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## Lab 7: Exploring DC-DC Converters: Boost and Buck

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Principles, Calculations, and Practical Applications in Power Electronics

Work done by :

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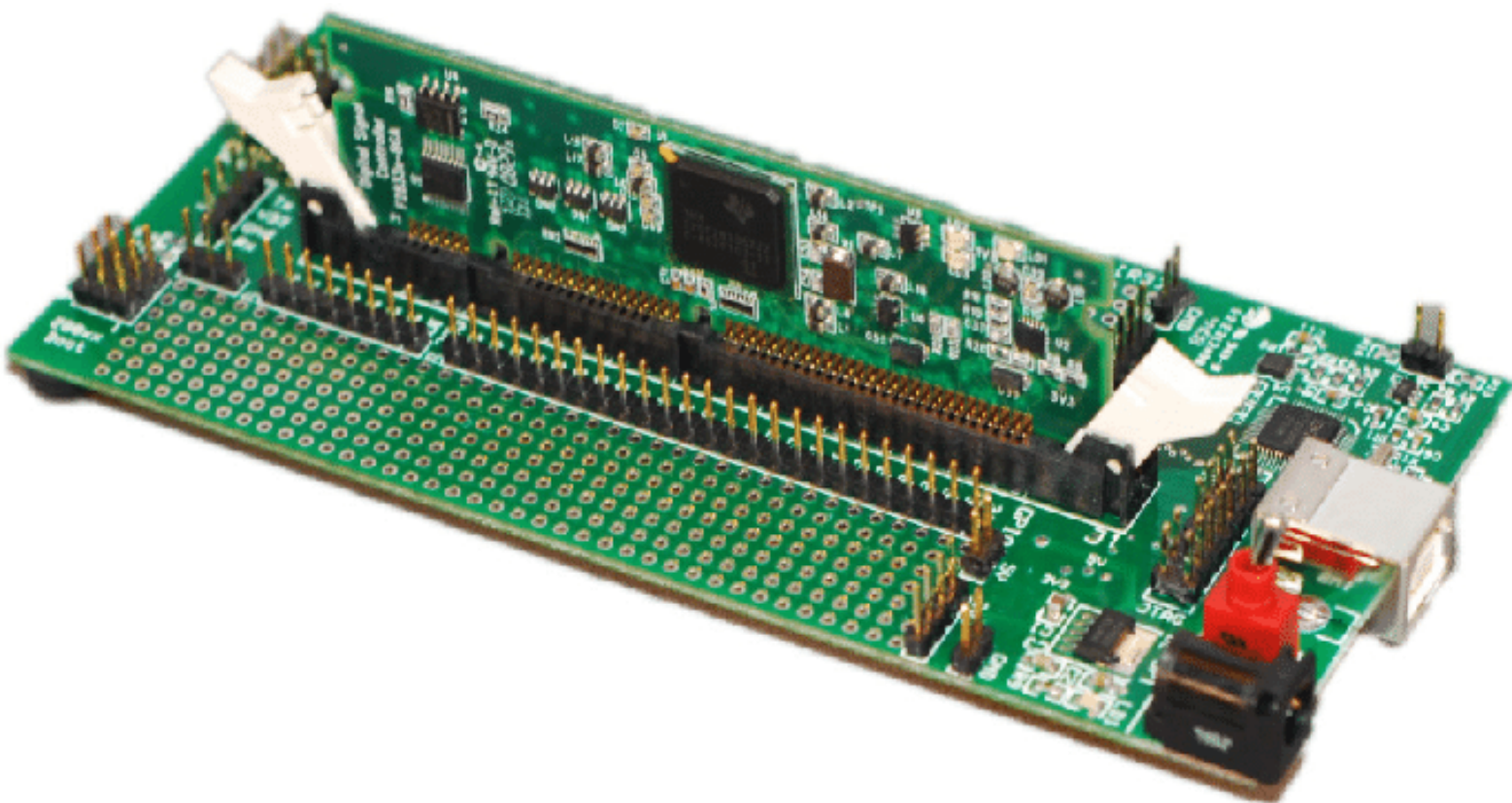
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# 1 Introduction

## 1.1 Presentation of DC-DC Converters

DC-DC converters are electronic devices that adjust the voltage level of direct current (DC) from one source to another level required by the loads or circuits. They play a crucial role in many electronic applications, enabling efficient energy management by adapting the voltage to more useful or safer levels.

### Boost Converter (Step-Up)

The **Boost** converter increases the output voltage above the input voltage. This type of converter is used when the required voltage is higher than that provided by the power source. It is essential in applications where it is necessary to increase the voltage to power components that require a higher voltage than that of the source.

### Buck Converter (Step-Down)

The **Buck** converter decreases the output voltage below the input voltage. It is particularly suitable for applications that require a voltage lower than that available at the input. This type of converter is ideal for situations where it is necessary to lower the voltage to meet the requirements of circuits or devices operating at a lower voltage.

## 1.2 Role and Applications of Boost and Buck Converters

DC-DC converters are essential in a multitude of applications, extending their utility from consumer electronics to complex industrial systems. Their ability to adjust voltage makes them indispensable in various contexts.

- **Mobile and Portable Applications:** **Boost** converters maximize the use of low-voltage batteries by raising the voltage to power circuits that require higher voltage levels, such as in mobile phones and laptops.
- **Power Systems:** **Buck** converters are essential for providing stable and regulated power to microprocessors and other sensitive components that require precise and constant voltages for optimal operation.
- **Renewable Energies:** Used to optimize energy conversion in solar and wind applications, **Boost** converters increase the voltage of the low currents generated to match the specifications of the grid or storage system.

