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Design Optimization of Synchronous Buck Converter (SBC)

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***Abstract:** Nowadays Switched-mode power converters are playing a significant role in the industries by providing higher efficiency for various applications. There are various applications that implement power supply and battery charge circuits for devices like smartphones, TVs, and various electronic devices When it comes to DC-DC Converters the most popular among the industries are buck converters and the efficient version of the buck converter is the Synchronous buck converter. The SBC steps down the voltage from higher to lower levels. Efficiency is a crucial parameter as the industry's focus is on delivering greater performance devices. The power converter's design must be optimized to maximize performance to achieve customer expectations. As a result, a thorough understanding of the synchronous buck converter and how to properly select the circuit components is critical. The proposed work aims at optimizing the Synchronous Buck Converter components such as Inductors, Capacitors, and Resistors. The idea of this optimization study is to improve the performance of the converter and reduce power losses and cost-cutting. In this paper, the control mode considered is peak current mode control.*
***Keywords:** Synchronous buck converter (SBC), Switch-mode power supply, Optimization of design.*

I. INTRODUCTION

In recent times, Switch Mode Power Converters (SMPS) are playing a prominent role in various applications due to their high-efficiency solutions. These are one of those silent (but loud electrically) gadgets that keep our electronics functioning. Despite their silence, they are the backbone of our board. DC-DC converters require careful component selection to deliver power efficiently to a load in power-hungry applications. SBCs are a common DC-DC converter topology that provides power conversion at high efficiency while stepping down the input voltage to a lower level. Inductors for these converters are a common component selection question. SBCs are designed to limit power loss through heat and minimize ripple in the current while using an inductor and other components.

II. SBC TOPOLOGY

A. *Working of SBC*

With a synchronous buck converter, the output voltage can be regulated to be lower than the input voltage, and the current can be delivered at a high rate while the power loss is minimized. In Figure 1, we can see two power MOSFETs, an output inductor, and an output capacitor making up the synchronous buck converter. The control technique of the two power MOSFETs gives rise to the name of this specific buck topology. ON/OFF states of the MOSFETs are synchronized by restraining them from turning ON at the same time and along with yielding the regulated output voltage. In the figure shown M1 and M2 are the high and low-side MOSFETs respectively. When M1 is ON M2 is off and the load is supplied through the high side MOSFET. In this mode inductor current increases and in turn, charges the filter. Now in the second mode M2 is turned ON and M1 turns off and now the load is supplied through low side MOSFET. In this mode inductor, the current decreases and discharges the filter. MOSFETs here are controlled such that they don't turn on at the same time which leads to direct short to ground.

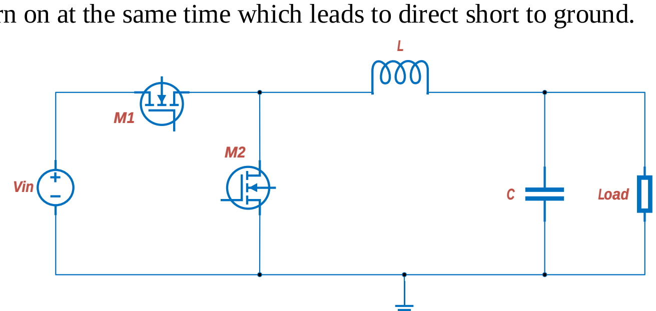

Figure 1 Synchronous Buck Converter

The duty cycle of the Synchronous Buck Converter is determined by the high side MOSFET ON–time.

$$Duty\ (D) = \frac{t_{ON(High\ Side)}}{t_{ON(High\ Side)} + t_{OFF(High\ Side)}} = \frac{V_{out}}{V_{in}} \quad \text{(eq.1)}$$

For example, if the duty cycle is 0.3 then this depicts that the high side MOSFET will be ON for 30% of time and if considering the input voltage (Vin) as 30V then the output voltage produced will be 30% of Vin which is approximately 9V.

