDs need an LED driver to convert the power supply into a more suitable one because LEDs require a constant direct current whose magnitude is lower than the power supply. This work is done by LED Drivers.

The purpose of this thesis is to compare two LED drivers for multi-colour LED system. This comparison is done based on some output parameters.

Chapter 1

Literature Review and Problem Definition

This Chapter deals with general discussions on LED drivers. Also, it consists of discussions on multi-string LED systems and the basic concepts of two different kinds of multiple output Buck Drivers. At last, this chapter consists of the problem statement of the work and the steps of the execution of the work of this thesis.

1.1 LED Drivers and selection of LED Driver

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, an LED driver is a self-contained power supply that regulates the power required for a LED or array of LEDs.
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.
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 provide 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.

The 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 compliance with international regulatory standards such as the UL1310 in regard to safety.

1.2 Multiple output Buck Drivers for multicolor LEDs

Depending on the specific application requirements, the LED can either be arranged in series as a single string (or a single LED chip), or in parallel forming a multi-string structure (for medium and high power applications). [15] Recently, with the significant improvement of LED lighting technologies, LED has become a new-generation light source for a variety of applications, including city landscape lighting, street lighting, automobile lights, and so on. In many applications, multiple-string LED system, driving with independent dimming function is necessary, such as color-temperature control, multiple dimming control and lighting in power-saving mode. [14].

But, achieving a compact and low-cost LED driver design is challenging for applications where multiple parallel LED strings are needed. This is because extra functionalities such as current balancing, individual string current regulation, or open/short circuit fault protection are typically demanded in such multi-string LED systems. [15]

Generally, the control schemes for the multi-string LED systems can be classified into two types -

- Voltage source mode (VSM) driver control
- Current source mode (CSM) driver control

1.2.1 VSM Driver

Voltage-source mode (VSM) converter produces a single common output bus voltage (V_0) connected with all LED strings. The VSM SIMO dc-dc converter is shown in Fig. 1.1.

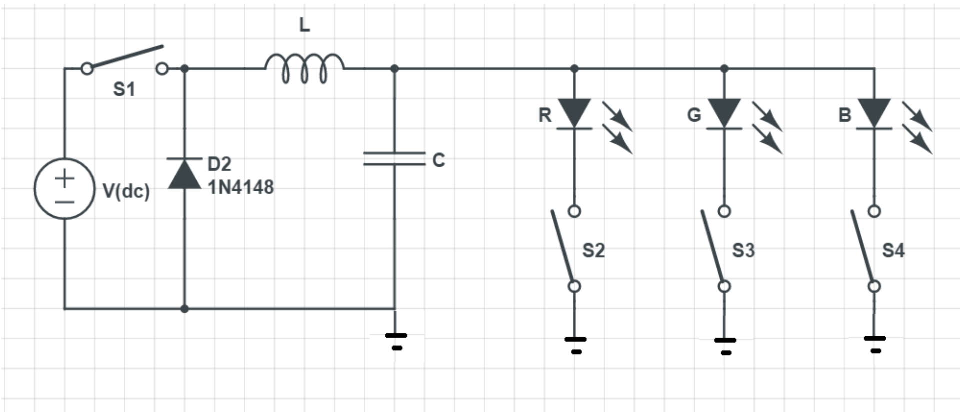


Figure 1.1: VSM SIMO DC-DC CONVERTER
[15] [16]

The VSM buck converter is supposedly fed by a voltage source. The output The output voltage of the VSM buck converter is controllable via the duty cycle and the cell consists of a switch, a diode, and an inductor which serves as a high-frequency switching power storage. The output capacitor simply serves a filtering function for voltage delivery.

The voltage gain of the VSM buck converter are determined as - [14]

$$M = \frac{V_0}{V_{in}} = D \tag{1.1}$$

where - M = Voltage gain of the VSM driver, V_0 = Output voltage of the circuit, V_{in} = Input voltage of the circuit, D = Steady state duty cycle.

This topology is not proper for LED applications because the peak value of the output current for each LED string is N times larger than the desired current for the N number of LED strings. Therefore, the LED strings may be burned out.

1.2.2 CSM Driver

Current-source mode (CSM) converter and a series structure are effectively the dual versions of the usual dc-dc converter and the parallel configuration.
One inductor is needed to construct a constant current for feeding the CSM converters that drive the LEDs.The CSM SIMO dc-dc converter is shown in Fig. 1.2.

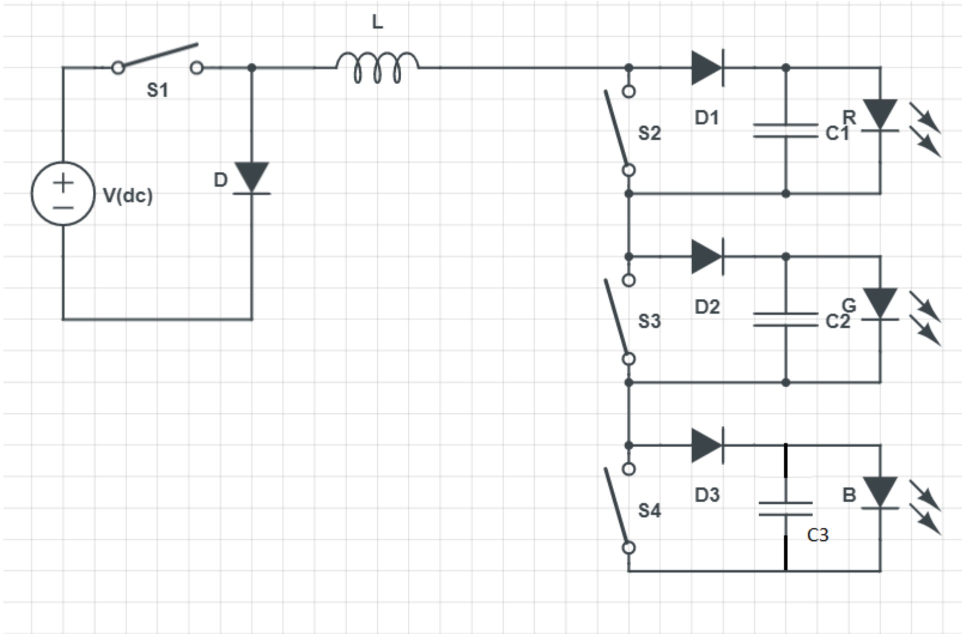


Figure 1.2: CSM SIMO DC-DC CONVERTER
[15]

This converter makes full use of the properties of the CSM converter to achieve independent dimming function and guarantee good cross-regulation performance, while significantly simplifying the control circuit.
CSM buck converter is fed by a current source. CSM buck converter consists of a switch, a diode, and a switching storage capacitor. The output inductor serves a filtering function delivering current to the load.

The current gain of the CSM buck converter are determined as - [14]

$$M^{'} = \frac{I_0}{I_{in}} = 1 - D \tag{1.2}$$

where - $M^{'}$ = Current gain of the CSM driver, I_0 = Output current of the circuit, I_{in} = Input current of the circuit, D = Steady state duty cycle.

1.3 Problem Description

Traditionally Voltage source mode single-inductor multiple-output (VSM SIMO) DC-DC buck converters are used for colour mixing of LEDs. Recently, as an alternative to this driver, Current source mode single-inductor multiple-output (CSM SIMO) DC-DC driver topology has been proposed.