## 1.3 Links with Previous Labs

The *Boost* and *Buck* converters rely on several power electronics concepts covered in previous practical sessions. Understanding these principles is essential to mastering the operation of these converters.

- **PWM Control:**

Pulse Width Modulation (*PWM*) is used to control the output voltage. This technique allows for fine regulation of energy in converters.

These principles provide a solid foundation for integrated learning, enabling students to better understand and innovate in the field of power electronics.

# 2 The Boost Converter

## 2.1 Operating Principle

The **Boost** converter, also known as a step-up converter, is a type of DC-DC circuit that increases the output voltage above the input voltage. It is widely used in applications where devices require a higher voltage than what the power source can directly provide.

### 2.1.1 Increasing the Output Voltage

The basic principle of a **Boost** converter involves the use of an inductor, a switch (typically a transistor), a diode, and a capacitor. Here is how the voltage is increased:

- **Energy Storage:** When the switch is closed, current flows through the inductor, and energy is stored in its magnetic field. During this phase, the diode is reverse-biased and blocks the current from passing to the output.
- **Energy Release:** When the switch opens, the current path through the inductor is cut off. The voltage across the inductor sharply increases due to the inductor's attempt to maintain the current. This voltage increase reverses the bias of the diode, making it conductive and allowing current to flow to the capacitor and the load. The voltage on the capacitor is thus increased to a value higher than that of the input.

This cycle of charging and discharging the inductor, controlled by the state of the switch, allows the voltage to be raised to a level higher than the initial input voltage.

## 2.2 Theory and Calculations

In this section, we will address the theoretical aspects of calculations associated with a Boost converter, focusing on the output voltage formula and its practical application across different duty cycle values.

### 2.2.1 Output Voltage Formula

The output voltage of a Boost converter is determined by a relationship that directly depends on the duty cycle and the input voltage. The essential formula for calculating the output voltage of a Boost converter is as follows:

$$V_{\text{out}} = \frac{V_{\text{in}}}{1 - D}$$

where:

- $V_{\text{out}}$  is the output voltage,
- $V_{\text{in}}$  is the input voltage,
- $D$  is the duty cycle expressed as a percentage or fraction.

This equation shows that the output voltage increases as the duty cycle approaches 1 (100

### 2.2.2 Applying the Formula to Different Duty Cycle Values

To illustrate the impact of the duty cycle on the output voltage, let's examine a few scenarios with a fixed input voltage of 40V:

- **For  $D=0.5$  (50%):**

$$V_{\text{out}} = \frac{40V}{1 - 0.5} = 80V$$

At a duty cycle of 50%, the output voltage is doubled compared to the input voltage.

- **For  $D=0.4$  (40%):**

$$V_{\text{out}} = \frac{40V}{1 - 0.4} = 66.7V$$

With a duty cycle of 40%, the output voltage is approximately 1.67 times the input voltage.

- **For  $D=0.2$  (20%):**

$$V_{\text{out}} = \frac{40V}{1 - 0.2} = 50V$$

A duty cycle of 20% increases the output voltage by 25% compared to the input voltage.

- **For  $D=0.8$  (80%):**

$$V_{\text{out}} = \frac{40V}{1 - 0.8} = 200V$$

A duty cycle of 80% multiplies the input voltage by five, reaching the theoretical limit of this specific Boost converter model.

These examples clearly show that modifying the duty cycle can significantly influence the output voltage of the Boost converter. However, it is essential to consider that extreme duty cycle values can lead to practical issues such as increased switching losses and degradation of the overall system efficiency. Careful design and simulation are required to optimize the duty cycle according to the specific requirements of the application while minimizing risks and inefficiencies.

## 2.3 Limits and Practical Realities

This section examines the practical constraints of Boost converters, highlighting the differences between theoretical results and actual performance, as well as the various factors that influence the efficiency and reliability of these devices.

### 2.3.1 Theoretical vs Practical Comparison

Theoretical calculations of Boost converters provide an idealized estimation of the output voltage based on perfect operating assumptions, where components have no losses and conditions are optimal. However, in practice, several factors lead to significant deviations between theoretical results and actual measurements:

- **Inherent Losses:** Components such as inductors, capacitors, diodes, and transistors have internal resistances and inefficiencies that generate power losses in the form of heat. For example, the voltage drop across the diode and the resistance of the inductor effectively reduce the output voltage compared to theoretical predictions.
- **Switching Dynamics:** The transitions between ON and OFF states of the transistor are not instantaneous. These switching delays introduce additional losses and can affect the stability of the output voltage, especially at high switching frequencies.
- **Signal Stability:** The presence of noise and fluctuations in the input voltage or load can alter the performance of the Boost converter, affecting its ability to maintain a stable output voltage.

### 2.3.2 Factors Influencing Performance

Several key factors determine the efficiency and performance of a Boost converter under real conditions:

- **Component Selection:** Choosing high-quality components that are appropriate for the required specifications is crucial. For example, an inductor with a high saturation value and low series resistance will help minimize losses and improve the dynamic response of the converter.
- **Circuit Design:** A careful design that minimizes trace lengths on the PCB and optimizes the layout of components can reduce Joule effect losses and electromagnetic interference, thereby enhancing overall efficiency.
- **Thermal Management:** Given that power losses result in an increase in component temperature, efficient heat management is essential to maintain reliability and longevity of the converter. The use of heat sinks, cooling plates, and good ventilation are key strategies.
- **Duty Cycle Adjustment:** Precise adjustment of the duty cycle according to load conditions and input voltage is vital to optimize performance. An improperly adjusted duty cycle can lead to unstable or insufficient output voltage.
- **Surge Protection:** Protection circuits such as voltage regulators and protection diodes can prevent damage from accidental voltage spikes, thus ensuring the safety and durability of the converter.