III. OPTIMIZATION OF INDUCTOR

It all comes down to the converter's operating principles and how the inductor works in tandem with the other components to deliver a dependable and trouble-free operation. Some of the factors which greatly affect the inductor selection for a converter are 1. The rated inductance value of the inductor and how greatly it impacts the ripple current of the converter. 2. Depending on the converter’s output current requirement, DC current rating is directly in link with the rise in temperature of the inductor and the DC resistance. 3. Saturation current is typically given on all datasheets for power inductors. It is defined as the applied DC current at which the inductance value falls by a given amount below its measured value when no DC current is applied. 4. In association with the switching frequency and substance used in manufacturing the inductor the core loss also plays a significance. 5. The physical size of an inductor is proportional to the amount of energy it can store. Varying core materials may store different quantities of magnetic energy per volume, although inductor size is mostly determined by energy storage within the same core material. The mentioned considerations affect the reliability of inductors and some converters. When the inductor ripple current does not recover to its starting value at the start of the following switching cycle, subharmonic oscillation develops. In peak current mode control, these oscillations occur when the duty cycle is more than 50%.

$$L_{out} \geq \frac{V_{out}}{f_{sw} * (ripple * I_{out})} \quad \text{(eq.2)}$$

Lower the inductor value higher the peak-to-peak current along with small size and low cost whereas for a higher inductance value lower the peak-to-peak current along with a reduction in RMS and ripple current but raising the requirement of large output capacitors.