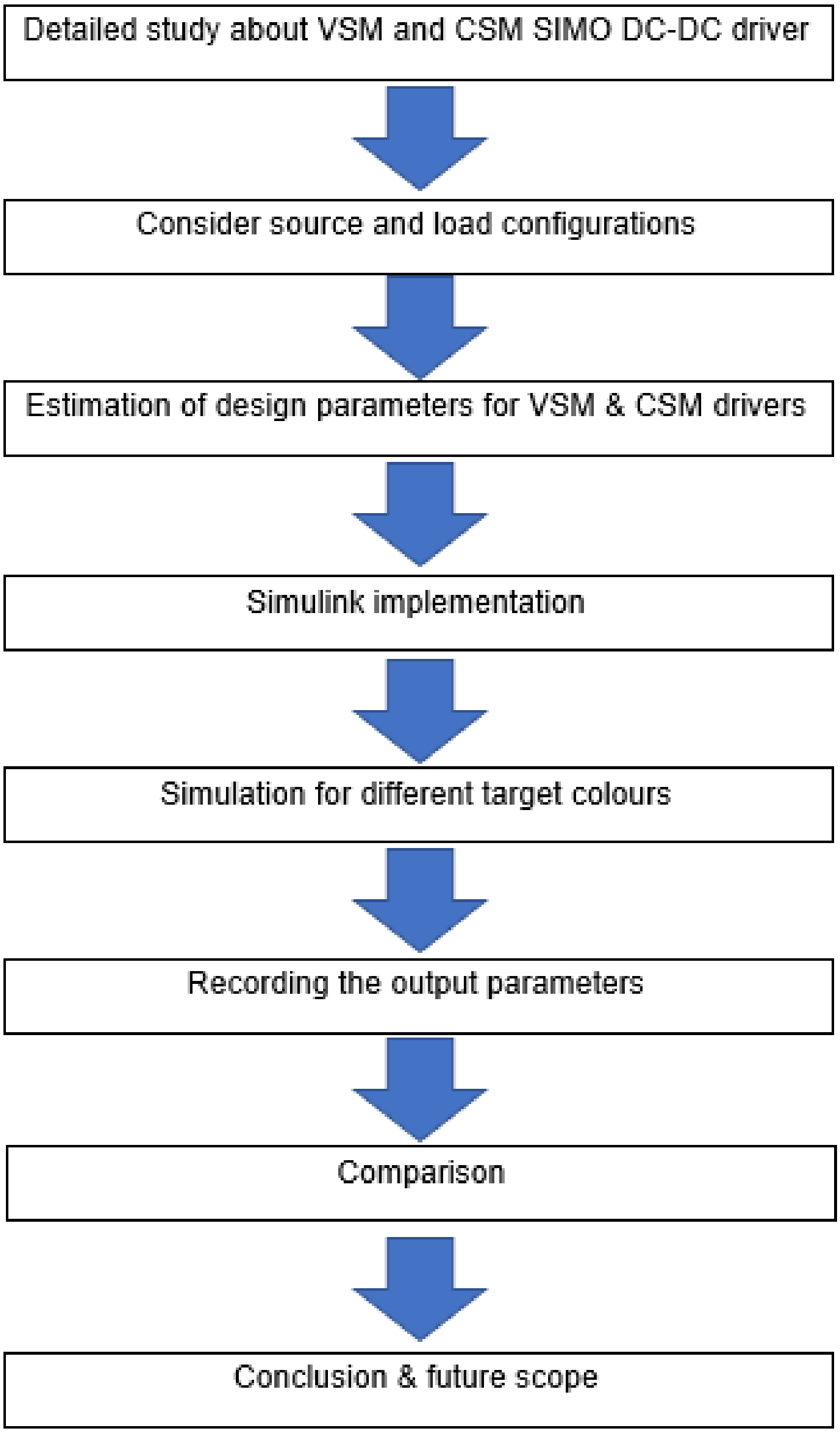
In this thesis the two driver topologies, VSM and CSM are to be compared for same source and load configurations in MATLAB - SIMULINK environment.

The comparison is to be carried out based on efficiency, colour mixing and dimming performance, flicker, and cost of fabrication.

1.4 Objective

- To compare VSM SIMO driver and CSM SIMO driver for colour mixing applications on the basis of efficiency, colour mixing and dimming performance, flicker, and cost.

1.5 Steps of Execution



Chapter 2

Design of VSM and CSM SIMO Buck Converter

In this thesis VSM & CSM SIMO DC-DC drivers are compared, keeping the same source conditions and same load configurations.

This Chapter deals with the discussions on the source & load configurations for both the driver circuits. Also, it consists of discussions on the design parameters for both the VSM & CSM drivers.

2.1 Modelling the LED load

Some basic electrical parameters must be considered when implementing an LED device into a design. [4]

- Power Dissipation: It is the maximum power that can be dissipated in LED before it gets permanently damaged.
- Continuous Forward Current: It is the maximum permissible forward current through the LED.
- Reverse Voltage: It is the maximum permissible voltage that can be applied to the diode in reverse polarity. An LED will not conduct with a reverse voltage applied but if that voltage is over the maximum reverse voltage capacity, LED failure will occur.
- Reverse current: It is the maximum permissible value of reverse current.
- Forward Voltage: It is the maximum allowable forward voltage across the LED for safe operation.

I-V Characteristics are nothing but the current-voltage characteristics of an LED. I-V graph of LED is a representation of the relationship between the current flowing through the LED as a function of the voltage across it. Points to be observed from the I-V graph of an LED:

- The forward voltage of an LED.
- The forward current flows through the LED.
- The resistive load offers by LED.

The I-V characteristic of a LED is shown in Fig. 2.1.

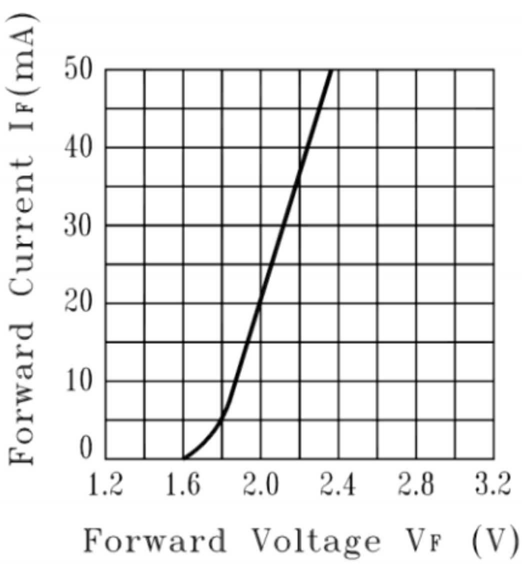


Figure 2.1: I-V Characteristic of a LED
[5]

The linear model of the LED approximates the I-V characteristic by a straight line that is tangent to the actual curve at the DC bias point. Fig. 2.2 shows the curve with the tangent line at the point (V_D, I_D). The curve intersects the horizontal axis at the voltage V_D and the vertical axis at the point I_D and this leads to a voltage plus resistance model. [13]

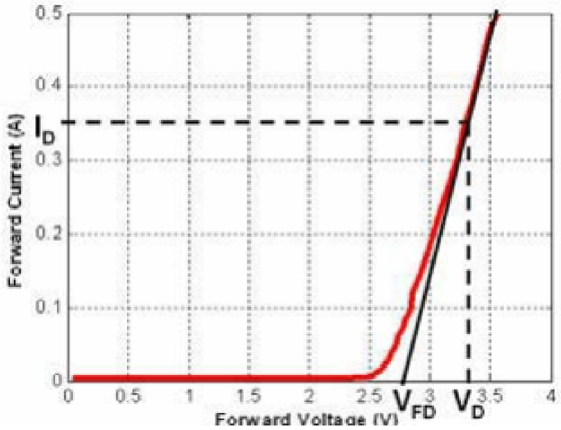


Figure 2.2: I-V Characteristic of a LED
[13] [17]

So, the simplified model of a LED is nothing but -

$$V_D = I_D R_D + V_{FD} \tag{2.1}$$

where - V_D is the voltage across the LED, R_D is the Dynamic Resistance of LED and V_{FD} is the forward voltage drop taken at the knee of the curve.

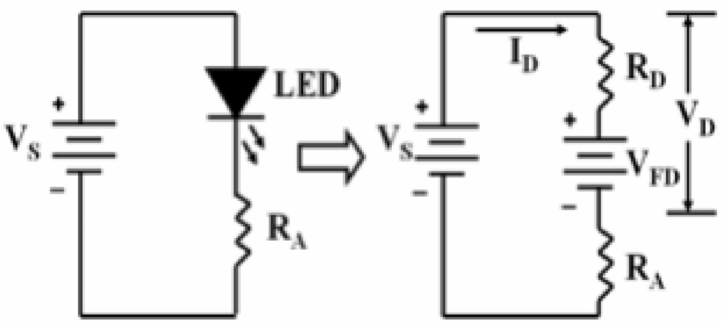


Figure 2.3: Simplified model of a LED
[13]

In this thesis, three different colours of LEDs chips are taken - Red, Green, and Blue. **The power dissipation of the Red LED chip is 0.8 W and the power dissipation of Blue and Green LED chips are 1.2 W.** [6] The V-I characteristics of these three LEDs are shown in Fig. 2.4.

