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Design of a 24-6 Volts Buck Converter

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ABSTRACT
This paper presents the design and implementation of a buck converter that steps down voltage from 24 volts to 6 volts. Buck converters are a type of DC-DC converter that efficiently reduce voltage while maintaining high levels of energy efficiency, making them essential in various electronic applications.
The design process involves not only selecting appropriate components but also simulating the conversion process to validate the efficiency and stability of the output voltage. This paper will detail the operating principles of the buck converter, the design calculation for component selection and simulation over two software; Proteus and Matlab.
Overall, this project contributes to advancing the understanding of DC-DC conversion technologies, ensuring a reliable power supply for a range of applications.

1 CHAPTER ONE

INTRODUCTION

1.1 Background of Study

Direct current to direct current (DC-DC) converters are among the simplest power electronics circuits designed to transform one voltage level into another through a switching mechanism. These converters have garnered increasing attention across various fields [1, 2]. For instance, when connecting devices such as laptops or chargers directly to a rectified power supply, there's a risk that they might malfunction or sustain damage due to excessive current or voltage. To prevent such issues and ensure the proper operation of electronic devices, it becomes necessary to adjust the voltage to an appropriate level[3].

In this project, we focus on the buck converter configuration for our analysis and design. The buck converter effectively reduces a higher DC supply voltage to a lower DC output voltage, making it ideal for low-power applications where a lower output voltage is needed [1].As a type of switched-mode power supply, a buck converter typically includes at least two semiconductor components, namely a diode and a transistor. However, modern designs often utilize a second transistor for synchronous rectification instead of a diode. Additionally, at least one energy storage component, such as a capacitor or inductor (or a combination of both), is included in the circuit[2].

1.2 Aim of Study

The aim of this project is to design a buck converter that lowers input DC voltage to DC output voltage for low power applications for devices which 6volts is required. The output voltage level is regulated by the PI control circuit to ensure the output voltage is always on set point.

1.3 Objective of Study

The procedure involved in this project consists of designing and simulating the buck converter and its control circuit using Proteus and MATLAB software.The input stage consists of a 220/24V ac transformer and a rectifier circuit. The output stage consists of the proportional integral controller. All these components function as subsystems within the overallbuck converter.

1.4 Scope of Study

In this paper, I demonstrate how to model a buck converter using rudimentary blocks of Simulink, while achieving the same level of accuracy comparable toanother simulation tool I used called PROTEUS. The first chapter gives introduction, background, objective and scopes. In chapter two I presented a conciseliterature review covering theories on power converters,pulse-width modulation (PWM) technique, step-down operations and switching power losses in MOSFETs are discussed while buck converter design, parameter calculation and control circuit design are discussed in chapter three. In chapter four, details of the Simulink model of the buck converter, and its various subsystem simulation is shown, and its results are discussed. Finally, the last part in this project provides the conclusions, applications and references.

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2 CHAPTER TWO

LITERATURE REVIEW

2.1 DC TO DC VOLTAGE CONVERSION METHODS

A DC-DC converter is atype of power supply designed to converts direct current sources from one voltage level to another. In other words, it takes input current and directs it through a switching element, which turns the DC signal into an AC square wave signal. This wave then passes through another filter which turns it back into a DC signal of the desired voltage[3, 4].

DC-DC converters (power supply IC's) are of two types, depending on the method used for conversion[5]:

Linear
Switched

2.1.1 Linear Converter

A linear DC-DC converter employs a resistive voltage drop to generate and regulate a given output voltage.It is also sometimes called a series regulator because the control elements are arranged in series between the input and output[4, 5].

A linear converter can only generate a voltage that is lower than the input voltage. However, it has the advantage of simple circuit configuration, fewer external parts and are less noisy as compared to a switched circuit and do not need energy management through a control loop[6].

2.1.2 Switched Converters

A switched-mode DC-DC converts by storing the input energy periodically and then releasing that energy to the output at a different voltage[5]. The energy storage can occur in either a magneticcomponent like an inductor or a transformer, or in an electric field component such as a capacitor,[7, 8]. Transformer-based converters provide isolation between the input and the output. Switch mode converters offer three main advantages[6]:

- Higher switching frequencies allow for smaller passive components, resulting in reduced losses and less heat generation. [6].
- Energy stored in an inductor can be converted to output voltages that are lower than the input (buck), higher than the input (boost), or feature reverse polarity (buck-boost) [9].
- Improved conversion efficiency compared to linear converters.

In summary, a switched DC/DC converter typically consists of power switch, an inductor, a diode and a capacitor to transfer the energy from the input to the output. These can be arranged in a variety of ways to realize the different converters[10]:

Buck,
Boost or
Buck-Boost Inverter Types[8].

2.2 Buck Converter

This topology is widely utilized for power distribution in intricate systems such as server motherboards, broadband communication boards, and chargers. It efficiently supplies the necessary low voltage from a higher voltage bus that serves multiple converters within the system.[11][12].