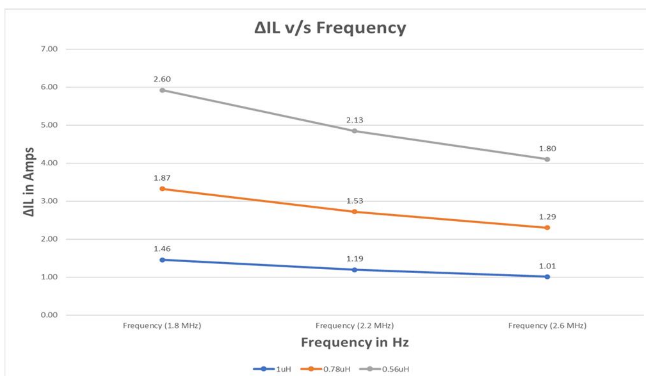

Figure 2 Ripple Current v/s Frequency

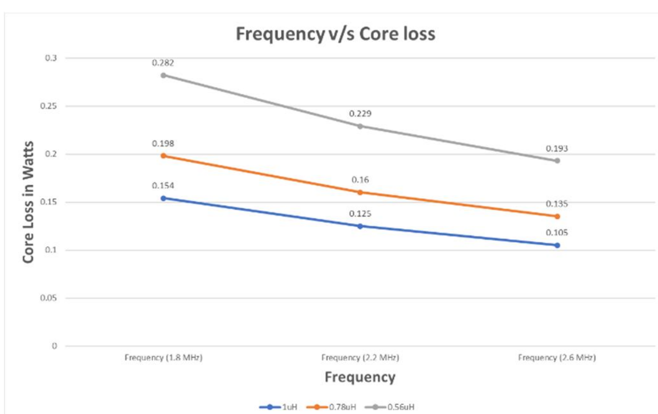

Figure 3 Frequency v/s Core Loss

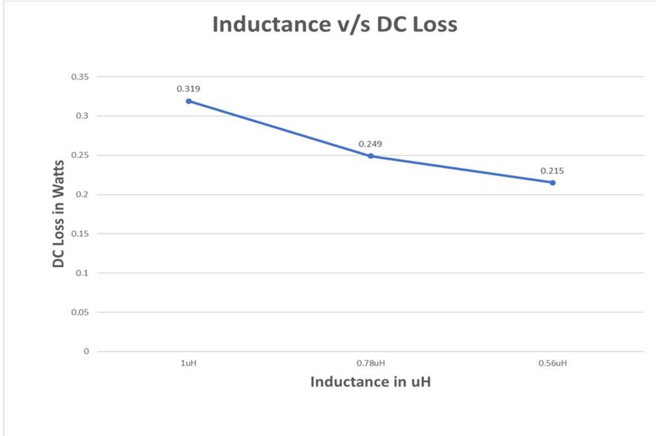

Figure 4 Inductance v/s DC Loss

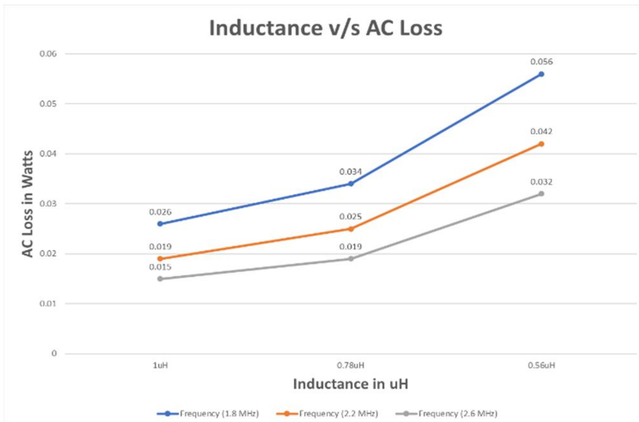

Figure 5 Inductance v/s AC Loss

Design parameters considered for study: Vin = 12V; Vout = 3.3V; Iout = 4A; T = 85°C; The calculated data and comparison of various parameters for three different values of Inductors is shown below and the non-ideal condition equations considered and listed.

→ K_f (Frequency Constant) is 1.173 for -11 material
→ K_b (Flux Density Constant) is 2.213 for -11 material
→ Vo = Output Voltage
→ Vin = Input Voltage
→ L = Output Inductance
→ fsw = Switching Frequency
→ Io = Output Current of converter
→ fe = Effective Frequency
→ Pcore = Core Loss; Pac = AC Loss; Pdc = DC Loss;

$$duty = \frac{V_O}{V_{IN}} \qquad \text{(eq.3)}$$

$$L = \frac{V_O}{f_{SW} * 0.3 * I_O} \qquad \text{(eq.4)}$$

$$f_e = \frac{f_{SW}}{2\pi * (duty - duty^2)} \qquad \text{(eq.5)}$$

$$ET = \frac{V_O}{f_{SW}} (1 - duty) * 10^6 \qquad \text{(eq.6)}$$

$$ET_{100} = \frac{ET}{B_{pk}} * 100 \qquad \text{(eq.7)}$$

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$$I_{ripple} = \frac{V_O}{L * 10^6 * f_{SW}} (1 - duty) * 10^6 \quad \text{(eq.8)}$$

$$R_{oper} = DCR * \frac{234.5 + T + 40}{259.5} \quad \text{(eq.9)}$$

$$I_{rms} = \sqrt{{I_O}^2 * \left(\frac{1}{12}\left(\frac{(V_{IN} - V_O) * V_O}{V_{IN} * L * f_{SW}}\right)^2\right)} \quad \text{(eq.10)}$$

$$P_{dc} = {I_{rms}}^2 * DCR \quad \text{(eq.11)}$$

$$P_{ac} = 0.00340 * {I_{ripple}}^2 * \sqrt{f_{SW}} * R_{oper} \quad \text{(eq.12)}$$

$$P_{core} = K_0 * f_e^{0.173} * B_{pk}^{2.213} * f_{sw} * 10^{-14} \quad \text{(eq.13)}$$

$$P_{Total} = P_{dc} + P_{ac} + P_{core} \quad \text{(eq.14)}$$

Parameter	Frequency (1.8 MHz)	Frequency (2.2 MHz)	Frequency (2.6 MHz)	Frequency (1.8 MHz)	Frequency (2.2 MHz)	Frequency (2.6 MHz)	Frequency (1.8 MHz)	Frequency (2.2 MHz)	Frequency (2.6 MHz)
	1.80	2.2	2.6	1.80	2.2	2.6	1.8	2.2	2.6
Time	5.6E-07	4.5E-07	3.8E-07	5.6E-07	4.5E-07	3.8E-07	5.6E-07	4.5E-07	3.8E-07
Ripple	0.33								
Duty Cycle (Vin = 12V, Vo = 3.3V)	0.275								
Inductance (uH)	**2**	**2**	**2**	1	1	1	0.78	0.78	0.78
ΔI_L (Amps)	0.76	0.62	0.52	1.51	1.24	1.05	1.94	1.59	1.34
I_(L_Peak)	4.38	4.31	4.26	4.76	4.62	4.52	4.97	4.79	4.67
I_(RMS(Max))	4.0039	4.0026	4.0019	4.0156	4.0104	4.0075	4.0256	4.0171	4.0123
DCR	5.8m ohm(Max)	5.8m ohm(Max)	5.8m ohm(Max)	2.50 m ohm(Max)	2.50 m ohm(Max)	2.50 m ohm(Max)	2.10 m ohm (Max)	2.10 m ohm (Max)	2.10 m ohm (Max)
P_Core (W)	0.06	0.049	0.041	0.157	0.127	0.107	0.201	0.163	0.137
P_dc (W)	0.115	0.115	0.115	0.051	0.051	0.051	0.04	0.04	0.04
P_ac (W)	0.01	0.008	0.006	0.026	0.019	0.015	0.034	0.025	0.019
P_Total (W)	0.185	0.172	0.162	0.234	0.197	0.173	0.275	0.228	0.196
Output Voltage Ripple (mV)	1.73E-03	1.35E-03	1.10E-03	3.47E-03	2.70E-03	2.20E-03	4.45E-03	3.46E-03	2.82E-03
Saturation Current for 20% of margin	5.25	5.17	5.11	5.71	5.54	5.43	5.97	5.75	5.61
Saturation Current rated	14	14	14	20	20	20	22	22	22
Design Margin(Sat)	62.47%	63.06%	63.47%	71.46%	72.28%	72.85%	72.88%	73.85%	74.51%