In conclusion, although Boost converters offer a flexible and powerful method for increasing voltage, their performance in practice strongly depends on the circuit design, the quality of components used, and the management of operational conditions. A thorough understanding of these factors allows for maximizing efficiency while minimizing risks and failures.

## 3 Boost Circuit Configuration

### 3.1 General Circuit Description

The circuit of a Boost converter is designed to effectively increase the output voltage above the input voltage. It consists of several key components whose arrangement is crucial for optimal operation. Here is an introduction to the main components of the Boost circuit and their configuration:

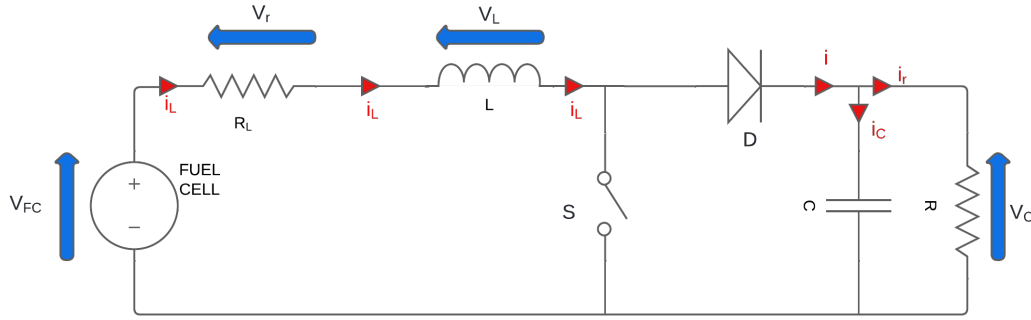


Figure 1: Boost Circuit Diagram

- **Inductor (L):** The inductor is one of the most critical components of the Boost converter. It is used to store energy in the form of a magnetic field when current passes through it. The inductor must have sufficient capacity to handle current peaks without saturation and with minimal magnetic losses.
- **Switch (S):** Typically a transistor, such as a MOSFET or an IGBT, that acts as a switch in the circuit. It is controlled by a pulse width modulation (PWM) signal that determines the duty cycle of the converter. The state of the switch (open or closed) controls the timing and duration during which energy is stored in the inductor or transferred to the load.
- **Diode (D):** The diode in a Boost circuit acts as a one-way valve that allows current to flow to the output (the capacitor and the load) but prevents current from flowing back to the inductor when the switch is open. It must be capable of handling high voltages and switching quickly to minimize switching losses.
- **Capacitor (C):** The capacitor in the Boost circuit smooths the output voltage and provides a constant energy source to the load. It reduces voltage fluctuations (ripple) caused by the switching cycles of the switch and the discharge of the inductor.
- **Load (R):** The load connected to the circuit can vary depending on the specific application. It receives energy from the capacitor and is directly affected by variations in the output voltage of the converter.

This configuration allows the Boost converter to provide an output voltage higher than the input voltage, suitable for applications requiring higher voltage for their operation. Understanding the role and arrangement of each component is essential to optimize the circuit design and ensure its efficiency and reliability under various usage conditions.

## 3.2 Analysis of the ON State

### 3.2.1 Introduction to Fundamental Electrical Formulas

Before delving into the specific analysis of the ON state of the Boost converter, let's recall the fundamental formulas that govern the behavior of electrical components in the circuit:

- **Inductor:** The voltage across the inductor is given by Faraday's law of electromagnetic induction:

$$V_L = L \frac{dI_L}{dt}$$

where  $L$  is the inductance and  $\frac{dI_L}{dt}$  is the rate of change of current through the inductor.

- **Capacitor:** The current through the capacitor is related to the change in voltage across its terminals by the following relationship:

$$I_C = C \frac{dV_C}{dt}$$

where  $C$  is the capacitance and  $\frac{dV_C}{dt}$  is the rate of change of voltage across the capacitor.

- **Ohm's Law:** The voltage drop across a resistor is directly proportional to the current flowing through it:

$$V_R = I_R \cdot R$$

where  $I_R$  is the current through the resistor and  $R$  is the resistance value.



### 3.2.2 ON State Loop Configuration

In the ON state of the Boost converter, the switch is closed, allowing current to flow through the inductor. During this phase, we identify two main loops in the circuit: the loop including the inductor and the source, and the loop including the capacitor and the load (although primarily inactive due to the blocking diode).

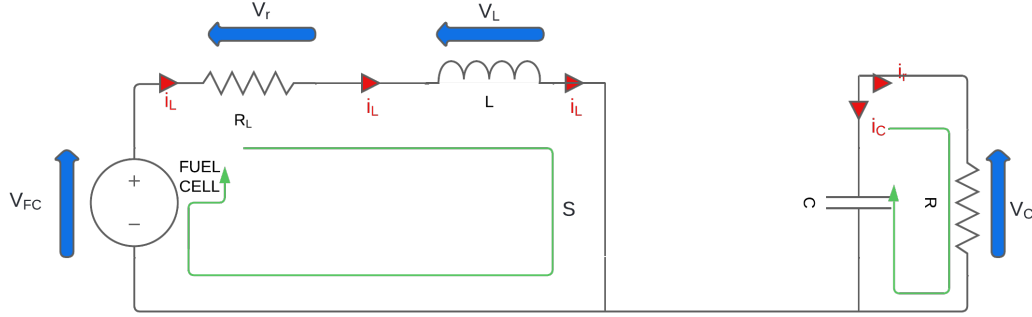


Figure 2: Boost Circuit Diagram in ON State

#### First Loop (Inductor and Source):

- For this loop, we apply Kirchhoff's Voltage Law (KVL), which states that the sum of the voltages in the loop must be zero:

$$V_{FC} - V_L - V_r = 0$$

which gives us

$$V_{FC} - L \frac{di_L}{dt} - i_L R_L = 0$$

where  $R_L$  represents the resistance of the closed switch.