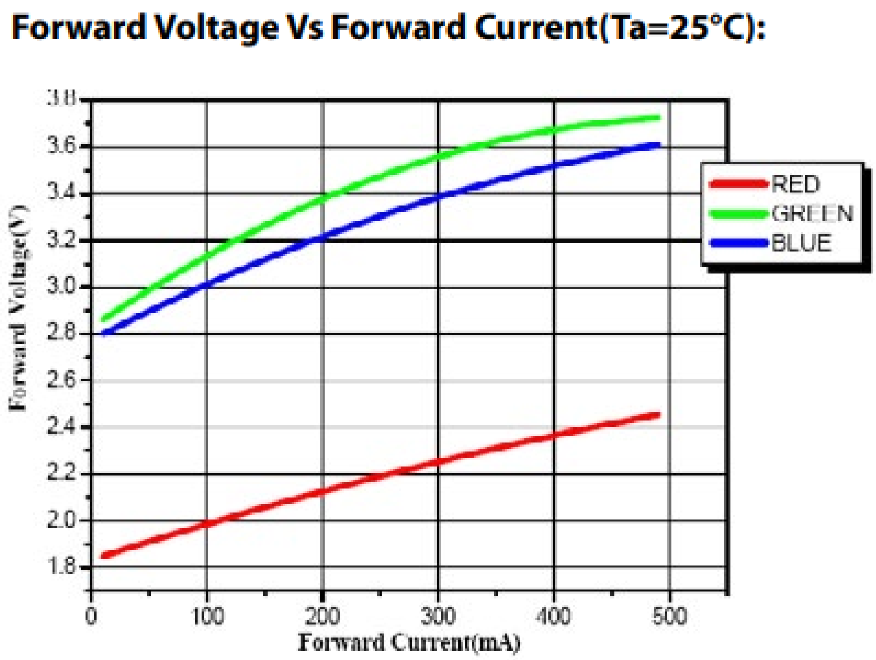


Figure 2.4: V-I characteristics of RGB LEDs
[6]

The forward current (I_D) for all three LED chips is considered 350 mA.
Now, from Fig. 2.4 the voltage across the LED (V_D) and the forward voltage drop taken at the knee of the curve (V_{FD}) for these three LED chips are found and from these two values, it is possible to calculate the Dynamic Resistance (R_D) of these chips. [6]

Table 2.1: **Voltages across the LED and the Dynamic Resistances of R,G,B LED chips**

	Red LED Chip	Green LED Chip	Blue LED Chip
V_D (V)	2.3	3.48	3.7
V_{FD} (V)	2	3	3.28
$R_D = \frac{(V_D - V_{FD})}{I_D}$ (Ω)	0.86	1.37	1.2

In these circuits actually, there are three strings of R, G, and B LEDs and it is considered that each string has 4 LEDs of the same colour.

Table 2.2: **Voltages across the LED strings and the Dynamic Resistances of R,G,B LED strings**

	Red LED String	Green LED String	Blue LED String
V_D (V)	9.2	13.92	14.8
V_{FD} (V)	8	12	13.12
R_D (Ω)	3.44	5.48	4.8

2.2 Design Parameters of VSM SIMO Driver

For this thesis the typical VSM circuit before and after replacing the LED loads with LED linear modelling is shown in Fig. 2.5. and Fig. 2.6 respectively.

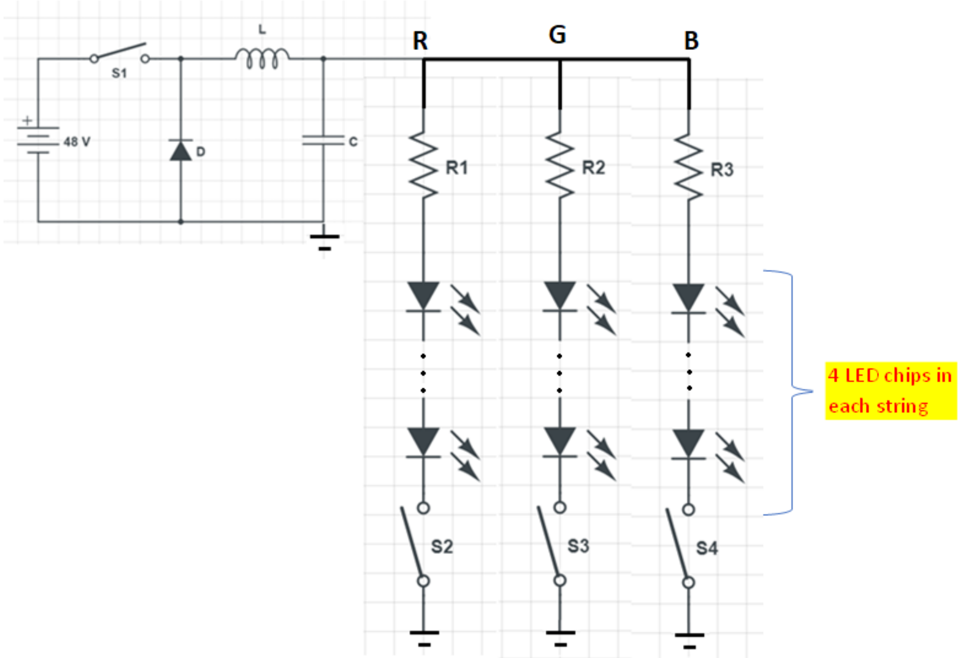


Figure 2.5: Typical VSM model with LED loads

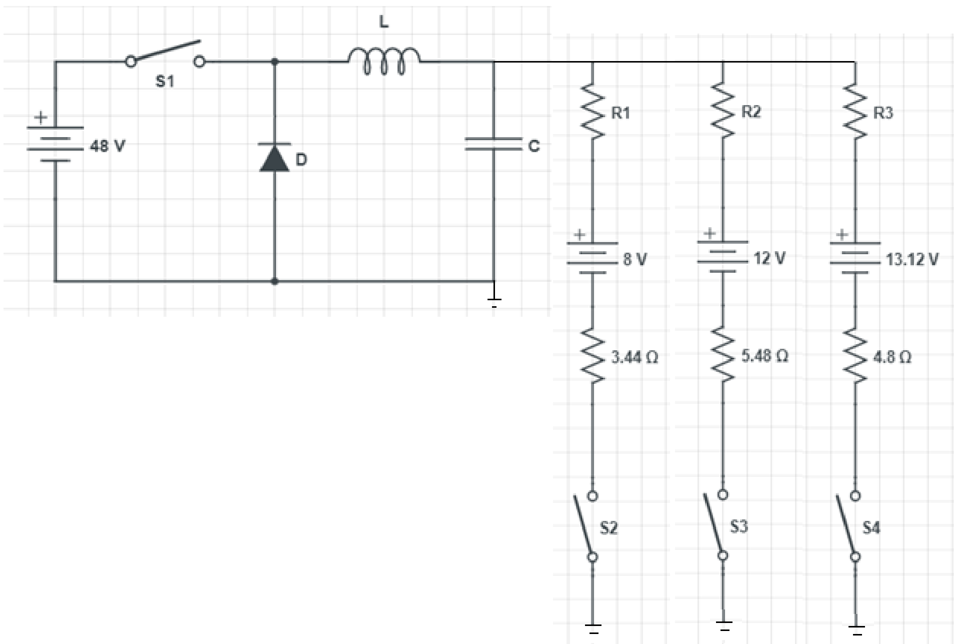


Figure 2.6: Typical VSM model after replacing LEDs by linear modelling

In this thesis some parameters are considered as mentioned below -

- Input Voltage = 48 V (DC)

- Input switching frequency (f_s) = 50 kHz
- Output Current = 350 mA
- Output voltage = 15 V
- Ripple factor = $\frac{\Delta V_0}{V_0}$ = 10% = 0.1

With the help of all this consideration, the design parameters are calculated of VSM SIMO DC-DC driver.

- $$Dutycycle(D) = \frac{Output\,Voltage}{Input\,Voltage} = \frac{15}{48} = 0.3125 \tag{2.2}$$

- Used resistance value =
$$R_{(1,2,3)} = \frac{V_D - V_{FD}}{I_D} \tag{2.3}$$

$R_1(\Omega)$	$R_2(\Omega)$	$R_3(\Omega)$
16.57	3.09	0.57

Here, these resistors are used to achieve the same output voltage (15 V) in all three parallel branches of the VSM driver circuit.

- $$\begin{aligned} L_{min} &= \frac{(1-D)R}{2f} \\ &= \mathbf{19.525}\ \mu H \end{aligned} \tag{2.4}$$

where -
$$\frac{1}{R} = \frac{1}{R_{Red\,String}} + \frac{1}{R_{Green\,String}} + \frac{1}{R_{Blue\,String}}$$

$R_{Red\,String} = R_1 + R_D$ (for red string)
$R_{Green\,String} = R_2 + R_D$ (for green string)
$R_{Blue\,String} = R_3 + R_D$ (for blue string)

- $$\begin{aligned} C_{min} &= \frac{(1-D)}{8L_{min}(\Delta V_0/V_0)f^2} \\ &= \mathbf{17.605}\ \mu H \end{aligned} \tag{2.5}$$

From the above calculations, the exact values [7] are calculated. But, for simulation purposes taking the capacitor and inductor values as per market availability according to above mentioned calculated values.