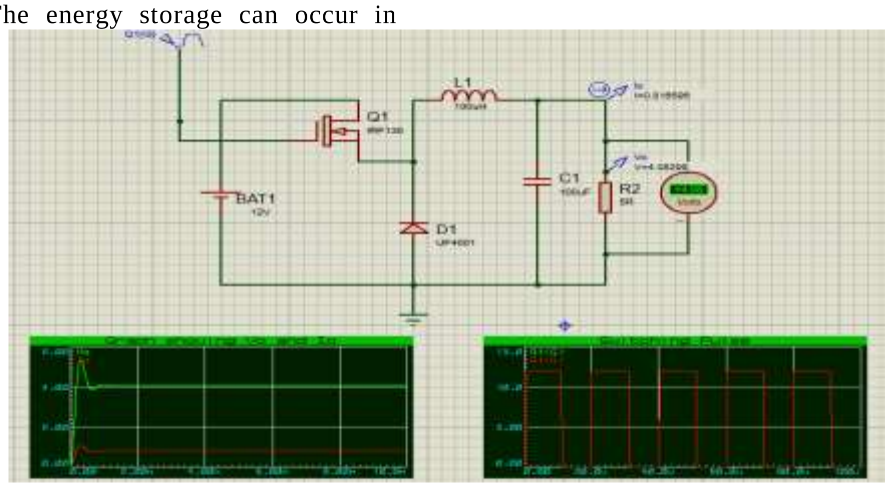

Figure 1A typical buck converter circuit showing the switching pulses, output voltage and output current waveforms

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The buck converter, is shown in Fig. 1comprises of dc input voltage source Vs, controlled switch S, diode D, filter inductor L, filter capacitor C, load resistance R, and output voltage Vo.

Typical waveforms in the converter are also represented, under the assumption that the inductor current is always positive. The state where the inductor current is never zero for any period of time is called the continuous conduction mode (CCM)[12]. It can be seen from the circuit that when the switch S is in ON state, the diode D is reverse-biased. When the switch S is OFF, the diode conducts to support an uninterrupted current in the inductor. Therefore, when the converter is ON, Vo = Vs and when the converter is OFF, Vo = 0[5]

The relationship between the input voltage, output voltage, and the duty ratio D can be derived as follows:

When the converter is ON

$V_s = (V_l + V_o)$Equation 2.2.1

Therefore, $V_l = (V_s - V_o)$Equation 2.2.2

$L\,{}^{di}/_{dt} = V_s - V_o$Equation 2.2.3

$L\,{}^{\Delta i}/_{T_{on}} = V_s - V_o$Equation 2.2.4

$\Delta i = \frac{V_s - V_o}{L} T_{on}$Equation 2.2.5

expression represents the peak-to-peak current load

When the converter is OFF

Polarity reversal and discharging occurs at the inductor. The current passes through the free wheel diode and the inductor to the load[9]. Thus:

From

$L\,{}^{di}/_{dt} = V_o$Equation 2.2.6

$L\,{}^{\Delta i}/_{T_{off}} = V_o$Equation 2.2.7

$\Delta i = \frac{V_o}{L} T_{off}$Equation 2.2.8

By equating $\Delta i = \frac{V_s - V_o}{L} T_{on}$Equation 2.2.5 and $\Delta i = \frac{V_o}{L} T_{off}$Equation 2.2.8:

$$\Delta i = \frac{V_s - V_o}{L} T_{on} = \frac{V_o}{L} T_{off}$$

$\frac{V_s - V_o}{V_o} = \frac{T_{off}}{T_{on}}$Equation 2.2.9

$$\frac{V_s}{V_o} = \frac{T_{off}}{T_{on}} + 1$$

$\frac{V_s}{V_o} = \frac{T}{T_{on}}$ where $T = T_{on} + T_{off}$ Equation 2.2.10

$\frac{V_o}{V_s} = \frac{T_{on}}{T} = D$Equation 2.2.11

Relationship between $V_o, V_s \& D$ for a buck converter

Substitute$\Delta i = \frac{V_s - V_o}{L} T_{on}$Equation 2.2.5 into

$\frac{V_o}{V_s} = \frac{T_{on}}{T} = D$Equation 2.2.11

$\Delta i = \frac{V_s - DV_s}{L} DT$Equation 2.2.12

$\Delta i = \frac{V_s(1-D)D}{Lf}$Equation 2.2.13

Where $T = \frac{1}{f}$ which is the chopping frequency

2.3 Boost Converter

The average voltage output Vo in a boost converter is greater than the voltage input Vs. It consists of boost inductor L, controlled switch S, diode D, filter capacitor C, and load resistance R.Fig.2 shows a configuration of a boost converter[11]-[12].

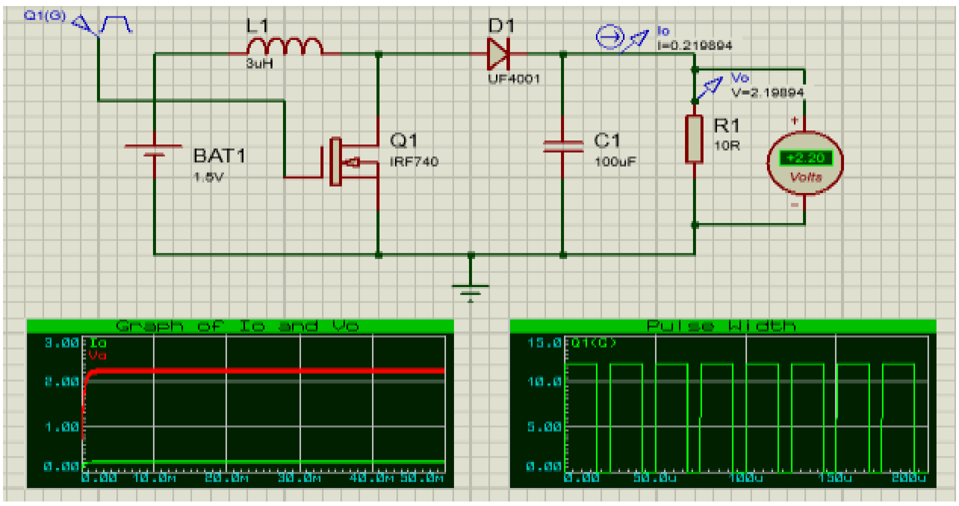

Figure 2A typical boost converter circuit showing the switching pulses, output voltage and output current waveforms