Table 1 Inductor Optimization Comparison Study for various parameters for 4A Load Current

The above table depicts the comparison of three different inductance values for the same design. We can see a significant decrease in the ripple current with increase the inductance value also decreasing the total power loss. Comparatively the cost of 2uH inductor is lesser than 1uH which makes is more feasible to selection.

L0 (µH)	DCR Ω (Typ)	ET100	K0	K1
0.78	0.00180	1.09	22.84	0.0034
1	0.00230	1.12	18.87	0.0034
2	0.00520	1.99	25.92	0.0024

Table 2 Constants for Inductor Power Loss Calculation

IV. OPTIMIZATION OF CAPACITOR

The circuit you're dealing with, and the type of current being used are the two main factors to consider when choosing a capacitor (AC, DC, etc.). A polarised or non-polarized capacitor may be required; therefore, you should decide. The amount of charge that is held in a capacitor determines its voltage. Although they pass AC, they can impede DC signals. Additionally, ripples may be removed using capacitors. A capacitor may balance the voltage if a line carrying DC electricity has ripples by absorbing the peaks and filling in the valleys. The amount of voltage to which you may expose a capacitor determines its rating rather than its voltage. For instance, if your power source is 12 volts, you should pick a capacitor with at least twice that amount of voltage, such as 25 volts, just to be cautious.

The capacitor should be placed at a location that is appropriate for it. For instance, if the capacitor is linked to the battery, there is a chance that it might experience a circumstance where the voltage doubles or jumps during start-up (ex. Normal voltage is 12V but due to jump start it may be subjected to 24V). As a result, the capacitor you choose must be able to handle aberrant voltage. Additionally, you must ensure that a capacitor with a working voltage higher than necessary won't grow too big and produce cross-over or noise problems. Making the right capacitor selection will help you save time and money. Given that they are utilised in so many various types of electrical equipment, the sheer number of capacitors available on the market might be confusing. When choosing how to purchase capacitors for applications, it's necessary to consider their size, shape, material, and placement. We ran an optimizer (developed in house) to choose the right rated capacitor.

Sl No	Capacitors Number	Stress		Capability		Design Margin		Comments/Suggestion
		Min (V)	Max (V)	Min (V)	Max (V)	Min (%)	Max (%)	
1	C__11	__	27.50	-50.00	50.00	__	45.00	Selected Capacitor is in good design margin
2	C__12	__	27.50	-50.00	50.00	__	45.00	Selected Capacitor is in good design margin
3	C__13	__	27.50	-50.00	50.00	__	45.00	Selected Capacitor is in good design margin
4	C__14	__	3.80	-16.00	16.00	__	76.25	Can be downsized to 10V
5	C__15	__	3.80	-16.00	16.00	__	76.25	Can be downsized to 10V
6	C__16	__	3.80	-6.30	6.30	__	39.68	Can be upsized to 10V
7	C__17	__	3.80	-10.00	10.00	__	62.00	Selected Capacitor is in good design margin
8	C__18	__	5.50	-50.00	50.00	__	89.00	Can be downsized to 10V or 16V
9	C__19	__	5.50	-50.00	50.00	__	89.00	Can be downsized to 10V or 16V
10	C__20	__	5.50	-50.00	50.00	__	89.00	Can be downsized to 10V or 16V

Table 3 Capacitor Optimization Comparison Study for Stress

V. OPTIMIZATION OF RESISTOR

Every resistor has a maximum power rating that is expressed in watts. This can be anything from 1/8th watt and several watts for power resistors. A first pass analysis would be performed by the engineer to check that the resistor is working within its rated value.

