INTERNATIONAL BURCH UNIVERSITY

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

# Synchronous and Bidirectional DC–DC Converters

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## ABSTRACT


DC-DC converters have a crucial role in converting unregulated DC voltage from sources like rectifiers, batteries, and renewable energy sources into regulated DC voltage with defined outputs.

They are used in switched mode power supplies (SMPS), DC motor controllers, battery chargers, and renewable energy systems. Synchronous DC-DC converters boost efficiency by decreasing conduction losses. The do this at low output voltages by using MOSFETs for active rectification. Both the high-side and low-side switches (transistors) are actively controlled to optimize efficiency. Conventional synchronous converters use diodes, leading to increased power losses.

Bidirectional DC-DC converters, which can transfer power in both directions, are essential for tasks such as battery management systems in electric vehicles, energy storage, and regenerative braking. These converters can function in both boost and buck modes, giving flexibility in controlling energy flow. Combining synchronous and bidirectional functionalities together creates converters that are both highly efficient and adaptable, making them suitable for modern energy systems. Simulation tools are essential for designing and modifying both of these converter types.



**Keywords:** DC-DC Converters, Synchronous Converters, Bidirectional Converters, Power Electronics, Buck, Boost, Buck-Boost, Switch, MOSFET

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(Reference: CADENCE PCB SOLUTIONS. "Synchronous vs. Nonsynchronous DC/DC Conversion." Cadence PCB Solutions, https://resources.pcb.cadence.com/blog/synchronous-vs-nonsynchronous-dc-dc-conversion. Retrieved 22 May 2024.)

**FIGURE 7.** An Example of a Synchronous DC-DC Converters (LT8390)

(Reference: Craig Peacock. "LT8390 Synchronous Buck-Boost DC-DC Converter." CircuitMaker, 2019. https://circuitmaker.com/Projects/Details/Craig-Peacock-4/LT8390-Synchronous-Buck-Boost-DC-DC-Converter. Retrieved May 22, 2024.)

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(Reference: Zhan, David (2018). "Design Considerations for a Bidirectional DC/DC Converter." Renesas Electronics Corp., Principal Engineering Manager, Industrial Analog & Power Group.)

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(Reference: Lia, B. Y., Xu, C., Li, C., & Guan, Z. (2017). Working principle analysis and control algorithm for bidirectional DC/DC converter. Journal of Power Technologies, 97(4), 327–335.)

**FIGURE 10.** Bidirectional DC-DC Converter with Supercapacitor and BJT’s

(Reference: Perdigão, Marina & Trovao, Joao Pedro & Alonso, J.M. & Saraiva, Eduardo. (2015). Large-Signal Characterization of Power Inductors in EV Bidirectional DC–DC Converters Focused on Core Size Optimization. Industrial Electronics, IEEE Transactions on. 62. 3042-3051. 10.1109/TIE.2015.2402632.)

**FIGURE 11.** 4-Switch Bidirectional DC-DC Converter Waveform

(Reference: Zhan, David (2018). "Design Considerations for a Bidirectional DC/DC Converter." Renesas Electronics Corp., Principal Engineering Manager, Industrial Analog & Power Group.)

## LIST OF ABBREVATIONS

| | |
|---|---|
| **SMPS** | Switched Mode Power Supplies |
| **DC** | Direct Current |
| **MOSFET** | Metal-Oxide Semiconductor Field-Effect Transistor |
| **D** | Duty Cycle |
| **PWM** | Pulse-Width Modulation |
| **BJT** | Bipolar Junction Transistor |

# 1. INTRODUCTION

DC-DC converters are designed to convert unregulated voltage source into a regulated DC voltage source whose output is specified. They are classified into three main categories, that is:

- Step down (buck) converter,

- Step up (boost) converter, and

- Step up-down with voltage inversion (buck-boost) converter.

Bidirectional DC-DC converters, can be implemented using different converter configurations, including buck, boost, and buck-boost configurations.