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The relationship between the input voltage, output voltage, and the switch duty ratio D can be derived as follows:
When the converter is ON:
The load is short circuited, resulting in the voltage output for the period T_{on} to be zero[6].During this phase, the current in the boost inductor increases linearly and the diode is off at this point.[6]

$V_o = \frac{1}{T}\int_0^{T_{on}} V_s dt$ Equation 2.3.1

$\therefore V_s = V_l = L\, {di}/{dt}$ Equation 2.3.2

$V_s = L\frac{\Delta i}{T_{on}}$ Equation 2.3.3

$\Delta i = \frac{V_s}{L}T_{on}$ Equation 2.3.4

Δi is the peak-to-peak inductor current
When the converter is off:
Discharge occurs through the inductor

$V_L = V_o - V_s$ Equation 2.3.5

$L\frac{\Delta i}{T_{off}} = V_o - V_s$ Equation 2.3.6

$\Delta i = \frac{V_o - V_s}{L}T_{off}$ Equation 2.3.7

By equating $\Delta i = \frac{V_s}{L}T_{on}$ Equation 2.3.4 and $\Delta i = \frac{V_o - V_s}{L}T_{off}$ Equation 2.3.7

$$\frac{V_s}{L}T_{on} = \frac{V_o - V_s}{L}T_{off}$$

$\frac{V_o}{V_s} = \frac{T}{T_{off}}$ Equation 2.3.8

But $D = \frac{T_{on}}{T}$ Equation 2.3.9

$V_o = \frac{V_s}{1-D}$ Equation 2.3.10

Relationship between $V_o, V_s \& D$ for a boost converter.

2.4 Buck – Boost Converter

A topology of the buck-boost converter is shown in Fig. 3 The converter consists of dc input voltage source V_s, control switch S, inductor L, diode D, filter capacitor C, and load resistance R[11],[12]&[13]. With the switch ON, the inductor current increases while the diode is maintained off[8]. When the switch is turned OFF, the diode provides a path for the inductor current. This orientation makes it possible to increase or reduce the voltage input level[8].

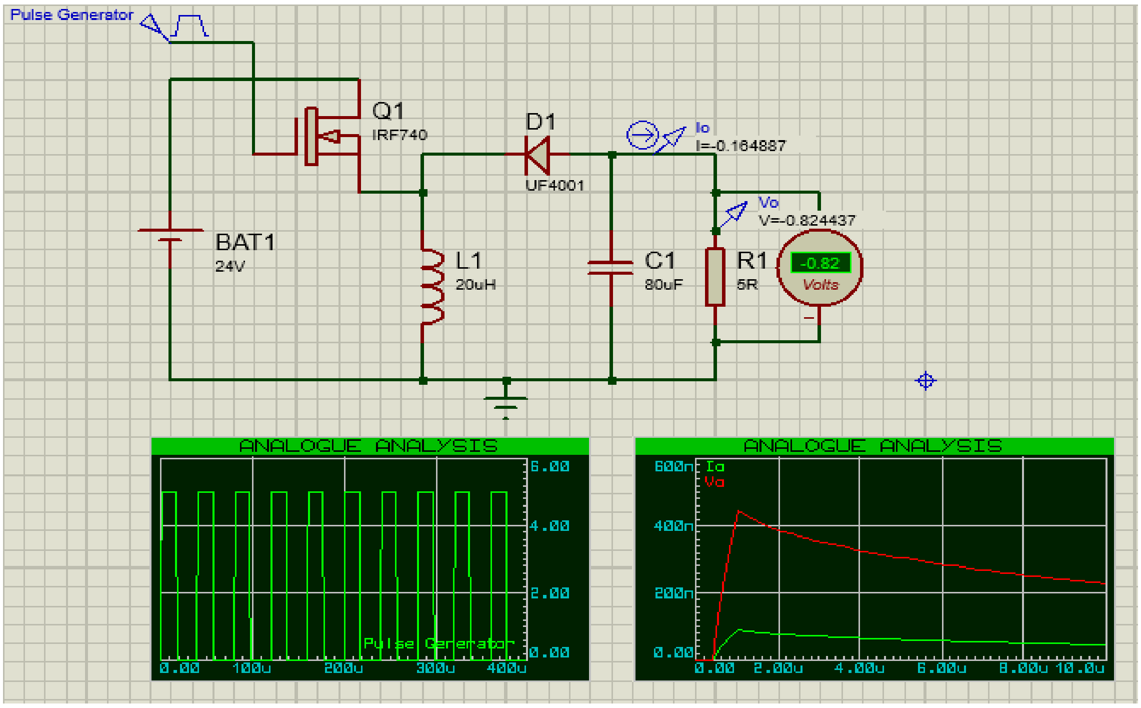

Figure 3A typical buck - boost converter circuit showing the switching pulses, output voltage and output current waveforms

The relationship between the input voltage, output voltage, and the switch duty ratio D can be derived as follows:
When the converter is ON:

The inductor becomes charged by the source voltage. Therefore, $V_s = V_L$

$V_s = L\frac{di}{dt} = L\frac{\Delta i}{T_{on}}$ Equation 2.4.1

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$\Delta i = \frac{V_s}{L}T_{on} \times \frac{T}{T}$Equation 2.4.2
$\Delta i = \frac{DV_s}{Lf}$Equation 2.4.3
whereΔi is the peak-to-peak inductor current
When the converter is OFF, here $V_o = -V_l$
$V_o = \frac{-L\Delta i}{T_{off}}$Equation 2.4.4
$\Delta i = \frac{-V_o T_{off}}{L}$Equation 2.4.5
By comparing $\Delta i = \frac{DV_s}{Lf}$Equation 2.4.3 and $\Delta i = \frac{-V_o T_{off}}{L}$Equation 2.4.5
$TDV_s = -V_o T_{off}$ Equation 2.4.6
$\frac{V_o}{V_s} = -\frac{TD}{T_{off}} \leftrightarrow \frac{TD}{T-T_{on}} \leftrightarrow \frac{TD}{T-DT}$Equation 2.4.7
$\frac{V_o}{V_s} = \frac{D}{1-D}$Equation 2.4.8
Relationship between $V_o, V_s \& D$ for a buck-boost converter.

3 CHAPTER THREE

DESIGN METHODOLOGY

In this project we design a 24V to 6V DC-DC buck converter. The design components may include:
Voltage source
Diode
The passive components; inductor and capacitor
Resistor
PWM source
Semiconductor switch

3.1 Duty Cycle, T_{on} and T

In chapter two, I have derived the relationship between the duty cycle of a buck converter, the input voltage and the output voltage:
$\frac{V_s}{V_o} = \frac{T}{T_{on}}$ where $T = T_{on+}T_{off}$ Equation 2.2.10 and
$\frac{V_o}{V_s} = \frac{T_{on}}{T} = D$Equation 2.2.11
Now, we'll derive values of other parameters of the buck converter
V_s = 24V
V_o =6V
Therefore, D = 6/24
D = 0.25
Let f_s =25, 000Hz
Period, T = $\frac{1}{f_s}$
T = $\frac{1}{25000}$ = 4×10^{-5} *seconds*
T = 0.04ms
To get the on time of the circuit we recall $\frac{V_s}{V_o} = \frac{T}{T_{on}}$ where $T = T_{on+}T_{off}$ Equation 2.2.10$\frac{V_o}{V_s} = \frac{T_{on}}{T} = D$Equation 2.2.11
 $T_{on} = D \times T$
= 0.25× (0.04×10^{-3})
= 0.01ms

3.2 The inductor value (L)

In chapter two, recall that:
$\Delta i = \frac{V_s - V_o}{L}T_{on}$ Equation 2.2.5
Where Δi is the inductor ripple current, and is 10% of the maximum output current.
By simplifying $\Delta i = \frac{V_s - V_o}{L}T_{on}$ Equation 2.2.5further:
$\Delta i = \frac{\frac{V_o}{D} - V_o}{L}DT$Equation 3.2.1
$L = \frac{V_o(1-D)}{f_s \Delta i}$Equation 3.2.2
Before we can use $L = \frac{V_o(1-D)}{f_s \Delta i}$Equation 3.2.2to calculate the inductor current, we must determine the inductor ripple current, Δi
From Ohms Law, $I_o = \frac{V}{R} \leftrightarrow \frac{6}{10}$ *where R is* 10Ω *on assumption*

$$I_o = 0.6\ A$$

I ripple (Δi)= 10% of I_o

$$\Delta i = 0.06A$$

By substituting the values of $\Delta i, D, f_s, and\ V_o$in equation 36 to get the inductance, L
$L = \frac{V_o(1-D)}{f_s \Delta i}$Equation 3.2.2

$$L = \frac{6(1 - 0.25)}{25000 \times 0.06}$$
$$L = 3mH$$

3.3 The Capacitance Value

It is essential to understand that the filter inductor current Δi in the continuous conduction mode comprise of a dc component $I_o$with a superimposed triangular ac component. Most of this ac component is conducted through the filter capacitor as a current I_c. Current $I_c$which creates a slight voltage ripple across the dc output voltage. To limit the peak-to-peak value of the ripple voltage below a specific value V_r, the filter capacitance C must exceed a minimum value denoted byC_{min}. And C_{min} is given by:
$C_{min} = \frac{(1-D)V_o}{8V_r L f_s^2}$Equation 3.3.1
Let ΔV_{co} *represent* $\frac{V_r}{V_o}$
$C_{min} = \frac{(1-D)}{8\Delta V_{co} L f_s^2}$Equation 3.3.2
ΔV_{co}which is the output voltage ripple is calculated as 5% of the output voltage

$$\Delta V_{co} = 5\%\ of\ V_o$$

=.05 × 6
=0.3v
Thus,$C_{min} = \frac{1-0.25}{8 \times 0.03 \times 25000 \times 0.3}$

$$C_{min} = 0.1667\mu F$$

3.4 Design of the PI Controller

From the matlab simulation of the buck converter, by using trial and error method; we obtain that the proportional gain Kp=0.5, and the integral gain Ki=200. In actualizing the proportional part of the PI, we make use of an inverting operational amplifier. Using the expression below:

$Kp = \frac{R_f}{R_i}$ Equation 3.4.1

$R_i = 10k\Omega, from\ assumption$

$Kp = 0.5\ from\ tunning$

$R_f = Kp * R_i$ Equation 3.4.2

$R_f = 0.5 * 10 = 5k\Omega$

In actualizing the integral part of the PI, we configure on inverting operational amplifier, to act as an integrator by using the expression below:

$Ki = \frac{1}{T_i}$; Equation 3.4.3

where T_i *is the time constant*

And $T_i = R_i C_i$ Equation 3.4.4

From matlab simulation Ki=200

$T_i = 0.1$sec

From literature, to design a good PI, the C_i should be low, on that assumption $C_i = 0.1\mu F$

Recall that $T_i = R_i C_i$

$R_i = T_i / C_i$

$R_i = 1000k\Omega$

Table 1Table of Calculated Design Parameters

Parameter	Value
Input Voltage V_{in} (as specification)	24V
Output Voltage V_o (as specification)	6V
Resistance R (as specification)	10Ω
Frequency f_s	25kHz
Period (T)	0.04ms
Period (T_{on})	0.01ms
Period (T_{off})	0.03ms
Duty cycle D	0.25
Capacitance (C)	0.1667µF
Inductance (L)	3mH
Proportional gain Kp	0.5
Integral gain Ki	200

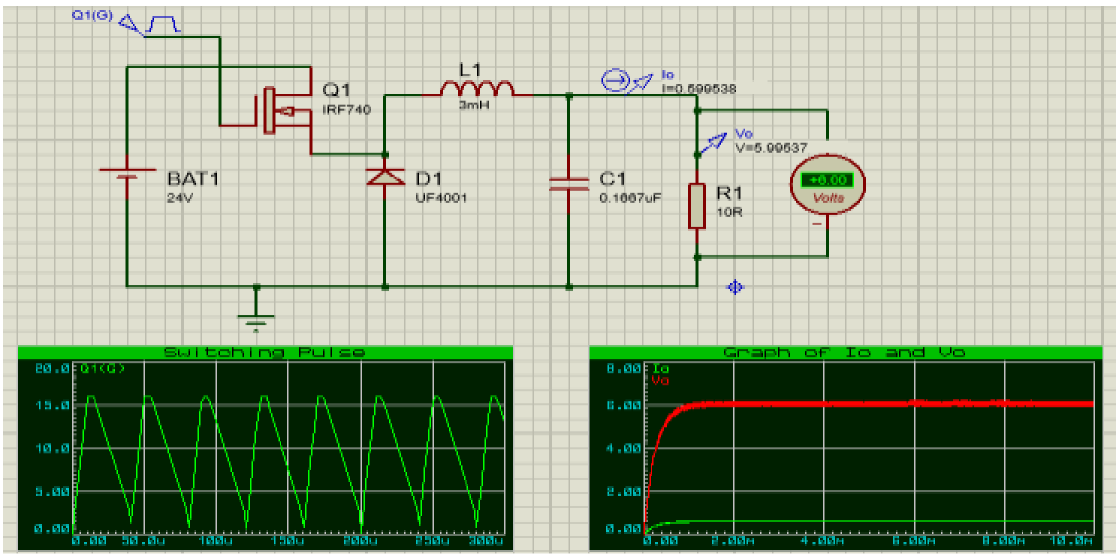

Figure 4Physical Circuit of a 24v to 6v Buck Converter, Showing the Switching Pulse and Output Waveforms

From the graph notice that the output voltage Vo, experienced an overshoot before constant 6volts. In order to eliminate this overshoot, we incorporate a PI controller in the circuit.

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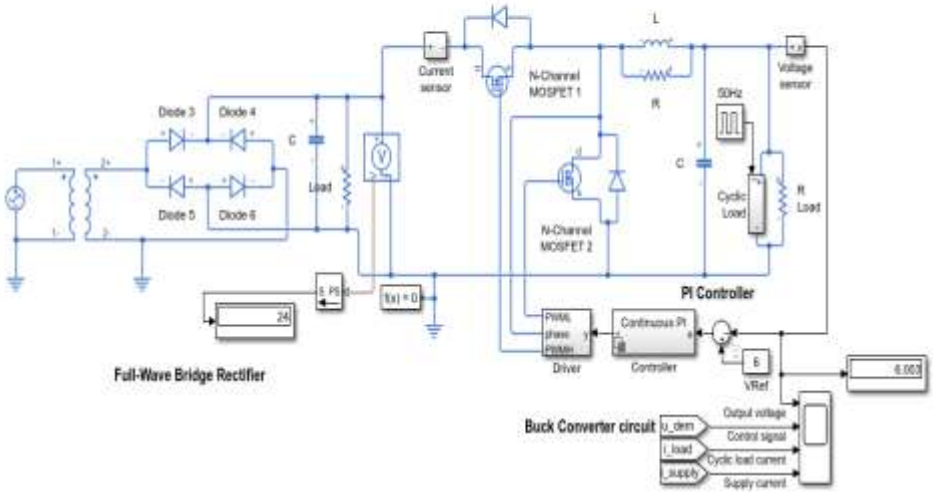

Figure 5Matlab simulation of a 24v to 6v Buck Converter, Showing rectifier circuit, Pi converter and buck converter circuit

4 CHAPTER FOUR

Simulation Results

The above MATLAB model in fig 5 consists of a rectifier circuit, the buck converter circuit; and PI controller; with calculated fields.