The formula is $P=I^2 R$,

where P is the power lost in the resistor, I is the current flowing, and R is the resistance. Unfortunately, things may become much more difficult; in order to perform exact work, the engineer needs consider the resistor's thermal derating curve. This indicates how much the maximum power dissipation above a specific temperature must be reduced by the designer.

De-rating frequently takes place at relatively high temperatures, so this could seem speculative, but a power circuit in an enclosed housing in a hot area can regularly surpass the cut in point, necessitating a reduction in the maximum power dissipation. It's also important to remember that power loss lowers the maximum operating voltage of a resistor. Every resistor has a Maximum Dissipated Power Rating that specifies how much power it is safe to dissipate without endangering the resistor itself. Resistors that are connected to a circuit with more power than they can handle frequently catch fire and harm the circuit. A heatsink or other cooling mechanism is necessary when a resistor is being used close to its maximum power rating.

The resistor power rating is a crucial factor to consider when choosing a resistor for a particular application. The purpose of a resistor is to prevent current from flowing across a circuit by dissipating excess power as heat. When a low-wattage resistor is used in a circuit where a large power dissipation is anticipated, the resistor overheats and burns out the circuit as well. It is crucial that we select a resistor that can withstand the highest amount of power dissipated. For instance, the resistance to be selected for a circuit with 12V and 50mA of current flowing through it would be,

$R = V/I = 12 * 50e\text{-}3$

$R = 240\Omega$

And the power dissipated would be $P = V * I = 12 * 50e\text{-}3$

$P = 0.6$Watts or 600mWatts

Hence it is ideal to choose a resistor with 240Ω resistance and 660mW rating which is available in the market.

Choosing a resistor more than 660mW can increase the cost and the size.

Note:- No Resistors were altered during the hardware implementation. The below table is for reference purpose and the combined outcome of the study.

Sl No	Resistors Number	Stress		Capability		Design Margin		Comments/Suggestion
		Min (mW)	Max (mW)	Min (mW)	Max (mW)	Min (%)	Max (%)	
1	R__11	71.45	80.31	__	100.00	__	19.69	Selected Resistor is in good design margin
2	R__12	0.99	1.21	__	100.00	__	98.80	Can be downsized
3	R__13	71.45	80.31	__	50.00	__	-60.63	Can be Upsized

Table 4 Resistor Optimization Comparison Study for Stress

VI. HARDWARE IMPLEMENTATION RESULTS

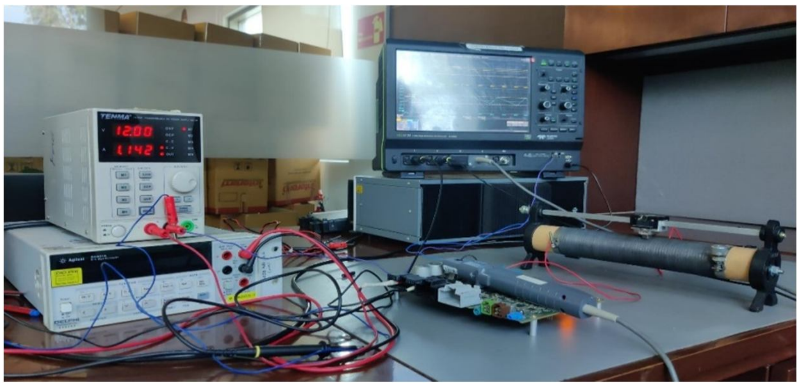

Figure 6 Hardware Implemented Circuit

For the optimization study on the existing board, the over designed components are identified and replaced with much optimal value. The downsize of the capacitor is mentioned in the below table. For the output inductor the focus was to reduce the ripple current. Along with the performance enhancement the focus was also given on the cost aspects which is further discussed.