Synchronous DC-DC converters can be implemented within each of the three main categories (buck, boost, and buck-boost) to improve efficiency by replacing diode rectifiers with actively controlled switches, which are usually MOSFETs.

Bidirectional DC-DC converters, allow for power to be transferred in both directions and can be used in tasks like managing batteries in electric vehicles, storing energy, and operating regenerative braking systems. Bidirectional converters with both boost and buck modes manage energy flow according to the dynamic needs of energy systems. They offer flexibility in power flow direction, but this often comes at the cost of increased losses compared to synchronous converters, which operate primarily in a single direction.

One important development that improves efficiency in DC-DC conversion is the use of synchronous rectification. In the past, converters typically used diodes for rectification, which resulted in higher power losses. However, nowadays, synchronous converters use MOSFETs for active rectification, actively managing both high-side and low-side switches to improve efficiency, particularly at low output voltages. Synchronous converters are the preferred in applications where high efficiency and reduced conduction losses are crucial.

## 2. OVERVIEW OF DC – DC CONVERTERS

In DC – DC converters, energy conversion is performed in power stage of the converter. This stage is comprised of different switches, transformer, inductors and capacitors. The output voltage can be increased, decreased, or change its sign compared to the input voltage. This will determine the DC – DC converter type.

DC-DC converters work by switching a semiconductor device on and off, creating a rectangular waveform at the output. Figure 1 shows this principle. The average output voltage is controlled by adjusting the duty cycle (D), which is the ratio of the switch on-time to the total switching period.

D is the fraction of time that the switch spends in position 1, and is a number between 1 and 0, usually expressed in percentage. The formula for the output voltage is shown in Equation 1.

$$v_s = \frac{1}{T_s}\int_0^{T_s} v_s(t)dt = \frac{1}{T_s} D T_s V_g = D V_g$$

**EQUATION 1.** DC – DC Converter Output Voltage

By varying the duty cycle, the converter can either step up or step down the input voltage to the desired level. The process relies on the principles of inductor volt-second balance and capacitor charge-second balance to ensure a stable output. For resistive load, the capacitor will smooth out the voltage waveform, providing a more constant output voltage.

When the switch is on, the inductor stores energy from the input voltage, and when the switch is off, it releases this energy to the load. Small voltage ripples are usually neglected. All of this ensures proper steady state operation of these converters. If the switches are ideal, the output voltage is the same as the input voltage when we close the switch. The output voltage should be zero when switch state is open. But in reality, the voltage drop across switches is not zero when they conduct, and the switch actually goes through a linear state, which means we have losses. [1]