4.1 Rectifier Circuit

The rectifier circuit comprises of an ideal AC transformer and a full-wave bridge rectifier. The entire model effectively converts 240 volts AC to 24 volts DC.

The transformer has a turns ratio of 14, which steps the input voltage to approximately 16.97 volts rms; (16.97*√2= 24 volts pk-pk). The ac voltage is then converted to dc by a combination of the full-wave bridge rectifier and a smoothing capacitor. The resistor is included to the model to represents a typical load.

The model is serves as the supply dc voltage source to the buck converter designed in this project.

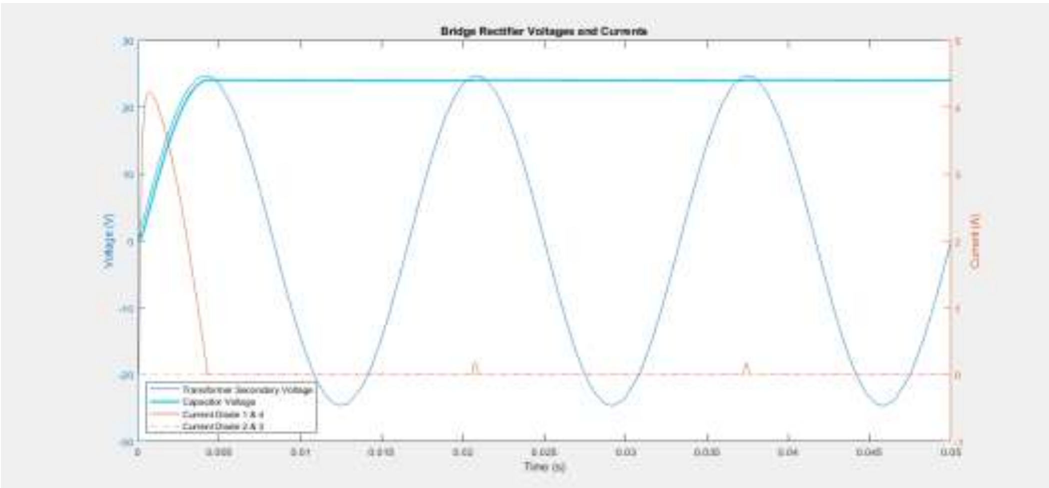

Figure 6Plot illustrating the voltages and currents in a bridge rectifier, demonstrating the conversion of AC voltage into DCvoltage

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The plot above illustrates how to convert AC voltage to DC Voltage. The blue line represents the AC voltage on the source side of the bridge rectifier. Current can traverse the diode bridge through two separate paths. The alternating peaks seen through diodes 1 and 4, as well as through diodes 2 and 3, shows that the current flowing to the capacitor maintains a unidirectional flow, despite the changing polarity of the voltage. The variations in the load voltage, known as ripple, occur due to cycles of capacitor's charging and discharging.

4.2 Buck Converter Circuit

The output dc voltage of the rectifier is utilized to model a switching power supply that converts a 24V DC supply into a regulated 6V DC output. The model uses the calculated values of the inductance L, smoothing capacitor C and PI controller from chapter 3.

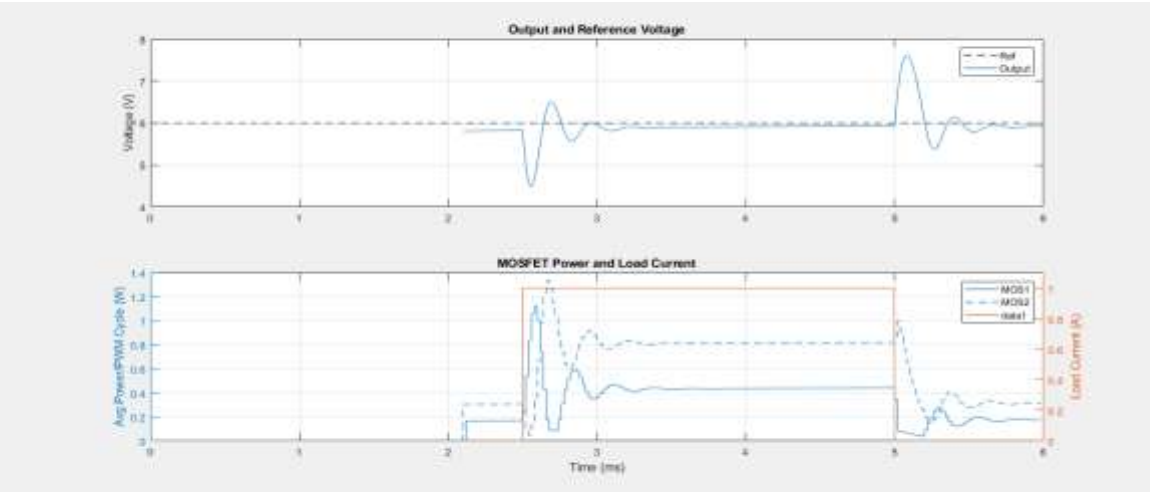

Figure 7displaying the output voltage in relation to the reference, along with the variation in load current and the average power dissipation of the two MOSFETs over the PWM cycle

Modeling the switching devices as MOSFETs instead of ideal switches allows for accurate representationof the on-resistances of the devices. Additionally, this model effectively captures the timing for switching on and off, which is primarily influenced by the values of the gate capacitance and the output resistance of the PWM driver.