Table 2.3: **Values of the parameters of VSM driver for simulation purpose**

L	C
$30\mu H(10 - 15\ A)$	$22\mu F(100 - 120V_{AC})$

2.3 Design parameters of CSM SIMO Driver

For the working purpose the typical CSM circuit before and after replacing the LED loads by LED linear modelling are shown in Fig. 2.7. and Fig. 2.8 respectively.

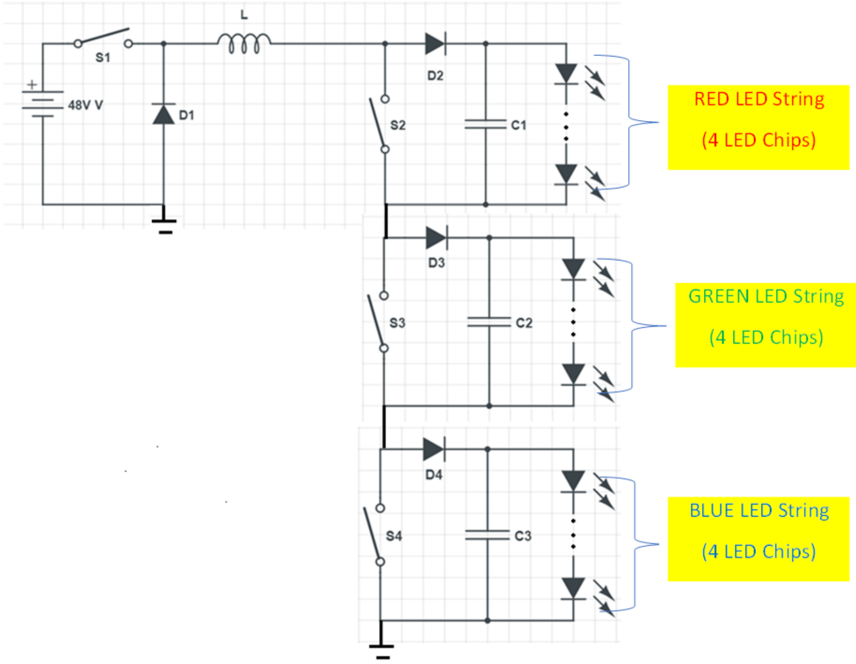


Figure 2.7: Typical CSM model with LED loads

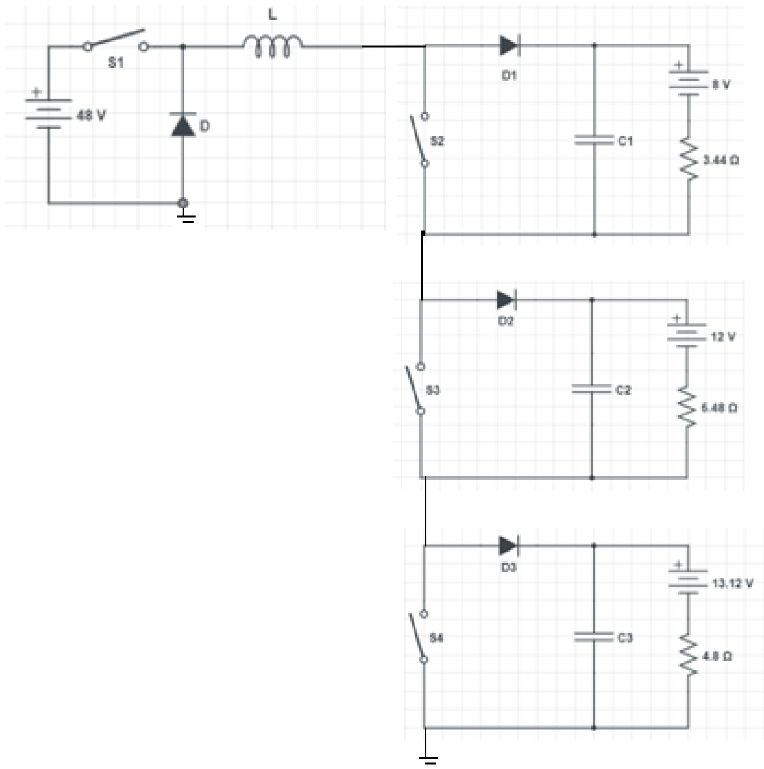


Figure 2.8: Typical CSM model after replacing LEDs by linear modelling

For the purpose of the simulation of that circuit, some parameters are considered as mentioned below -

- Input Voltage = 48 V (DC)
- Input switching frequency (f_s) = 50 kHz
- Output Current = 350 mA
- Ripple factor (K) = $\frac{\Delta V_0}{V_0}$ = 25% = 0.25

With the help of all this consideration, the design parameters are calculated for CSM SIMO DC-DC driver.

- Output Voltage (V_0) = Voltage drawn by Red LEDs string + Voltage drawn by Green LEDs string + Voltage drawn by Blue LEDs string = **37.92 V**
-
$$Dutycycle(D) = \frac{Output\,Voltage}{Input\,Voltage} = \mathbf{0.79}$$
-
$$\begin{aligned} L_{min} &= \frac{(1-D)R}{2f} \\ &= \mathbf{28.81}\ \mu H \end{aligned} \tag{2.6}$$

  where - R = $R_{RedString}$+$R_{GreenString}$+$R_{BlueString}$

-
$$C_{(R,G,B)} = \frac{P_{(R,G,B)}T_{ac}}{2\pi K (V_0)^2} \tag{2.7}$$

  where - $P_{(R,G,B)}$ = Power consumed by particular LED string = (No. of LEDs present in the string) $\times (V_{FD})_{R,G,B}$ $\times I_{LED}$

  By applying the above-mentioned equation (2.7) [15] the values of $C_1, C_2, andC_3$ are calculated.

$C_1(\mu F)$	$C_2(\mu F)$	$C_3(\mu F)$
421.42	276.12	267.06

From the above calculations, the exact values of the used inductor and capacitors are found.
But, for simulation purposes taking these parameters as per market availability according to the calculated values.

Table 2.4: **Values of the parameters of CSM driver for simulation purpose**

L	C_1	C_2	C_3
$51\mu H$ $(10-15\,A)$	$430\mu F$ $(220-250\,V_{AC})$	$300\mu F$ (220-250 V_{AC})	$270\mu F$ $(220-250\,V_{AC})$

Chapter 3

Simulation and Evalution

This Chapter deals with the setting of the target colours & simulated both the circuits for those chosen target colours in MATLAB - SIMULINK environment.

Also, this chapter consists of the output results after simulating both the circuits & compare both the circuits on the basis of these output parameters.

This chapter also deals with the cost calculations for both circuits.

3.1 Setting the Target Colour

In this thesis, an RGB colour chart made by "DOWNTOWN UPLIGHTING" [8] is used to find out the percentage of the primary colours (e.g. Red, Green, Blue) present in a target colour.

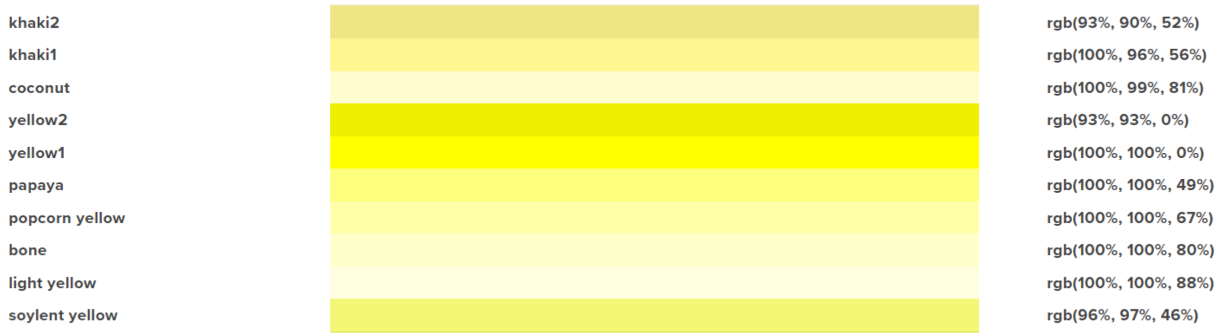


Figure 3.1: Small portion of the RGB colour chart

A very small portion of the above-mentioned "RGB colour chart" is shown in Fig. 3.1.

Let - **"YELLOW"** is selected as a target colour. Then it is clear from the above-mentioned chart that the percentages of the primary colours are **100% RED, 100% GREEN** and **0% BLUE**. That's means if these three primary colours mixed in this ratio then the achieved colour should be "YELLOW".