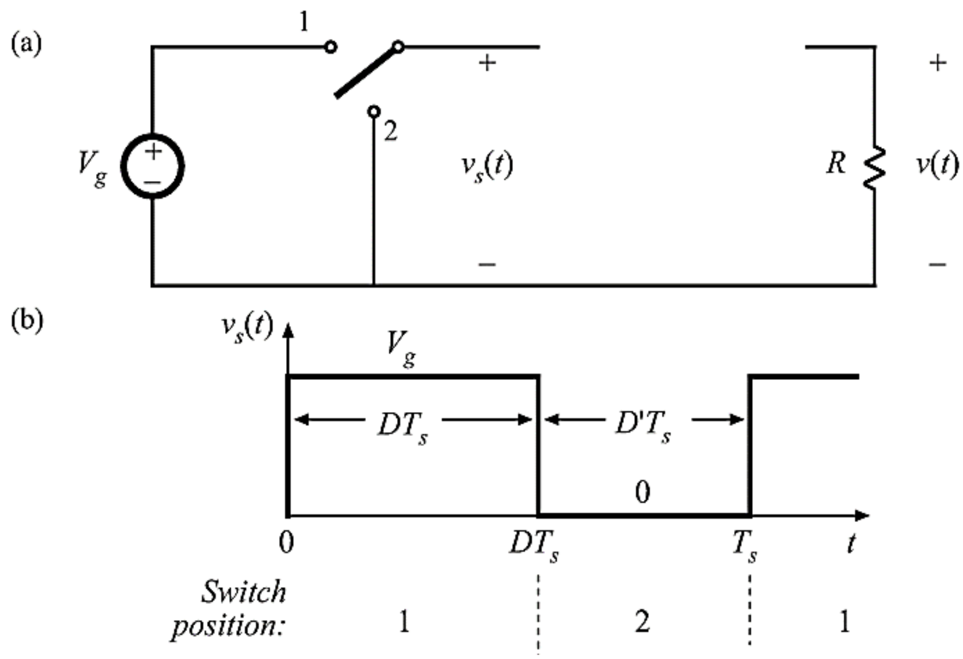


**FIGURE 1.** DC – DC Converter Circuit with its corresponding Output Voltage

(Reference: Erickson, R.W., Maksimović, D. (2020). Principles of Steady-State Converter Analysis. In: Fundamentals of Power Electronics. Springer, Cham.)

In the following subsections, boost, buck, and buck-boost converters will be discussed very briefly, in order for us to be able to understand synchronous and bidirectional DC-DC Converters.

## 2.1. Step - Up (Boost) Converter

From Figure 2, we observe a Boost Converter circuit. The voltage at the output will be increased compared to the input voltage. The operation of a boost converter can be categorized into two modes, Mode 1 and Mode 2. In Mode 1, which starts when the transistor $M_1$ is turned on at time t = 0, the input current increases and passes through the inductor L and transistor $M_1$. Mode 2 begins when transistor M1 is turned off at time t = $t_1$. [2]

During this mode, input current flows through the inductor L, capacitor C, the load, and diode $D_m$.

The current through the inductor decreases until the next cycle begins, with energy stored in inductor L being delivered to the load. The expression for output voltage is given in Equation 2. It shows how the output voltage is directly related to the duty cycle.

$$V_O = \frac{1}{1-D} V_S$$

**EQUATION 2.** Boost Converter Output Voltage

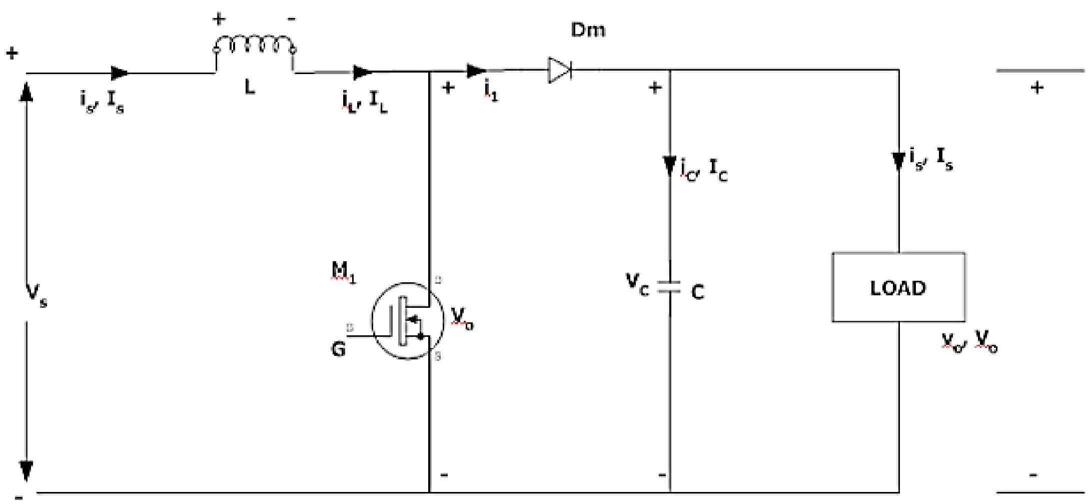


**FIGURE 2.** Boost Converter Circuit

(Reference: Fathah, A. (2013). Design of a Boost Converter. In: Bachelor of Technology Thesis, Department of Electrical Engineering, National Institute of Technology Rourkela. National Institute of Technology Rourkela, Rourkela-769008 (ODISHA).