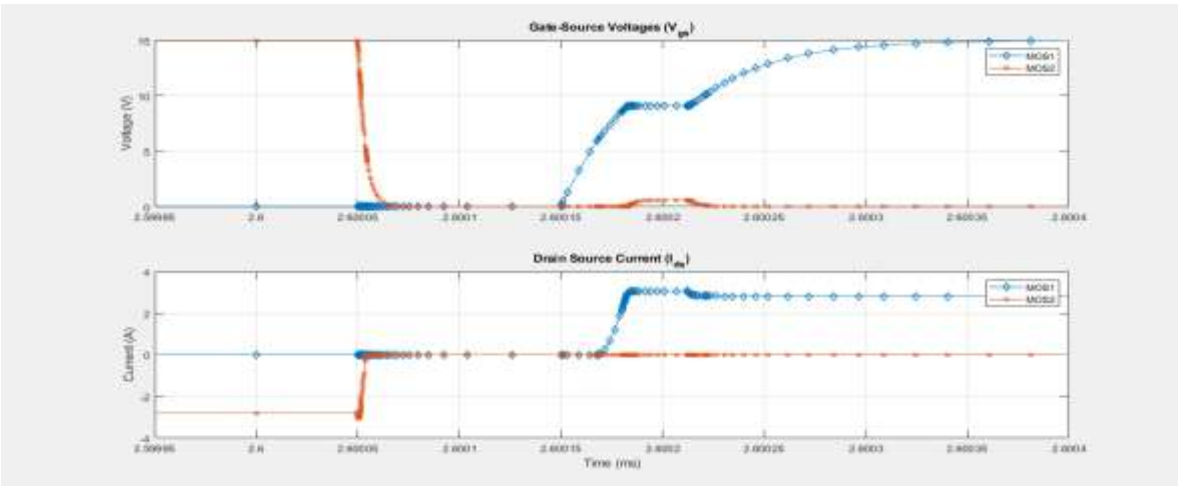

Figure 8Plot illustrating the timing of the on and off states for the two MOSFETs, along with the drain-source current

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4.3 The PI Circuit

The output from the buck converter is evaluated against a reference voltage using a difference amplifier. The resulting discrepancy (error) is processed by the PI controller to correct the error and bring it back to zero.

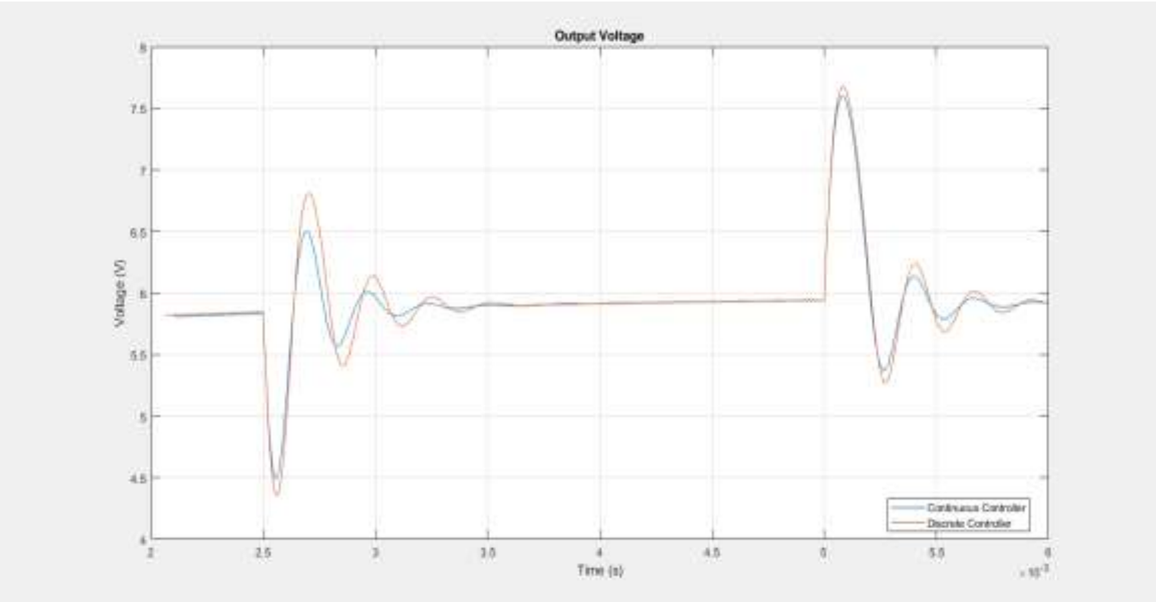

Figure 9 Plot demonstrating the performance of different implementations of a PI controller