This ratio of the primary colours is used to determine the ratio of the duty cycle used in the simulation circuits, which are explained in the next sections.

3.2 Simulink Models

In this section, the model circuits for VSM SIMO DC-DC Driver and CSM SIMO DC-DC Drivers are described. "MATLAB-SIMULINK" software is used to simulate both circuits.

3.2.1 VSM SIMO DC-DC Driver

A typical VSM SIMO DC-DC Driver model for simulation is shown in Fig. 3.2.

In this circuit, a 48 V DC voltage source is used on the input side. A current measuring device is connected in the series to determine the input side current. A MOSFET is used as an input side switch and the switching frequency is set at 50 kHz. An Inductor and Capacitor are connected as the VSM circuit design parameters and their values are taken as per the above discussion.
Three load branches are connected in parallel. In each branch, there are present current measurement devices to particularly measure the current flowing through each branch. Also, MOSFETs are used in each branch as a switching device and PWM generators are connected to the MOSFETs and constant values are connected to the PWM generators for giving the proper Duty Cycle in each branch. By changing these constant values set the duty cycles for each branch for a target colour.

Duty cycles are determined for this circuit according to the primary colours percentages in a Target Colour.

- **Duty cycle for a branch or the constant value for a branch = Percentage of the primary colour which indicates by that branch.**

If "YELLOW" is taken as a taget colour, then the primary colour percentages present in it acoording to the above mentioned RGB colour chart are 100% RED, 100% GREEN and 0%BLUE. So, in this circuit the duty ratios are set for three branches as **'1','1', and '0'**.

Also in this circuit, a voltage measurement device is connected to the output side to measure the output voltage. This output voltage is used to give a feedback loop to the input side. A reference output voltage is set, and an error signal is generated due to the variation of the reference voltage and the actual output voltage. This error signal feedback to the input side with the help of a PID controller. The reason behind using the reference output voltage in this circuit is nothing but, in this circuit, the output voltage in each branch is the same as they are connected in parallel.

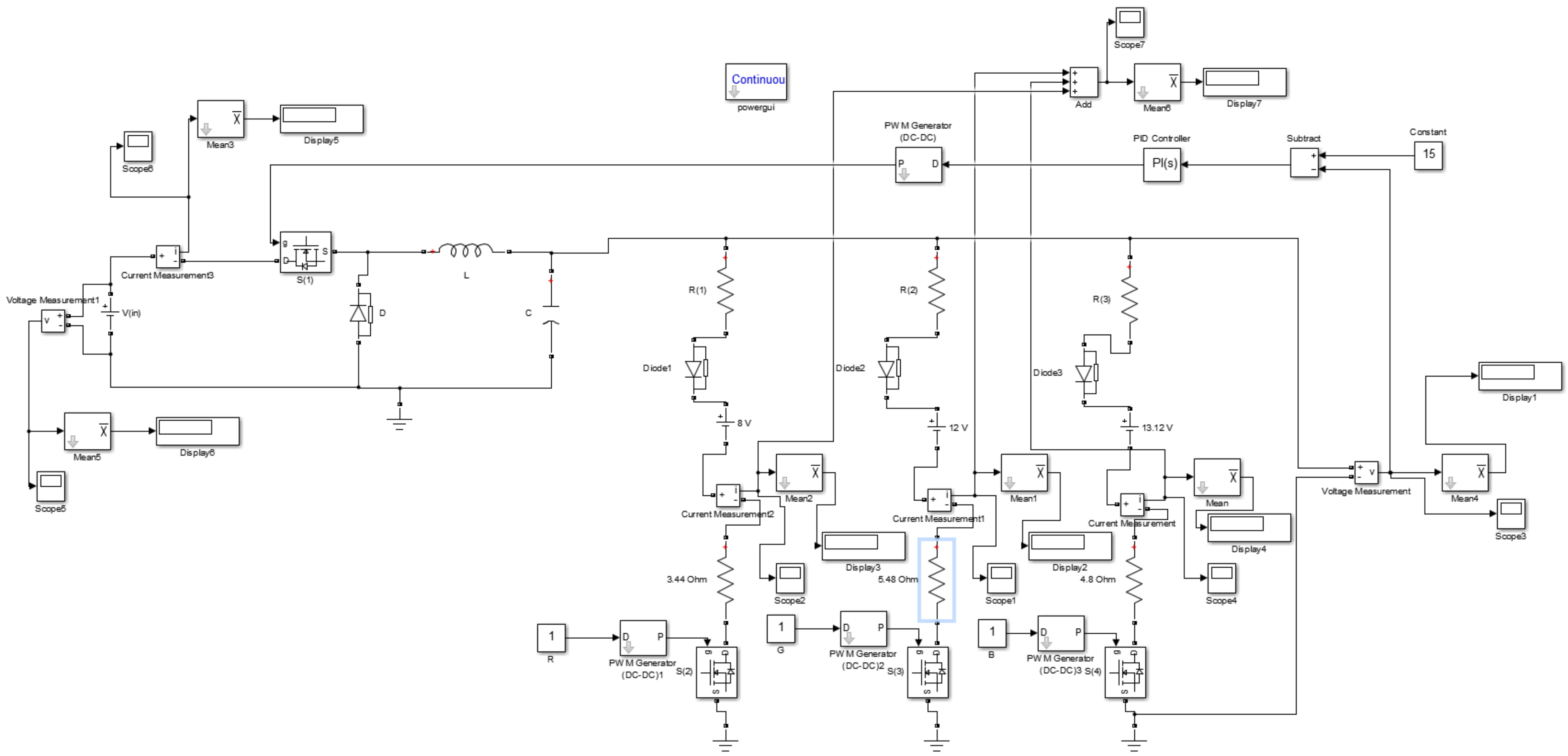


Figure 3.2: Typical VSM model for simulation

3.2.2 CSM SIMO DC-DC Driver

A typical CSM SIMO DC-DC Driver model for simulation is shown in Fig. 3.3.

In this circuit, a 48 V DC voltage source is used on the input side. A current measuring device is connected in the series to determine the input side current. A MOSFET is used as an input side switch and the switching frequency is set at 50 kHz. An Inductor is connected, and three Capacitors are connected across three load branches, as the CSM circuit design parameters and their values, are taken as per the above discussion.
Three load branches are connected in series. In each branch, there are present voltage measurement devices to particularly measure the voltage across each branch. Also, MOSFETs are used in each branch as a switching device and PWM generators are connected to the MOSFETs and constant values are connected to the PWM generators for giving the proper Duty Cycle in each branch. By changing these constant values set the duty cycles for each branch for a target colour.

Duty cycles are determined for this circuit according to the primary colours percentages in a Target Colour.

- **The duty cycle for a branch or the constant value for a branch = (1 - Percentage of the particular primary colour which indicates by that branch.)**

If "YELLOW" is taken as a target colour the primary colour percentages present in it according to the above-mentioned RGB colour chart are 100% RED, 100% GREEN and 0% BLUE. So, in this circuit the duty ratios are set for three branches as **'0','0','1'.**

Also in this circuit, a current measurement device is connected to the output side to measure the output current. This output current is used to give a feedback loop to the input side. A reference output current is set and an error signal is generated due to the variation of the reference current and the actual output current. This error signal feedback to the input side with the help of a PID controller. The reason behind using the reference output current in this circuit is nothing but, in this circuit, the output current in each branch is the same as they are connected in series.