## 2.2. Step – Down (Buck) Converter

The operation of a buck converter involves two modes based on the position of the switch. In the first mode, when switch is closed, current flows from the supply voltage through the inductor to the load, causing the inductor to charge. During this time, diode D is in reverse bias, preventing current from passing through it. The inductor reduces current ripple, resulting in a smoother output.

As the output voltage reaches desired level, the switch opens, and diode D becomes forward-biased. The inductor then maintains the current flow through the load resistor, discharging its stored energy as its current decreases. [3] Before the inductor fully discharges, the switch closes again, diode D turns off, and the cycle repeats for continuous current flow through the load. The circuit equivalent to this type of converter is shown in Figure 3. The output voltage of buck converter is directly related to the duty cycle once again, as shown in Equation 3.

$$V_O = DV_{in}$$

**EQUATION 3.** Buck Converter Output Voltage

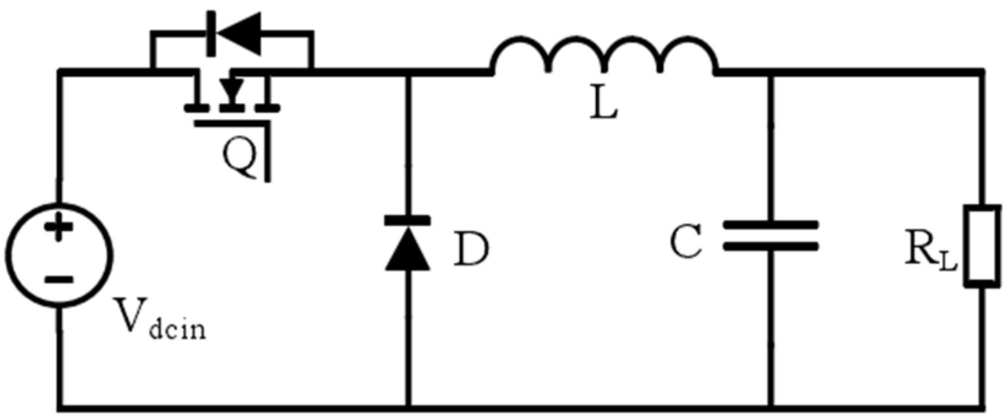


**FIGURE 3.** Buck Converter Circuit

(Reference: Li, Zhongkui & Rong, Qingfeng. (2023). Research on Transmission Efficiency Optimization of WPT System. Journal of Physics: Conference Series. 2525. 012024. 10.1088/1742-6596/2525/1/012024. )

### 2.3. Buck – Boost Converters

A buck-boost converter is a type of DC-DC converter that combines the principles of both buck and boost converters. It can produce an output voltage that is either greater or less than the input voltage, depending on the duty cycle of the switching component.

The operation of a buck-boost converter can be divided into two modes. Firstly, when the switch is turned on, the input voltage is applied across the inductor. The inductor stores energy by generating a magnetic field, causing the current through the inductor to increase. During this phase, the diode is reverse biased and isolates the output stage from the input.

When the switch is turned off, the inductor's magnetic field collapses, releasing the stored energy. The inductor current flows through the diode to the output capacitor and load. This energy transfer results in an increase in the output voltage. The output voltage polarity is inverted compared to the input voltage in a traditional buck-boost converter configuration.

An example of buck-boost converter is shown in Figure 4. Buck-boost converters have different variations, of which the following are the most common ones:

- **Non-Inverting Buck-Boost Converter** has a complex circuit design. It combines the functionalities of both buck and boost converters.

- **Inverting Buck-Boost** Converter is simple configuration where the output voltage is inverted. This variant involves only one MOSFET, and has smaller losses because of that.

- **Ćuk Converter** is a special type of buck-boost converter that offers advantages in terms of reduced ripple and improved efficiency.