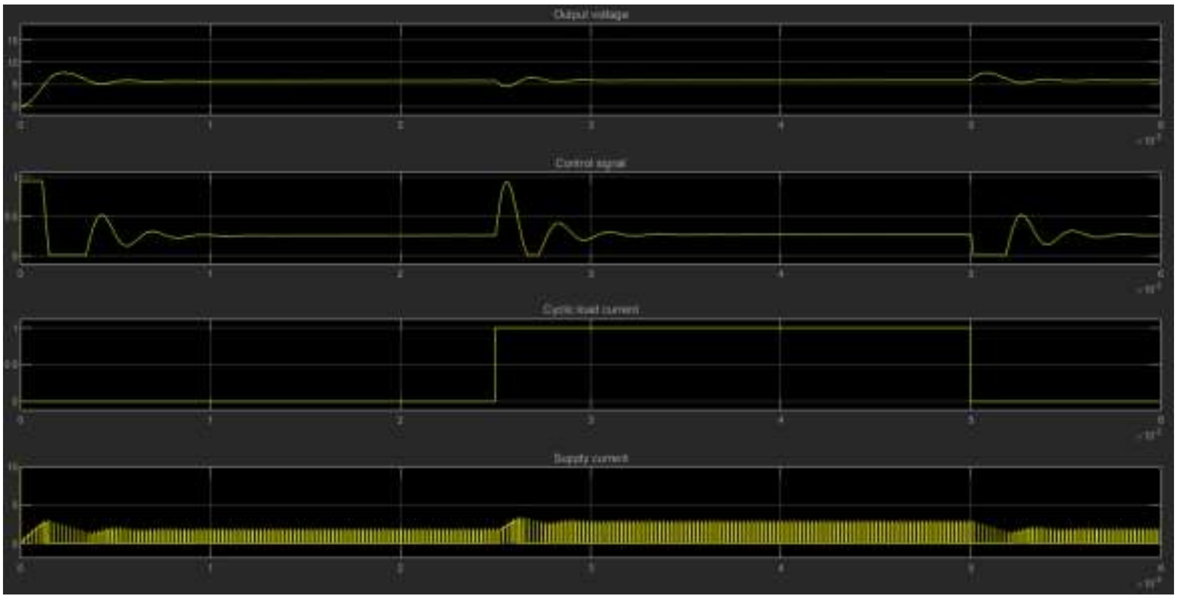

Figure 10Scope plot displaying the output voltage, control signal, cyclic load current, and supply current

5 CHAPTER FIVE

CONCLUSION

5.1 Conclusion

The findings of this research demonstrate that a buck converter can achieve a stable output voltage of 6V from a 24V input, as evidenced by simulations conducted in both Proteus and MATLAB.

These simulations effectively illustrated the complete conversion process, starting with the rectification of 220V AC to 24V DC, followed by the operation of the buck converter and the use of a PI controller to enhance output stability and response.

Results from the Proteus simulation showed that the buck converter efficiently reduced the voltage to the target 6V output with minimal ripple, highlighting its effectiveness in maintaining voltage regulation across various load conditions. Additionally, the MATLAB simulation provided important insights into the system's dynamic performance, showcasing how the PI controller improved overall stability and response time, thus reducing overshoot and settling time.

In summary, this project confirmed the theoretical foundations of DC-DC conversion and emphasized the practical application of simulation tools to model and optimize the performance of power electronic systems. Future research could focus on implementing the design in real-world scenarios, testing its robustness and reliability under different environmental conditions and load variations.

5.2 Application

The dc-dc converters are building blocks of distributed power supply systems in which a common dc bus voltage is converted to various other voltages according to requirements of particular loads. Such distributed dc systems are common in space stations, ships and airplanes, as well as in computer and telecommunication equipment.

5.2.1 UPS

A significant application of DC-DC converters lies within utility AC grid systems. In the event of a utility grid failure, it is crucial to have a backup power source, such as a battery pack, to ensure uninterrupted energy supply for critical loads. This demand for reliable power delivery has led to the development of various types of uninterruptible power supplies (UPS). DC-DC converters play a vital role in these UPS systems by adjusting the rectified grid voltage to match that of the backup source. [14]. During regular operation, energy flows from the grid to the backup source, while in emergencies, the backup source must supply power to the load, which is why bidirectional DC-DC converters are frequently employed[15][16].

5.2.2 Fuel Cells Battery Electric Vehicles

DC-DC converters are utilized in applications that connect AC networks with DC renewable energy sources such as fuel cells and photovoltaic systems.

A fuel cell vehicle (FCV) is a type of electric vehicle that generates electrical energy using a hydrogen-powered fuel cell, rather than solely relying on a battery. The maximum voltage output from the fuel cell is determined by the number of cells that can be connected in series, which is limited by current technology. As a result, this output voltage may not reach the optimal level needed to effectively supply the electric machine through its inverter.

To address this, a unidirectional DC-DC boost converter is used to increase the fuel cell voltage to match the electric machine's optimal requirements. Additionally, FCVs are considered hybrid systems because the fuel cell cannot operate in reverse.

Therefore, a battery is necessary to store energy generated during regenerative braking. To facilitate this, a reversible DC-DC converter is connected to the battery, providing a boost function during propulsion and a buck function during regenerative braking. This is accomplished using a bidirectional buck-boost DC-DC converter[17].

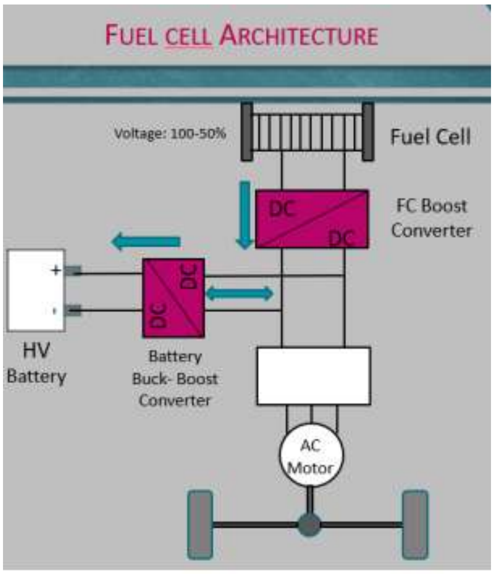

Figure 11Fuel cell Architecture

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