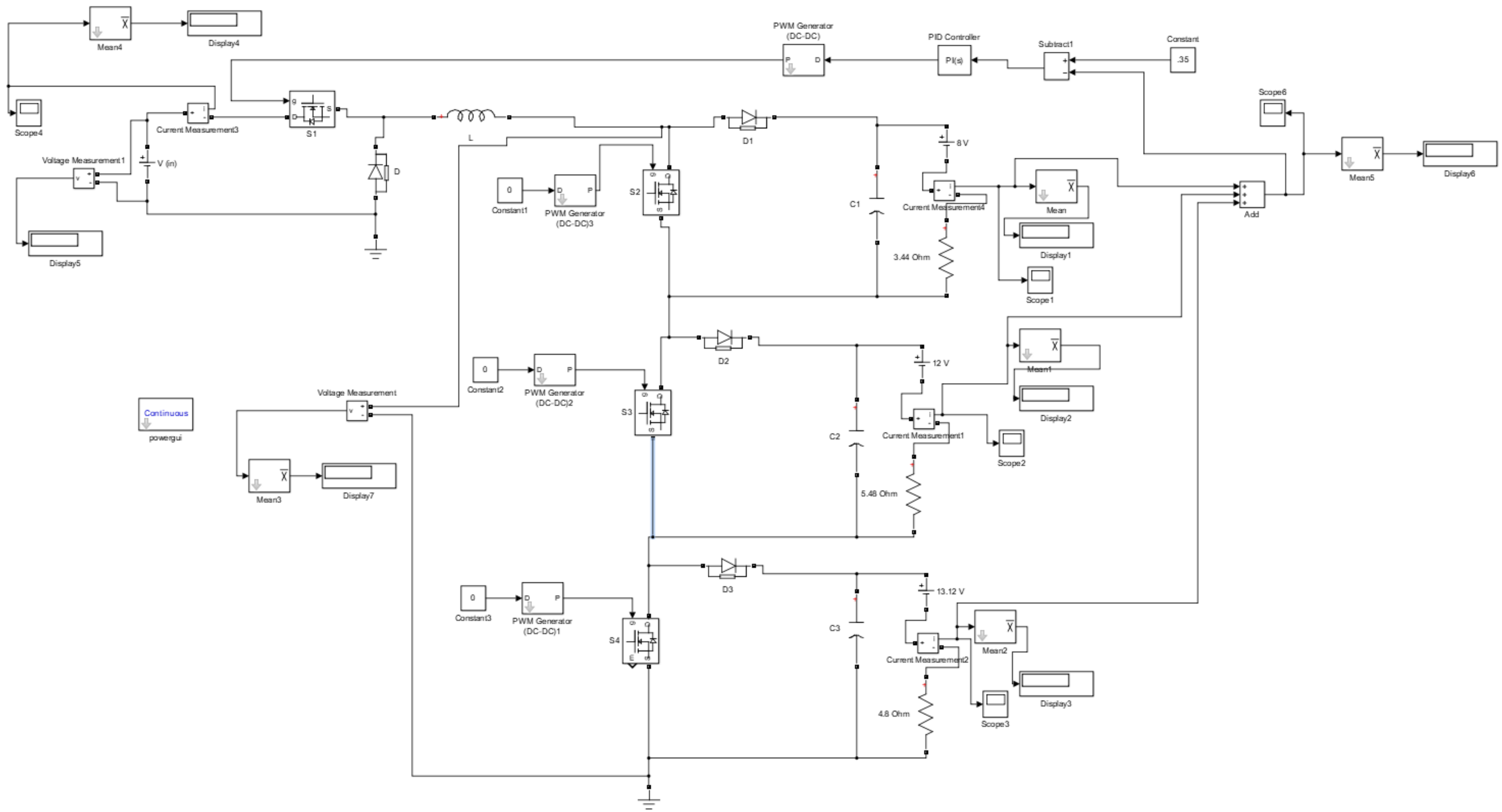


Figure 3.3: Typical CSM model for simulation

3.3 Simulation results and analysis

In this thesis, for seven different colours both the circuits are simulated. Also, note down their result values. The list of the seven colours is -

- **Primary Colours**
  - Red
  - Green
  - Blue
- **Secondary Colours**
  - Cyan
  - Yellow
  - Magenta
- **Tertiary Colours**
  - White

The electrical parameters value chart table for VSM SIMO DC-DC Driver for above mentioned seven colours is given below.
In this table, the duty ratios given to all three branches for a particular colour are noted and note down all three branches' current. Input and output voltage and current are also noted in this table. And with the help of these values' efficiency, the flicker index and the deviation in colour control are calculated also.

Where -

- Efficiency = $\frac{Output\ Power}{Input\ Power}$
- Deviation in Colour Control = $\frac{Desired\ Branch\ Current - Simulated\ Branch\ Current}{Simulated\ Branch\ Current} \times 100\%$
- Flicker Index = $\frac{I_{max} - I_{min}}{I_{max} + I_{min}} \times 100$

Table 3.1: **Electrical parameters for VSM SIMO DC-DC Driver**

Tar -get Col -our	Set Duty Ra- tio (%)	Desi -red Bra -nch Curr- ent (mA)	Simu - lated Bran -ch Curr -ent (mA)	Devi - ation in Col -our Con -trol (%)	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	Effi -cien -cy (%)	Fli - cker Ind -ex (%)
RED	$D_R = 100$ $D_G = 0$ $D_B = 0$	$I_R = 350$ $I_G = 0$ $I_B = 0$	$I_R = 347.8$ $I_G = 0.065$ $I_B = 0.054$	Δ R = 0.63	48	0.11 44	5.49 12	14.99	0.34 79	5.21 53	94.98	3.88
GRE EN	$D_R = 0$ $D_G = 100$ $D_B = 0$	$I_R = 0$ $I_G = 350$ $I_B = 0$	$I_R = 0.105$ $I_G = 345.5$ $I_B = 0.054$	Δ G = 1.3	48	0.11 36	5.45 28	15	0.34 57	5.18 49	95.09	8.14
BLU E	$D_R = 0$ $D_G = 0$ $D_B = 100$	$I_R = 0$ $I_G = 0$ $I_B = 350$	$I_R = 0.105$ $I_G = 0.065$ $I_B = 343.1$	Δ B = 2.01	48	0.11 27	5.40 96	15	0.34 33	5.14 95	95.19	12.83
CYA N	$D_R = 0$ $D_G = 100$ $D_B = 100$	$I_R = 0$ $I_G = 350$ $I_B = 350$	$I_R = 0.105$ $I_G = 345.7$ $I_B = 343.2$	Δ G = 1.24 Δ B = 1.98	48	0.22 42	10.7 616	15	0.689	10.3 35	96.03	21.11

Electrical parameters for VSM SIMO DC-DC Driver

YELLOW	D_R = 100 D_G = 100 D_B = 0	I_R = 350 I_G = 350 I_B = 0	I_R = 347.9 I_G = 345.6 I_B = 0.045	Δ R = 0.6 Δ G = 1.27	48	0.2255	10.824	15	0.6935	10.4025	96.11	13.42
MAGENTA	D_R = 100 D_G = 0 D_B = 100	I_R = 350 I_G = 0 I_B = 350	I_R = 347.9 I_G = 0.066 I_B = 343.2	Δ R = 0.6 Δ B = 1.98	48	0.2248	10.7904	15	0.6912	10.368	96.09	17.4
WHITE	D_R = 100 D_G = 100 D_B = 100	I_R = 350 I_G = 350 I_B = 350	I_R = 348 I_G = 345.8 I_B = 343.3	Δ R = 0.57 Δ G = 1.21 Δ B = 1.95	48	0.3361	17.328	15	1.037	15.555	89.77	26.62

After the VSM Driver's table is completed, this same table follows for the CSM SIMO DC-DC Driver. And the calculated parameters formulas are the same for the CSM circuit also.

So, the electrical parameters value chart table for CSM SIMO DC-DC Driver for above mentioned seven colours are given below.

Table 3.2: **Electrical parameters for CSM SIMO DC-DC Driver**

Target Colour	Set Duty Ratio (%)	Desired Branch Current (mA)	Simulated Branch Current (mA)	Deviation in Colour Control (%)	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	Efficiency (%)	Flicker Index (%)
RED	$D_R = 0$ $D_G = 100$ $D_B = 100$	$I_R = 350$ $I_G = 0$ $I_B = 0$	$I_R = 349.9$ $I_G = 0$ $I_B = 0$	Δ R = 0.02	48	0.0812	3.9	9.274	0.3499	3.2459	83.23	0.37
GREEN	$D_R = 100$ $D_G = 0$ $D_B = 100$	$I_R = 0$ $I_G = 350$ $I_B = 0$	$I_R = 0$ $I_G = 349.8$ $I_B = 0$	Δ G = 0.06	48	0.1163	5.5824	13.99	0.3498	4.8937	87.67	0.37
BLUE	$D_R = 100$ $D_G = 100$ $D_B = 0$	$I_R = 0$ $I_G = 0$ $I_B = 350$	$I_R = 0$ $I_G = 0$ $I_B = 349.8$	Δ B = 0.06	48	0.1228	5.8944	14.87	0.3498	5.202	88.25	0.49
CYAN	$D_R = 100$ $D_G = 0$ $D_B = 0$	$I_R = 0$ $I_G = 350$ $I_B = 350$	$I_R = 0$ $I_G = 349.2$ $I_B = 349.2$	Δ G = 0.23 Δ B = 0.23	48	0.2218	10.6464	28.66	0.3492	10.008	94	0.32

Electrical parameters for CSM SIMO DC-DC Driver

YELLOW	$D_R = 0$ $D_G = 0$ $D_B = 100$	$I_R = 350$ $I_G = 350$ $I_B = 0$	$I_R = 349.8$ $I_G = 349.8$ $I_B = 0$	Δ R = 0.06 Δ G = 0.06	48	0.1823	8.7564	21.58	0.3498	7.549	86.27	0.36
MAGENTA	$D_R = 0$ $D_G = 100$ $D_B = 0$	$I_R = 350$ $I_G = 0$ $I_B = 350$	$I_R = 349.7$ $I_G = 0$ $I_B = 349.7$	Δ R = 0.08 Δ B = 0.08	48	0.1882	9.0332	22.58	0.3497	7.896	87.41	0.36
WHITE	$D_R = 0$ $D_G = 0$ $D_B = 0$	$I_R = 350$ $I_G = 350$ $I_B = 350$	$I_R = 349.6$ $I_G = 349.6$ $I_B = 349.6$	Δ R = 0.11 Δ G = 0.11 Δ B = 0.11	48	0.2928	14.057	34.63	0.3496	12.107	86.13	0.38

After getting all these values these two circuits are compared based on their performances. In this thesis, these two circuits are compared with each other with respect to their "Efficiency", "Colour Deviation Control" and "Flicker Index", which are calculated in table 3.1 and 3.2.