- Rearranging the terms, we have:

$$\frac{di_L}{dt} = \frac{V_{FC} - i_L R_L}{L}$$

Thus, integrating this relation, we obtain:

$$i_L(t) = \int \frac{V_{FC} - i_L(t) R_L}{L} dt \quad (1)$$

This equation describes how the current in the inductor increases over time, thereby storing magnetic energy.

#### Second Loop (Capacitor and Load):

- Although primarily inactive during the ON state, it is crucial to note that any change in the inductor's current must be compensated by the capacitor's current in the OFF state, according to the nodal law:

$$0 = i_C + i_R$$

where  $i_R$  is the load current.

- Rearranging the terms, we have:

$$\frac{dV_C}{dt} = -\frac{i_R}{C}$$

Thus, integrating this relation, we obtain:

$$V_C(t) = -\int \frac{i_R}{C} dt \quad (2)$$

This equation will be fully active upon the opening of the switch, allowing the transfer of energy from the inductor to the capacitor and the load.

This systematic method of analysis using fundamental electrical formulas and applying Kirchhoff's laws enables precise understanding of the Boost circuit's behavior in the ON state and prepares the groundwork for the OFF state.

### 3.3 Analysis of the OFF State

## Introduction to Fundamental Electrical Formulas for the OFF State

Before starting the specific analysis of the OFF state of the Boost converter, let's recall the essential electrical formulas that will govern our study, some of which are the same as in the ON state and will not be repeated here:

- **Diode:** The diode becomes conductive in the OFF state, allowing the passage of current from the inductor to the capacitor:

$$V_D = 0$$

### 3.3.1 Configuration of the Single Loop in the OFF State

In the OFF state, we have a single main active loop in the circuit, which includes the inductor, the diode, and the capacitor. This configuration simplifies our analysis by focusing only on this loop.

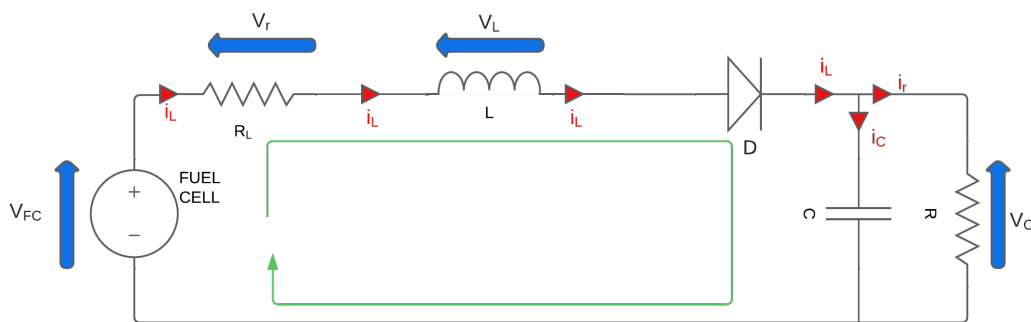


Figure 3: Boost Circuit Diagram in OFF State

### Application of Kirchhoff's Voltage Law (KVL):

- By applying Kirchhoff's Voltage Law to this loop, we formulate the following equation:

$$V_{FC} - V_r - V_L - V_D - V_C = 0$$

Since the diode ideally has no significant voltage drop,  $V_D$  can be neglected, simplifying the equation to:

$$V_{FC} - V_r - V_L - V_C = 0$$

which gives us

$$V_{FC} - L \frac{di_L}{dt} - i_L R_L - V_C = 0$$

- Rearranging the terms, we have:

$$\frac{di_L}{dt} = \frac{V_{FC} - i_L R_L - V_C}{L}$$

Thus, integrating this relation, we obtain:

$$i_L(t) = \int \frac{V_{FC} - i_L(t)R_L - V_C}{L} dt \quad (3)$$

### Derivation of the Fourth Equation with Kirchhoff's Current Law (KCL):

- To complete our system of equations for the OFF state, we apply Kirchhoff's Current Law at the point where the inductor's current divides between the capacitor's current and the load current:

$$i_L = i_C + i_R$$



- Rearranging the terms, we have:

$$\frac{dV_C}{dt} = \frac{i_L - i_R}{C}$$

Thus, integrating this relation, we obtain:

$$V_C(t) = \int \frac{i_L - i_R}{C} dt \quad (4)$$

These equations established for the OFF state allow us to precisely calculate how energy is conserved and distributed in the Boost circuit, ensuring an efficient transition between ON and OFF states and stabilizing the output voltage for reliable applications.

### 3.4 Solving the Equations

The key equations governing the operation of Boost converters in ON and OFF states are essential for understanding and predicting the circuit behavior under different operating conditions. Here is a description of the four main equations, initially presented without integrating the duty cycle factor ( $d$ ), followed by an explanation of how this factor is integrated into the equations to reflect Pulse Width Modulation (PWM) control.