Components	Original Design	Optimized Design
Capacitor 1	0.01uF, 50V	0.01uF, 25V
Capacitor 2	0.01uF, 50V	0.01uF, 25V
Capacitor 3	0.1uF, 50V	0.1uF, 16V
Output Inductor	1uH, 2.3mΩ (DCR), 20A (Saturation)	1.5uH, 14mΩ (DCR), 18A (Saturation)

Table 5 Optimized Components Values

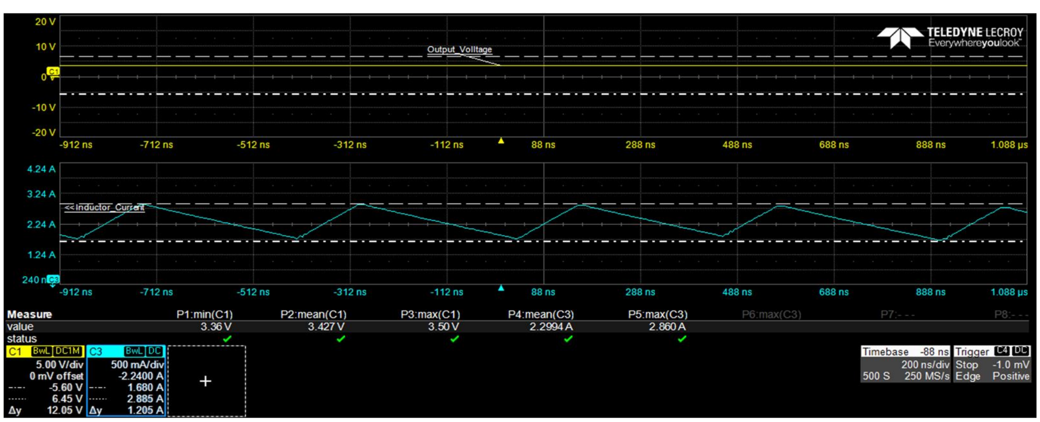

Figure 7 Output Voltage and Inductor Current Waveform before Optimization (1uH Inductor)

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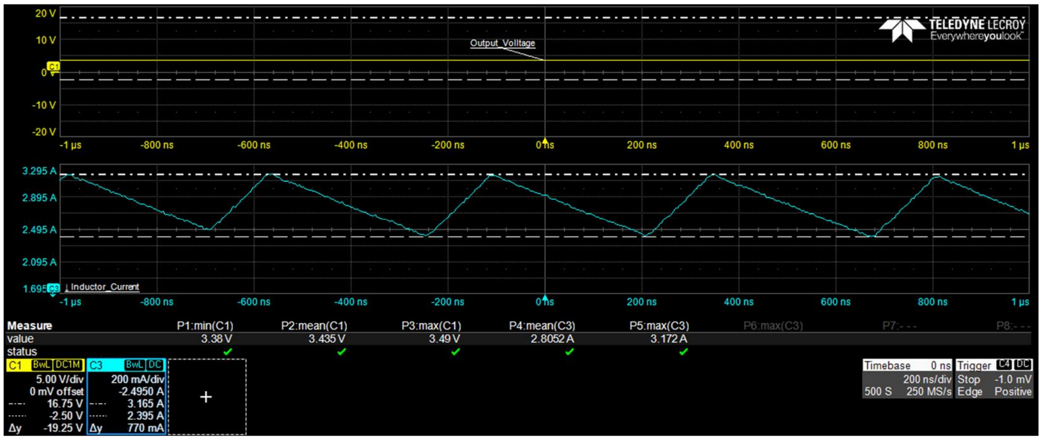

Figure 8 Output Voltage and Inductor Current Waveform after Optimization (1.5uH Inductor)

VII. CONCLUSION

Study on the passive components of selected synchronous buck converter is carried out and the optimum solution of reduction of cost, size and improvement in the design performance is achieved. In the optimized design three capacitors were downsized and a high inductor value was replaced to reduce the ripple current and is proven with the hardware results.