- **Efficiency :** The term "Efficiency" refers to the peak level of performance that uses the least amount of inputs to achieve the highest amount of output. So, the efficiency of an LED driver is the ratio of energy emitted by the driver to the power it consumes from the electric line.
  So, if the highly efficient LED driver is used then -
  - Energy and cost will save.
  - Driver lifespan will be increased.

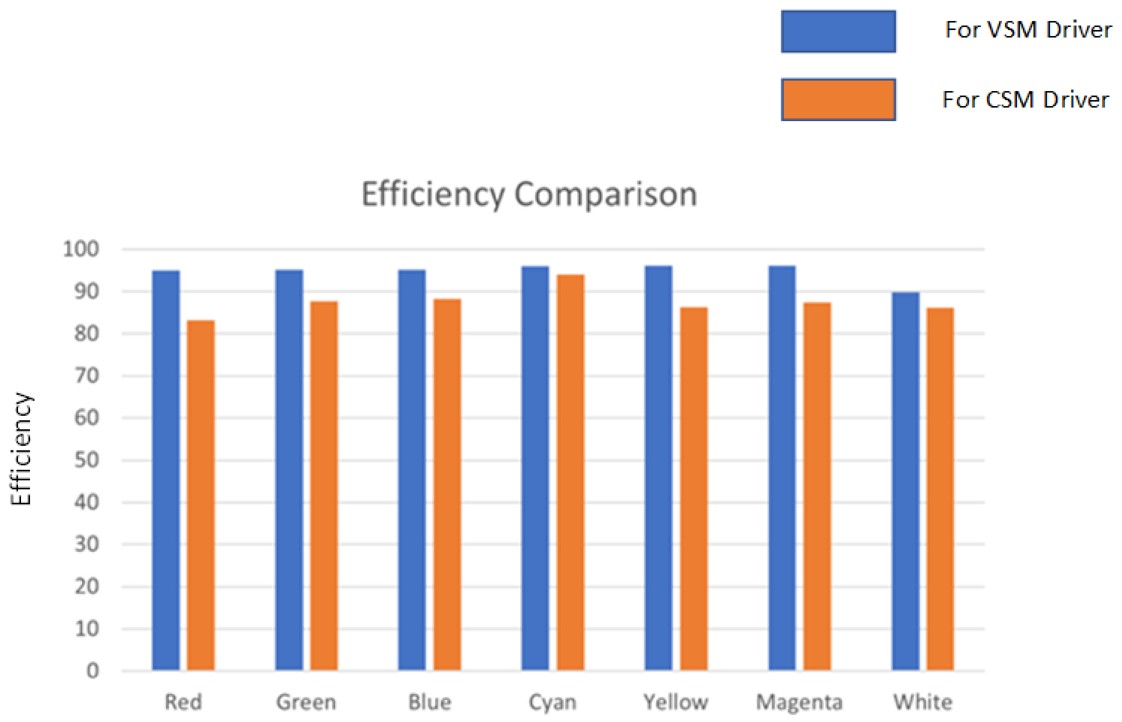


Figure 3.4: Comparison of Efficiency

From the above graph, it is clear that for each target colour the efficiency of VSM SIMO DC-DC Driver is better than the CSM SIMO DC-DC driver.

If a SIMO DC-DC LED driver delivers efficiency greater than 90% then the driver is quite good [9]. According to this standardization the efficiency of the CSM driver is slightly poor, while the efficiency of the VSM driver is good enough.

- **Colour Deviation Control :**

  Colour deviation in an LED driver means how much the achieved colour deviates from the target colour. Multi-channel LED drivers can operate at different brightness for each individual LED channel. So, the achieved colour deviates from the target colour.
  If an LED driver has a minimum percentage in colour deviation, then it means this driver has good control of colour deviation.

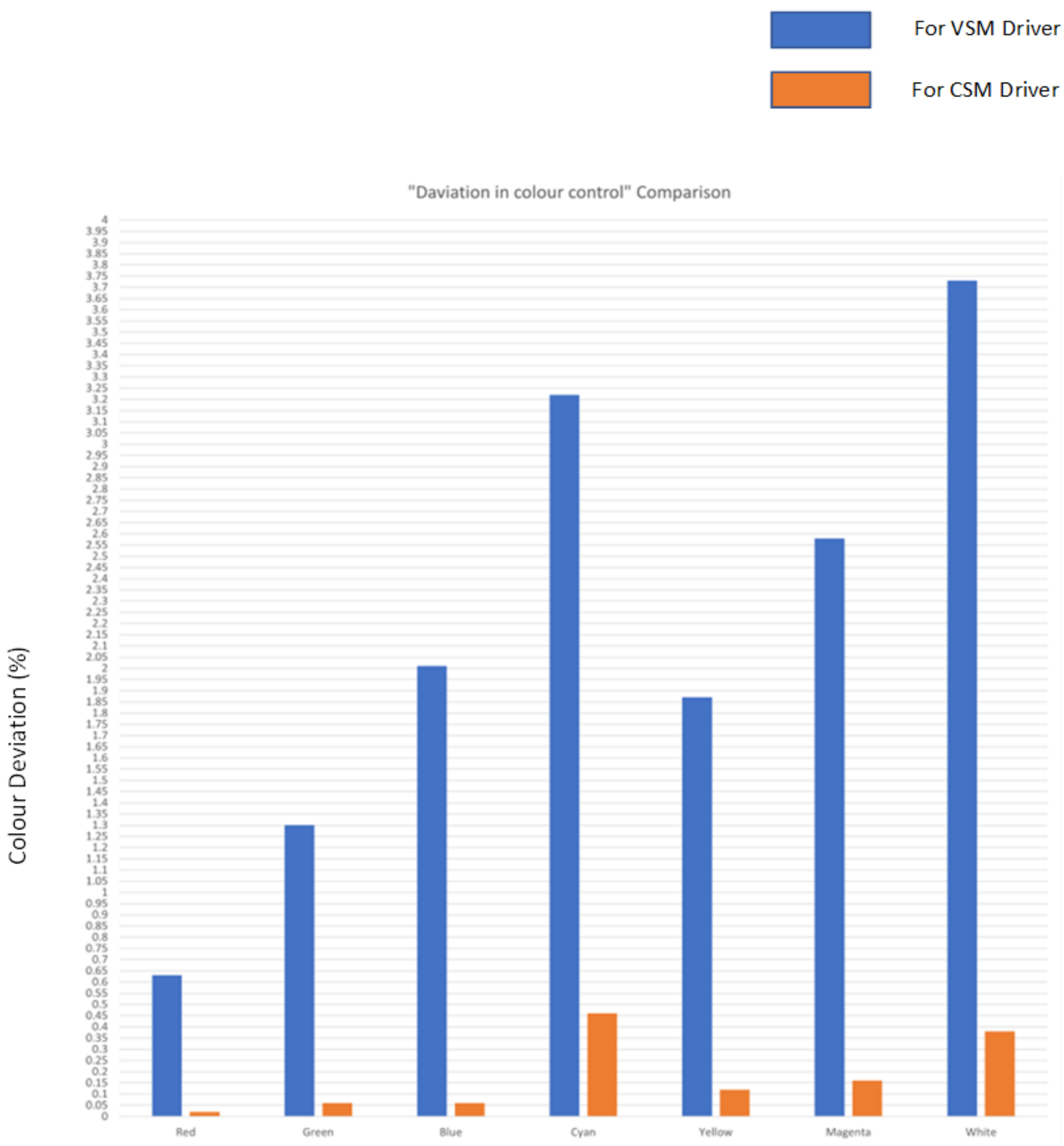


Figure 3.5: Comparison of Colour Deviation

From the above graph, there is a huge difference in colour deviations between both circuits. For each target colour, the deviation in the colour of the VSM SIMO DC-DC Driver is far greater than the CSM SIMO DC-DC driver. So, it's clear that the colour deviation control is good enough in CSM SIMO DC-DC Driver. That means the achieved colours are close enough to the target colour in this driver.