#### The Various Equations:

1. **Inductor Current Equation for ON State ( $i_L$ ):**

$$i_L(t) = \int \frac{V_{FC} - i_L(t)R_L}{L} dt \quad (5)$$

This equation is derived from Kirchhoff's Voltage Law and describes the increase of current through the inductor, where  $V_{FC}$  is the input voltage,  $R_L$  is the inductor resistance, and  $V_C$  is the capacitor voltage.

2. **Capacitor Voltage Equation for ON State ( $v_C$ ):**

$$V_C(t) = - \int \frac{I_R}{C} dt \quad (6)$$

This integration helps to determine how the voltage on the capacitor develops over time, where  $i_{CH}$  is the capacitor charge current.

3. **Inductor Current Equation for OFF State ( $i_L$ ):**

$$i_L(t) = \int \frac{V_{FC} - i_L(t)R_L - V_C}{L} dt \quad (7)$$

This equation reflects the discharge of the inductor in the OFF state, showing how the voltage across the inductor decreases, influencing the capacitor voltage.

4. **Capacitor Voltage Equation for OFF State ( $V_C$ ):**

$$V_C(t) = \int \frac{i_L - i_R}{C} dt \quad (8)$$

This equation models the rate of capacitor charging, indicating how the voltage develops on the capacitor from the inductor current and charge current.

### Integrating the Duty Cycle into the Equations

The duty cycle ( $d$ ) is a key parameter in managing a Boost converter, adjusting the proportion of switch activation time. The integration of ( $d$ ) into the above equations can be done as follows to more accurately reflect PWM control:

- **Modifying the Equations for the OFF State:**

$$L \frac{di_L}{dt} = V_{FC} - i_L R_L - (1 - d)V_C \quad (9)$$

$$C_b \frac{dV_C}{dt} = (1 - d)i_L - i_{CH} \quad (10)$$

These modifications help to understand how the duty cycle influences the redistribution of circuit energy, particularly how the fraction of time during which the switch is deactivated ( $1 - d$ ) affects the output voltage and capacitor charging.

These adjustments with the factor ( $1 - d$ ) demonstrate how precise duty cycle management can optimize the performance of the Boost converter, controlling output voltage and maximizing the energy efficiency of the system.

## 4 The Buck Converter

### 4.1 Operating Principle

The Buck converter, also known as a step-down converter, is a type of DC-DC circuit that reduces the output voltage below the input voltage. It is widely used in applications where devices require a voltage lower than what the power source can directly provide.

#### 4.1.1 Reducing the Output Voltage

The basic principle of a Buck converter involves the use of an inductor, a switch (typically a transistor), a diode, and a capacitor. Here is how the voltage is reduced:

- **Energy Storage:** When the switch is closed, current flows through the inductor, and energy is stored in its magnetic field. During this phase, the diode is reverse-biased, blocking the passage of current to the output.
- **Energy Release:** When the switch opens, the current path through the inductor is maintained via the freewheeling diode. The current gradually decreases as energy is transferred to the capacitor and the load. The voltage on the capacitor is adjusted to be lower than the input voltage through the regulation of current in the inductor.

This cycle of charging and discharging the inductor, controlled by the state of the switch, allows the voltage to be reduced to a level below the initial input voltage.

#### 4.1.2 Role of the Duty Cycle

The duty cycle, i.e., the proportion of time the switch is closed relative to the total cycle, plays a crucial role in controlling the output voltage of the Buck converter. The relationship between the duty cycle and the output voltage can be expressed by the formula:

$$V_{\text{out}} = D \times V_{\text{in}}$$

where  $V_{\text{out}}$  is the output voltage,  $V_{\text{in}}$  is the input voltage, and  $D$  is the duty cycle.

- **Decreasing the Duty Cycle:** By reducing the duty cycle (the duration for which the switch is closed), less energy is stored in the inductor during each cycle, which decreases the output voltage. A reduced duty cycle means that the switch is closed for a shorter duration, limiting the energy transfer to the load.
- **Limitations:** Although theoretically, a low duty cycle value can yield a very low output voltage, practical limitations such as the minimal voltage drop due to the diode and losses in the circuit define the minimum obtainable voltage and affect the stability of the converter.

In summary, managing the duty cycle is essential for regulating the output voltage in a Buck converter and must be precisely adjusted based on the load requirements and the characteristics of the power source.

### 4.2 Theory and Calculations

In this section, we explore the theoretical aspects and calculations associated with a Buck converter, focusing on the output voltage formula and its practical application across different duty cycle values.

#### 4.2.1 Output Voltage Formula

The output voltage of a Buck converter is determined by a relationship that directly depends on the duty cycle and the input voltage. The essential formula for calculating the output voltage of a Buck converter is as follows:

$$V_{\text{out}} = D \times V_{\text{in}}$$

where:

- $V_{\text{out}}$  is the output voltage,
- $V_{\text{in}}$  is the input voltage,
- $D$  is the duty cycle expressed as a percentage or fraction.

This equation shows that the output voltage decreases linearly with the reduction of the duty cycle. It underscores the importance of precisely adjusting the duty cycle to achieve the desired output voltage.

#### 4.2.2 Application of the Formula to Different Duty Cycle Values

To illustrate the impact of the duty cycle on the output voltage, consider a few scenarios with a fixed input voltage of 40V:

- **For D=0.5 (50%):**

$$V_{\text{out}} = 0.5 \times 40V = 20V$$

At a duty cycle of 50%, the output voltage is reduced by half compared to the input voltage.