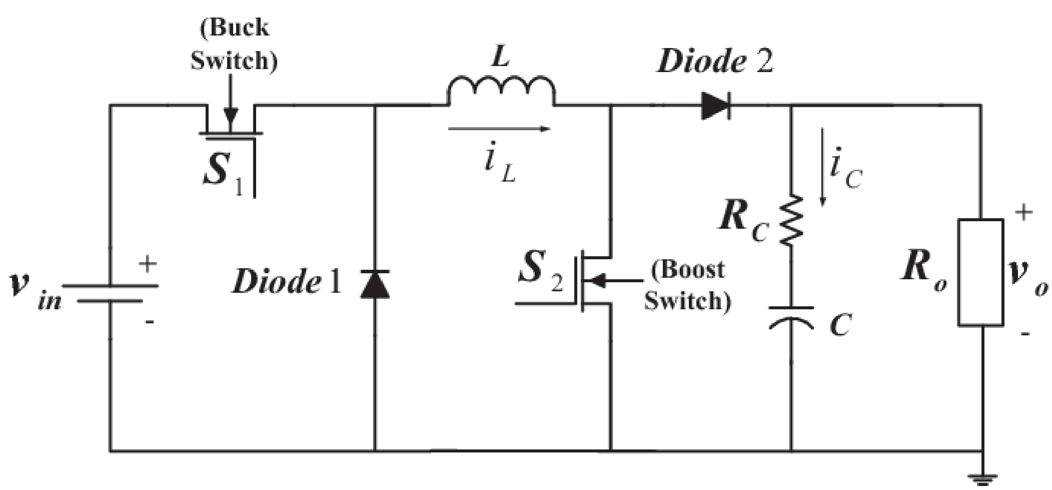


**FIGURE 4.** An Example of a Buck–Boost Converter

(Reference: Almasi, O.N., Fereshtehpoor, V., Khooban, M.H., & Blaabjerg, F. (2017). Analysis, control and design of a non-inverting buck-boost converter: A bump-less two-level T-S fuzzy PI control. ISA transactions)

## 3. SYNCHRONOUS DC-DC CONVERTERS

Synchronous DC-DC converters are using controlled switches instead of diodes for rectification. This approach is primarily used for reducing conduction losses and improving efficiency, especially at low output voltages. The synchronous DC-DC converter replaces the traditional diode with a low-resistance MOSFET, which is actively controlled to conduct during the specific phase of the switching cycle.

### 3.1. Design

As seen in Figure 5, two MOSFETS act as switch and there is no diode in this circuit, shown in Figure 5. One MOSFET is the high-side switch and the other one is low-side switch. Using MOSFETs without diodes will reduce conduction losses greatly.