- **Flicker Index :**
  The flicker index is a measure of the cyclic variation in the output of a light source, considering the waveform of the light output. It is the ratio of the area under the light output curve that is above the average light output level to the total area under the light output curve for a single cycle.
  The flickering of light is proportional to this flicker index.
  There are some adverse effects of flicker which are annoyance, reduced task performance, visual fatigue, headache, and epileptic attack by photosensitive persons.
  So, for a good LED driver the flicker index should be minimum.

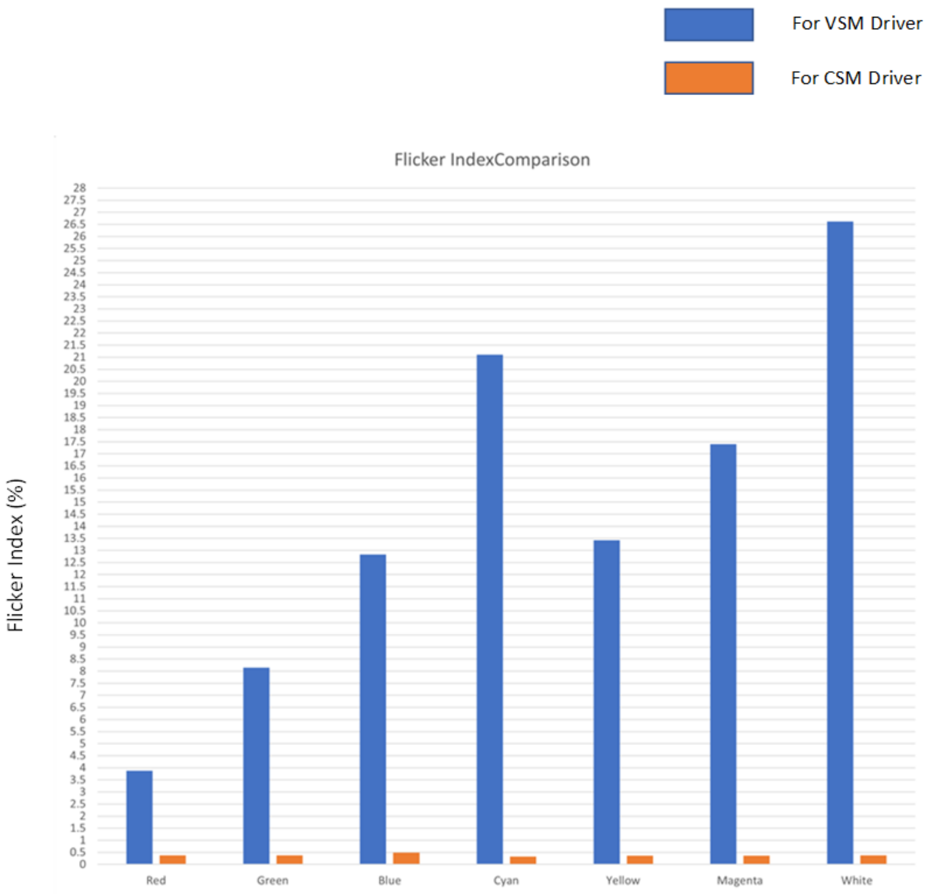


Figure 3.6: Comparison of Flicker Index

According to the above graph, there is a huge difference in the flicker index between both circuits. For each target colour the flicker index of the VSM SIMO DC-DC Driver is far greater than the CSM SIMO DC-DC driver.

3.3.1 Cost Analysis

After both circuits are studied and simulated, it is quite clear that the components of both circuits are quite similar. So, the total cost of both circuits is close enough.

Actually, in VSM Driver three extra resistors are connected. Also, in VSM Driver a 22 μ F capacitor is used and in CSM Driver there are three capacitors are used, they are 430, 300, and 270 μ F. At last in VSM Driver the connected inductor value is 30 μ H and in CSM Driver the connected inductor value is 51 μ H.

According to the online websites [10] [11], the values of these components are given below -

Table 3.3: **Cost of different componenets**

Component	Cost (in Rupees)
Resitor	2
Inductor (30 μ H and 51 μ H)	8.80
Capacitor (22 μ F)	10
Capacitor (430, 300, 270 μ F)	18

Table 3.4: **Total Cost comparison for both drivers**

Driver	Components	No. of units	Cost/unit	Total Cost
VSM	R	3	2	24.8
	L(30μ H)	1	8.80	
	C (22 μ F)	1	10	
CSM	R	0	2	62.8
	L(51μ H)	1	8.80	
	C (430,300,270 μ F)	3	18	

According to table 3.4, the VSM driver is **(62.8 - 24.8) = 38 rupees** cheaper than the CSM driver. So, the difference between the total cost for both circuits is not high enough.

Chapter 4

Conclusion and Future Scope

In this chapter, the thesis is concluded with a clear point of view. Also, this chapter consists of future scopes.

After simulating both the circuits in the MATLAB - SIMULINK environment, it is clear that the efficiency of the CSM SIMO DC-DC Driver is quite poor than the VSM SIMO DC-DC Driver. But the colour deviation control and the flicker index is good enough in CSM Driver. That means using the CSM Driver better colour appearance is achieved. Also, side by side the flickering in the light source is too low if CSM Driver is used. Because the relation between the percentage of flickering and the flicker index is proportional to each other. So, if the flicker index is low then the percentage of flickering is also low. Flickering lights can turn into a serious problem. It may cause a major electrical issue.
Also, the cost of the driver is an issue, but according to this thesis work the difference between the cost is not high enough.

After all this discussion it is concluded that the CSM driver is better to use if the efficiency and cost are slightly compromised.

Although there are some limitations to this thesis work. Both circuits are compared in a software environment. It will be better and more significant work if both circuits are compared with each other in a practical environment. Maybe in the practical environment, the results slightly differ from this work.

So, some future scopes are present in this thesis work. If the efficiency of the CSM Driver is improved, then this driver is completely better than the VSM Driver. Also, the comparison between these two circuits is done by only simulating the circuits in MATLAB - SIMULINK environment. So, in the future, if this work is done in hardware, then the work is enriched.

Chapter 5

Appendix

In this thesis, the duty cycles, which are used for different target colours, are taken from a look-up table. But there a mathematical process is available to calculate the duty ratios. This chapter deals with the mathematical process to calculate the duty ratios. This calculation process is also incorporated into this thesis in the future.

According to the **Application Note No. AN117** of the company **"OSRAM"** [12] the duty cycles of the RED, GREEN, and BLUE LED branches are calculated for a particular target colour, by using the following steps.

- Let -

  Tri-Stimulus Matrix of RGB = [A] = $\begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix}$

  where -
  $Y_i = I_i$ = Luminous Intensity [where - i = R,G,B]
  $X_i = Y_i \times \frac{x_i}{y_i}$ [where - (x_i, y_i) = chromaticity co-ordinates of the perticular primary colour]
  $Z_i = Y_i \times \frac{1-x_i-y_i}{y_i}$
  (The values of the $x_i, y_i and I_i$ is given or known).

- If the colour target chramaticity = (x_t,y_t), then it is also possible to build the

  Tri-Stimulus Matrix = T = $\begin{bmatrix} T_X \\ T_Y \\ T_Z \end{bmatrix}$

  Calculate the values of the T_X, T_Y, T_Z from the above mentioned steps.

- X is the matrix which stands for the duty cycles of the PWM, which are required to achieve the target colour and it is denoted as -

  X = $\begin{bmatrix} D_R \\ D_G \\ D_B \end{bmatrix}$

- **So, the formula is - A $\times$ X = T**

  or, **X = T** $\times \frac{1}{A}$

- So, $D_R = \dfrac{det \begin{bmatrix} T_X & X_G & X_B \\ T_Y & Y_G & Y_B \\ T_Z & Z_G & Z_B \end{bmatrix}}{det \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix}}$

  $D_G = \dfrac{det \begin{bmatrix} X_R & T_X & X_B \\ Y_R & T_Y & Y_B \\ Z_R & T_Z & Z_B \end{bmatrix}}{det \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix}}$

  $D_B = \dfrac{det \begin{bmatrix} X_R & X_G & T_X \\ Y_R & Y_G & T_Y \\ Z_R & Z_G & T_Z \end{bmatrix}}{det \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix}}$

So, according to them, this is the whole process to calculate the duty ratios for a target colour.

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