- **For D=0.75 (75%):**

$$V_{\text{out}} = 0.75 \times 40V = 30V$$

With a duty cycle of 75%, the output voltage is three-quarters of the input voltage.

- **For D=0.25 (25%):**

$$V_{\text{out}} = 0.25 \times 40V = 10V$$

A duty cycle of 25% reduces the output voltage to a quarter of the input voltage.

- **For D=0.1 (10%):**

$$V_{\text{out}} = 0.1 \times 40V = 4V$$

A duty cycle of 10% significantly minimizes the output voltage to only 10% of the input voltage.

These examples clearly illustrate that adjusting the duty cycle has a significant influence on the output voltage of the Buck converter. However, it is crucial to note that very low duty cycle values might not be practical due to switching dynamics and associated losses. Careful design and simulation are necessary to optimize the duty cycle according to the specific requirements of the application while minimizing risks and inefficiencies.

### 4.3 Limits and Practical Realities

This section examines the practical constraints of Buck converters, highlighting the differences between theoretical results and actual performance, as well as the various factors that influence the efficiency and reliability of these devices.

#### 4.3.1 Theoretical vs. Practical Comparison

Theoretical calculations of Buck converters provide an idealized estimation of the output voltage based on perfect operating assumptions, where components have no losses and conditions are optimal. However, in practice, several factors lead to significant deviations between theoretical results and actual measurements:

- **Inherent Losses:** Components such as inductors, capacitors, and transistors have internal resistances and inefficiencies that generate power losses in the form of heat. For example, the resistance of the inductor and conduction losses in the transistor effectively lower the output voltage compared to theoretical predictions.
- **Switching Dynamics:** The transitions between the ON and OFF states of the transistor are not instantaneous. These switching delays introduce additional losses and can affect the stability of the output voltage, especially at high switching frequencies.
- **Signal Stability:** The presence of noise and fluctuations in the input voltage or load can alter the performance of the Buck converter, affecting its ability to maintain a stable output voltage.

#### 4.3.2 Factors Influencing Performance

Several key factors determine the efficiency and performance of a Buck converter under real conditions:

- **Component Selection:** Choosing high-quality components that are appropriate for the required specifications is crucial. For example, an inductor with low series resistance and high saturation capacity will help minimize losses and improve the dynamic response of the converter.
- **Circuit Design:** A careful design that minimizes trace lengths on the PCB and optimizes the layout of components can reduce Joule effect losses and electromagnetic interference, thereby enhancing overall efficiency.

- **Thermal Management:** Given that power losses result in an increase in component temperature, efficient heat management is essential to maintain the reliability and longevity of the converter. Using heat sinks, cooling plates, and good ventilation are key strategies.
- **Duty Cycle Adjustment:** Precise adjustment of the duty cycle according to load conditions and input voltage is vital to optimize performance. An improperly adjusted duty cycle can lead to unstable or insufficient output voltage.
- **Surge Protection:** Protection circuits such as voltage regulators and protection diodes can prevent damage from accidental voltage spikes, thus ensuring the safety and durability of the converter.

In conclusion, although Buck converters offer an efficient method to reduce voltage, their performance in practice strongly depends on the circuit design, the quality of components used, and the management of operational conditions. A thorough understanding of these factors allows for maximizing efficiency while minimizing risks and failures.

## 5 Buck Circuit Configuration

### 5.1 General Circuit Description

The circuit of a Buck converter is designed to effectively reduce the output voltage below the input voltage. It consists of several key components whose arrangement is crucial for optimal operation. Here is an introduction to the main components of the Buck circuit and their configuration:

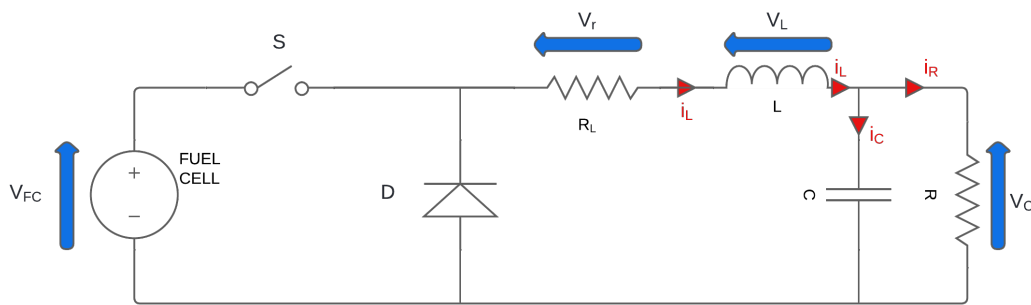


Figure 4: Buck Circuit Diagram

- **Inductor (L):** The inductor is an essential component of the Buck converter, used to store energy when the transistor is on and to supply it to the load when the transistor is off. It must have sufficient capacity to handle high currents without saturation while minimizing magnetic losses.
- **Switch (S):** Typically a transistor, such as a MOSFET or an IGBT, that functions as the main switch of the circuit. It is controlled by a PWM signal that adjusts the duty cycle, thereby controlling the amount of energy transferred from the input to the output.
- **Freewheeling Diode (D):** This diode allows current to continue flowing through the load and capacitor when the transistor is off, thus preventing current from returning to the source. It must handle the output currents without incurring excessive losses.
- **Capacitor (C):** The capacitor plays a critical role in stabilizing the output voltage by smoothing out variations due to the switching cycles of the switch. It must have adequate capacity to maintain a stable voltage at the load with minimal ripple.
- **Load (R):** The load connected to the circuit varies according to the application. It receives energy from the capacitor and its performance depends on the stability of the provided output voltage.