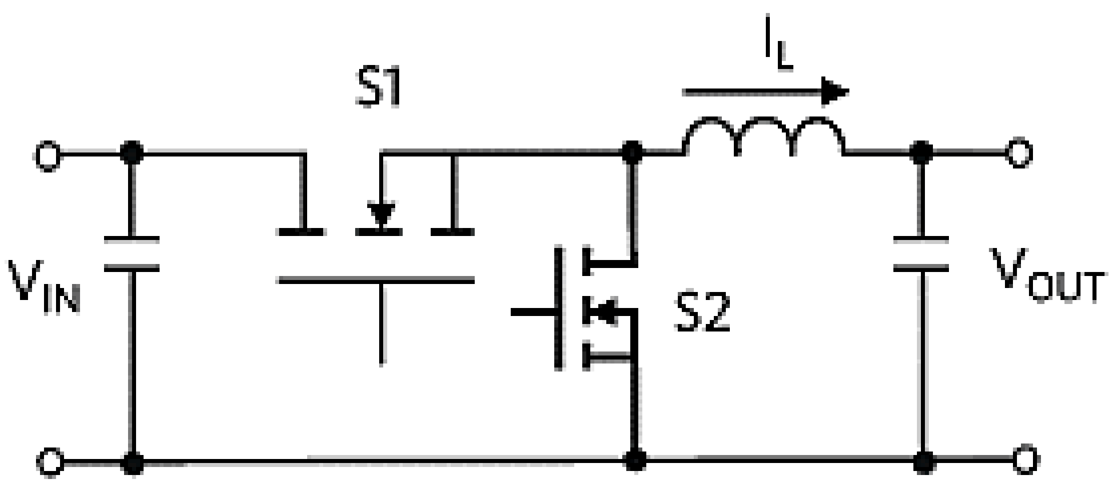


**FIGURE 5.** Synchronous DC-DC Converter Circuit

(Reference: Analog Devices (2016). "Synchronous or Nonsynchronous Topology? Boost System Performance with the Right DC-DC Converter." https://www.analog.com/en/resources/technical-articles/synchronous-or-nonsynchronous-topology-boost-system-performance-with-the-right-dcdc-converter.html . Retrieved May 22, 2024.)

Inductor and Capacitors are used as energy storage and for smoothing out the output. Inductor is placed after the second switch. The two capacitors are placed in parallel to the two voltages of interest. One is in parallel to the input, while the other one is in parallel to the load (output) voltage.

The inductor stores energy when current flows through it, while capacitor removes fluctuations in the output, providing a stable output voltage.

### 3.2. Operation

In each cycle, the high-side MOSFET is turned on to allow energy to flow from the input to the inductor and load. When the high-side MOSFET turns off, the low-side MOSFET is turned on, allowing the inductor to discharge and maintain current flow to the load. By using MOSFET instead of diode in this particular switch, switching losses are greatly reduced, which results in an increase in efficiency. [4]

The low-side MOSFET will conduct when the high-side MOSFET is off, greatly reducing the voltage drop compared to a diode and minimizes power losses. The duty cycle, which determines the output voltage, is defined by the time the high-side MOSFET is on compared to the total switching period. The same duty cycle principles would apply in nonsynchronous DC-DC converters. Various control methods, such as pulse-width modulation (PWM), are used to regulate the output voltage by adjusting the duty cycle of the switches.

From Figure 5 again, timing of the switching pulses sent to $S_1$ and $S_2$ controls our duty cycle. $S_1$ acts as a high-side MOSFET, while $S_2$ is low-side MOSFET.

The load will receive regulated output voltage. When $S_1$ is on, the input voltage is directly applied across the inductor. This means that the current will get to the load, through the inductor. The inductor will store energy by creating a magnetic field.

The capacitor is placed in parallel to the load, so it can help maintain a stable voltage. It does this by supplying current to the load. $S_2$ is off during this time, which means there is no path for conduction through it. $S_2$ is a semiconductor and it is reverse-biased during this cycle.

However, if we turn $S_1$ off, the current will no longer flow through, making it reverse-biased. $S_2$ will be turned on now, allowing the current to through it. Inductor current will be able to flow to the ground. All of the energy the inductor has stored, gets released. This will maintain the current flow to the load.

This inductor current will flow through $S_2$ to the load, maintaining the output voltage. In general, the inductor stores energy while $S_1$ is on and releases it as soon as $S_1$ turns off. As said, it makes sure that load is constantly provided with a steady current.

The capacitor is parallel to the load and it removes fluctuations from the output. It stabilizes the input voltage, giving the circuit a smooth supply. The output voltage is filtered by the capacitor. It makes the output stable and reduces any ripple.

Additionally, a concept of dead time is introduced. There is a short period during the changing states, when both $S_1$ and $S_2$ are on. This is known as dead time and is made to prevent potential short circuit faults. This makes sure that two MOSFETS are not conducting at the same time. [5]

### 3.2.1. Waveforms

General waveforms for the synchronous DC-DC Converter are observed in Figure 6.

The inductor current has a triangular shape. This shows us how the current increases and decreases during each switching cycle.

When $S_1$ ($Q_1$ in Figure 6) is on, the inductor current ($I_L$) will rise. This is because the energy inductor begins to store energy in its magnetic field.