Parameters	Original Design	Optimized Design
Output Voltage (V)	3.427	3.435
Inductor Avg Current (A)	2.294	2.805
Ripple Current Peak to Peak (A)	1.205	0.77

Table 6 Result Comparison

Components	Original Design	Optimized Design
	Cost	
	1 Unit (Rs)	1 Unit (Rs)
Capacitor 1	7.95/-	7.95/-
Capacitor 2	7.95/-	7.95/-
Capacitor 3	11.13/-	7.95/-
Output Inductor	128.79/-	112.10/-
Total	155.82/-	135.95/-

Table 7 Cost Comparison of the optimized components

VIII. AKNOWLEDGEMENT

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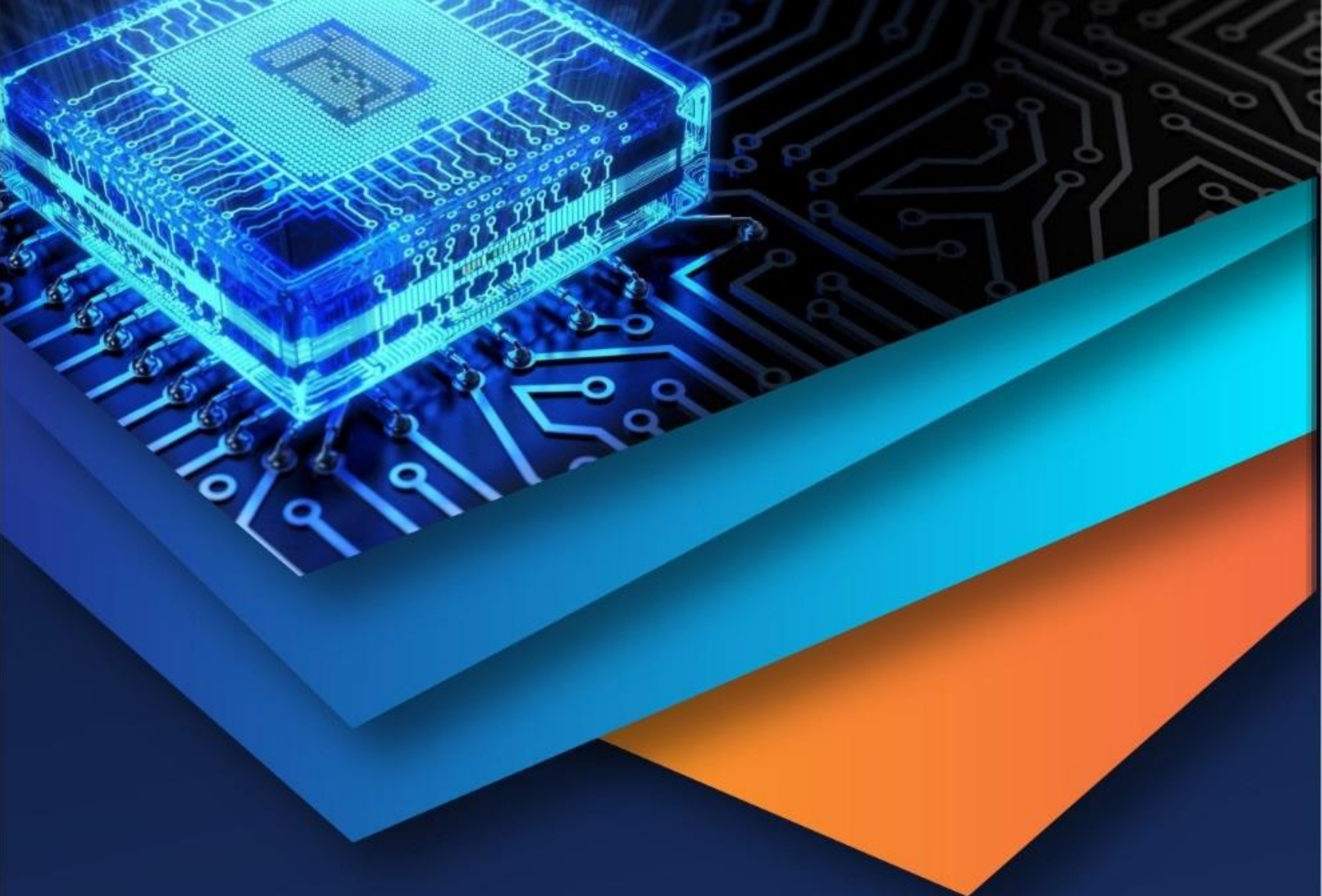

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