This configuration allows the Buck converter to provide a reduced output voltage relative to the input voltage, suitable for applications requiring a lower voltage for their operation. Understanding the role and arrangement of each component is crucial to optimize circuit design and ensure its efficiency and reliability under various usage conditions.

## 5.2 Analysis of the ON State

### 5.2.1 ON State Loop Configuration

In the ON state of the Buck converter, the switch is closed, allowing current to flow through the inductor. During this phase, we identify a main loop in the circuit: the loop including the inductor, the source, and the load.

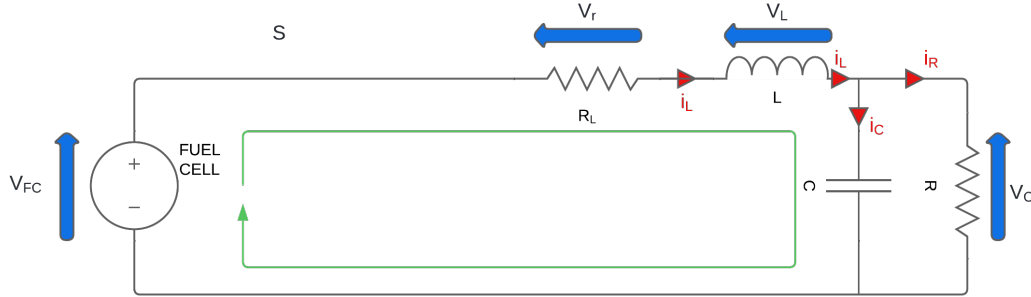


Figure 5: Buck Circuit Diagram in ON State

#### Main Loop:

- For this loop, we apply Kirchhoff's Voltage Law (KVL), which states that the sum of the voltages in the loop must be zero:

$$V_{FC} - V_R - V_L - V_C = 0$$

which gives us

$$V_{in} - i_L R_L - L \frac{di_L}{dt} - V_C = 0$$

where  $R_L$  represents the inductor resistance.

- Rearranging the terms, we have:

$$\frac{di_L}{dt} = \frac{V_{FC} - i_L R_L - V_C}{L}$$

Thus, integrating this relationship, we obtain:

$$i_L(t) = \int \frac{V_{FC} - i_L(t) R_L - V_C}{L} dt \quad (11)$$

This equation describes how the current in the inductor increases over time, thereby storing magnetic energy. This current is used to directly power the load while the switch is closed.

#### Second Loop (Capacitor and Load):

- Although primarily inactive during the ON state, it is crucial to note that any change in the inductor's current must be compensated by the capacitor's current in the OFF state, according to Kirchhoff's Current Law:

$$i_L = i_C + i_R$$

where  $i_R$  is the load current.

- Rearranging the terms, we have:

$$\frac{dV_C}{dt} = \frac{i_L - i_R}{C}$$

Thus, integrating this relation, we obtain:

$$V_C(t) = \int \frac{i_L - i_R}{C} dt \quad (12)$$

This equation will be fully active upon the opening of the switch, allowing the transfer of energy from the inductor to the capacitor and the load.

This systematic method of analysis using fundamental electrical formulas and the application of Kirchhoff's laws allows for a precise understanding of the behavior of the Buck circuit in the ON state and prepares the groundwork for an effective transition to the OFF state.

### 5.3 Analysis of the OFF State

Before starting the specific analysis of the OFF state of the Buck converter, it is useful to recall some essential electrical formulas that will govern our study; some are the same as in the ON state and therefore will not be reiterated here:

- **Freewheeling Diode:** In the OFF state, the freewheeling diode becomes conductive, allowing the current from the inductor to continue flowing to the capacitor and the load:

$$V_D = 0$$

#### Configuration of the Single Loop in the OFF State

In the OFF state, the Buck circuit presents a simplified configuration with a single main active loop, which includes the inductor, the freewheeling diode, and the capacitor. This configuration simplifies our analysis by focusing solely on this loop.

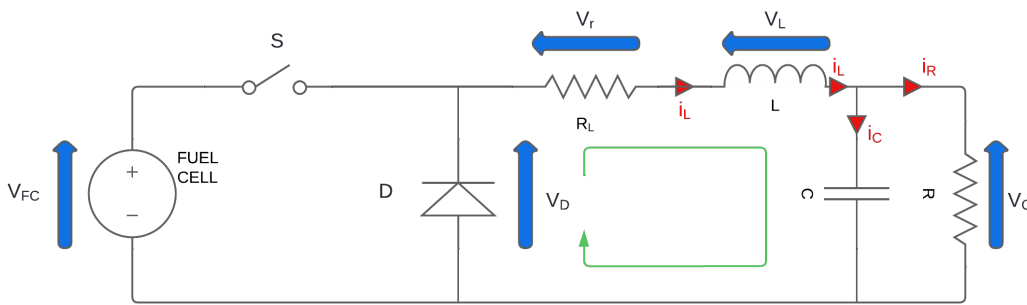


Figure 6: Buck Circuit Diagram in OFF State

#### Application of Kirchhoff's Voltage Law (KVL):

- By applying Kirchhoff's Voltage Law to this loop, we formulate the following equation:

$$V_D - V_r - V_L - V_C = 0$$

Since the diode ideally has no significant voltage drop ( $V_D \approx 0$ ), the equation simplifies to:

$$V_r + V_L + V_C = 0$$

which gives us

$$i_L R_L + L \frac{di_L}{dt} + V_C = 0$$

- Rearranging the terms, we get:

$$\frac{di_L}{dt} = \frac{-i_L R_L - V_C}{L}$$

Thus, integrating this relationship, we obtain:

$$i_L(t) = \int \frac{-i_L R_L - V_C}{L} dt \quad (13)$$

This relationship shows the decrease of current in the inductor and its impact on the voltage across the capacitor.