When $S_2$ ($Q_2$ in Figure 6) is on, the inductor energy gets released to the load, meaning that the inductor current will drop. Since we have continuous conduction inside of the circuit, this current will never be zero.

Because of this, the duty cycle when $S_1$ is on, needs to longer than the duty cycle when it is off. Otherwise, the inductor current could potentially fall to zero.

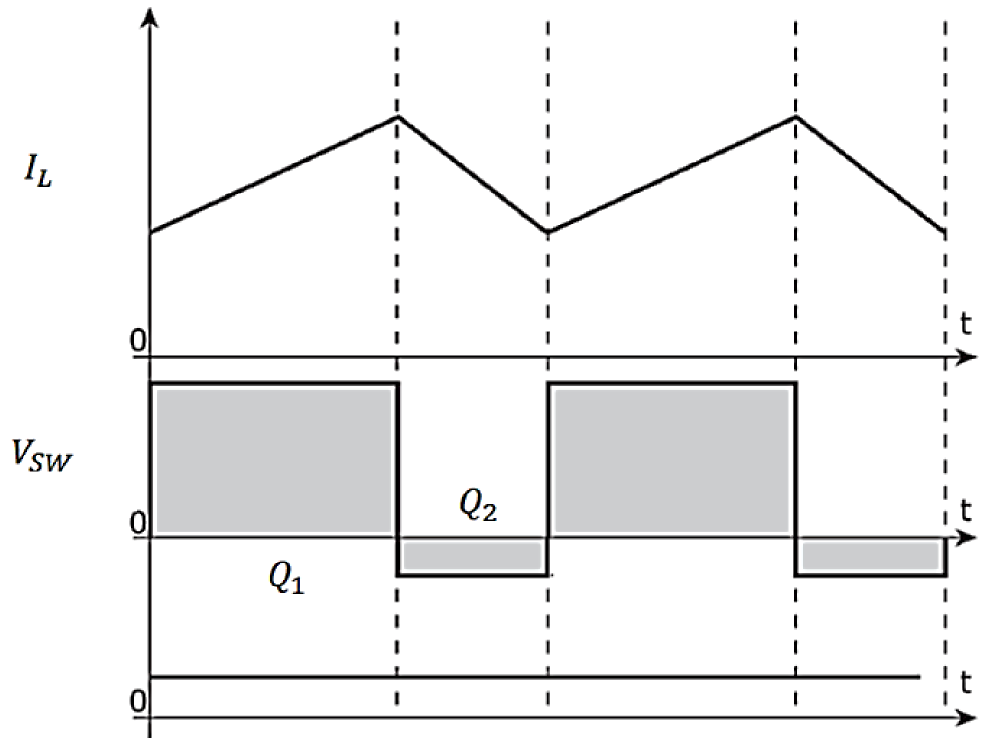


**FIGURE 6.** Voltage and Current Waveforms for Synchronous DC-DC Converter

(Reference: CADENCE PCB SOLUTIONS. "Synchronous vs. Nonsynchronous DC/DC Conversion." Cadence PCB Solutions, https://resources.pcb.cadence.com/blog/synchronous-vs-nonsynchronous-dc-dc-conversion. Retrieved 22 May 2024.)

$V_{SW}$ is our switching voltage. It shows us the voltage at the switch node from Figure 5. This voltage is, of course, between the input voltage and the ground. When $Q_1$ is on, the switching voltage is HIGH, meaning that it is equal to the input voltage). This will cause the inductor current to start increasing linearly. To get a stable DC/DC converter, PWM is very often applied to avoid disruptions when storing energy. [6]

When $Q_1$ is off, $Q_2$ is on, meaning that the value of the switching voltage drops to near zero. This value is close to the ground voltage, but it is not exactly zero. This is due to the effects of all other circuit elements.