#### Derivation of the Fourth Equation with Kirchhoff's Current Law (KCL):

- To complete our analysis for the OFF state, we apply Kirchhoff's Current Law at the point where the inductor's current divides between the capacitor's current and the load:

$$i_L = i_C + i_R$$

where  $i_R$  is the current through the load.

- Rearranging the terms, we have:

$$C \frac{dV_C}{dt} = i_L - i_R$$

Thus, integrating this relationship, we obtain:

$$V_C(t) = \int \frac{i_L - i_R}{C} dt \quad (14)$$

This equation illustrates how the capacitor's voltage is affected by the inductor's current and the load current, thereby stabilizing the output voltage when the switch is open.

These established equations for the OFF state allow us to precisely calculate how energy is conserved and distributed in the Buck circuit, ensuring an efficient transition between ON and OFF states and stabilizing the output voltage for reliable applications.

## 5.4 Solving the Equations

The key equations governing the operation of Buck converters in the ON and OFF states are crucial for understanding and predicting the circuit behavior under different operating conditions. We describe here the four main equations, initially without the duty cycle factor ( $d$ ), and then explain how to integrate this factor into the equations to reflect Pulse Width Modulation (PWM) control.

### The Various Equations:

1. **Inductor Current Equation for the ON State ( $i_L$ ):**

$$\frac{di_L}{dt} = \frac{V_{FC} - i_L R_L - V_C}{L} \quad (15)$$

This equation, derived from Kirchhoff's Voltage Law, describes the accumulation of current in the inductor when the switch is closed, where  $V_{in}$  is the input voltage,  $R_{on}$  is the switch resistance, and  $V_C$  is the voltage across the capacitor.

2. **Capacitor Voltage Equation for the ON State ( $V_C$ ):**

$$\frac{dV_C}{dt} = \frac{i_L - i_R}{C} \quad (16)$$

This formula explains how the voltage on the capacitor is affected by the inductor current and the load current while the switch is closed.

3. **Inductor Current Equation for the OFF State ( $i_L$ ):**

$$\frac{di_L}{dt} = \frac{-i_L R_L - V_C}{L} \quad (17)$$

This equation illustrates the decrease of current in the inductor when the switch is open, influencing the voltage across the capacitor.

4. **Capacitor Voltage Equation for the OFF State ( $V_C$ ):**

$$\frac{dV_C}{dt} = \frac{i_L - i_R}{C} \quad (18)$$

This formula shows the rate of charging of the capacitor based on the inductor current and the load current, determining the stability of the output voltage when the switch is open.

## Integrating the Duty Cycle into the Equations

The duty cycle ( $d$ ) is a key parameter in managing a Buck converter, adjusting the proportion of time the switch is closed. Integrating ( $d$ ) into the above equations can be done in the following way to more accurately reflect PWM control:



- **Modifying the Equations for the ON State:**

$$\frac{di_L}{dt} = \frac{(d)V_{FC} - i_L R_L - V_C}{L} \quad (19)$$

$$\frac{dV_C}{dt} = \frac{i_L - i_R}{C} \quad (20)$$

These adjustments help to understand how the duty cycle influences the energy distribution of the circuit, particularly how the fraction of time during which the switch is activated ( $d$ ) affects the output voltage and the charging of the capacitor.

These modifications with the factor ( $d$ ) demonstrate how precise duty cycle management can optimize the performance of the Buck converter, controlling the output voltage and maximizing the energy efficiency of the system.

## 6 Conclusion

This practical work on Boost and Buck converters has allowed for an in-depth exploration of the operating principles, theoretical calculations, and practical realities of these essential devices in power electronics. By addressing both types of converters, we have been able to understand how they manipulate DC voltage to meet the varied needs of electronic applications, whether it is to increase or decrease the output voltage relative to the input voltage.

### Synthesis of Learning

1. **Operating Principles:** The Boost converter increases the output voltage above the input voltage, while the Buck converter reduces it. Their operation relies on the efficient use of inductors, capacitors, diodes, and transistors or switches controlled by PWM.
2. **Theory and Calculations:** The equations developed for each state (ON and OFF) in the Boost and Buck circuits illustrate how voltage and current are regulated. The importance of the duty cycle as a key parameter for adjusting the output voltage has been highlighted, showing its direct influence on circuit performance.
3. **Limits and Practical Realities:** The lab sessions revealed that, despite theoretical predictions, the actual performance of converters is often limited by factors such as inherent component losses, switching dynamics, and electromagnetic interference. These elements underscore the importance of careful design and rigorous component selection.

### Implications and Future Applications

The skills and knowledge acquired in this lab are crucial for students and professionals in electronics and electrical engineering, as they equip participants with the necessary tools to design and implement solutions based on efficient energy converters tailored to modern energy needs.

### Perspectives

Continuing to explore these technologies by integrating advanced concepts such as multi-stage converters and digital control techniques can open new avenues for improving the efficiency, compactness, and reliability of power electronic systems. This will also prepare students to tackle more complex technical challenges and to innovate in the field of power electronics.

In conclusion, this lab has not only reinforced the technical understanding of Boost and Buck converters but also set the stage for future explorations in broader and more demanding applications, building on a solid foundation of theory and practice.