### 3.3. Real-Life Applications

Synchronous DC-DC Converters are primarily used in situations where high efficiency is required. This includes portable electronic devices like mobile phones, tablets and laptops. Battery life is crucial in these devices. Because of that, these converters need to maximize power efficiency.

Data control centers and servers also rely on synchronous DC-DC converters. Power efficiency needs to be maximized in order to reduce operational costs. This helps achieve a better power distribution. Additionally, the equipment will be much safer.

These converters are also used in low voltage applications, inside of embedded systems. Microprocessors, microcontrollers and small memory storing devices operate at very small voltage levels. Because of their size, power is efficiency is crucial for their optimal functioning.

Automotive industry also have synchronous DC-DC converters implemented inside of them, especially electric and hybrid vehicles. They are not only crucial for supporting different sensors, but they also ensure low heat generation in steering and battery management. Similar to automotive, these converters are also implemented in aerospace industry as well.

Additionally, medical equipment, telecommunication and industrial robotic very often use synchronous DC-DC converters to ensure the best possible power efficiency.

### 3.4. Advantages and Disadvantages

As mentioned, using MOSFETs instead of diode will reduce conduction losses greatly. MOSFETs have advanced control techniques, leading to lower switching losses as well. Since the losses are reduced, this means that less heat is generated, reducing the need for cooling systems.

Due to low voltage drop across components, they are very efficient in converting low input voltage to even lower output voltage. Additionally, transient response is very fast with excellent voltage regulation under different loading conditions. Their design is compact, as seen in Figure 7.

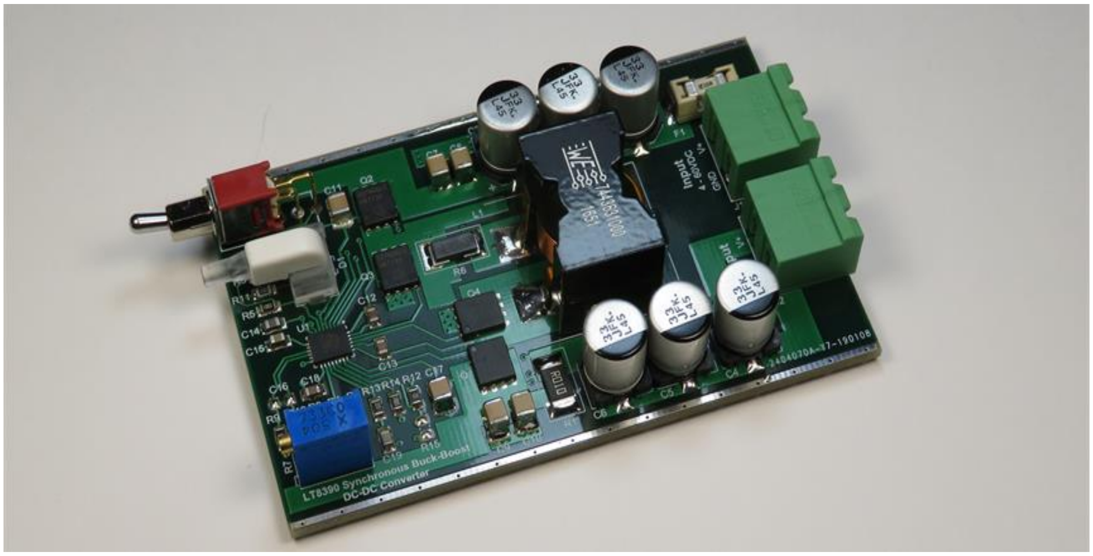


**FIGURE 7.** An Example of a Synchronous DC-DC Converters (LT8390)

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The converters in Figure 7 is specifically used for powering laptops, computers and televisions from different batteries.

However, synchronous DC-DC converters have certain disadvantages and constraints that come with using them. Designing control equipment for the MOSFETs can be extremely challenging, since it is very difficult to ensure the proper protection from short circuits.

That is why the concept of dead time is difficult to design. We know that the MOSFETs cannot operate at the same time. High-quality MOSFETs with their complementary circuitry are expensive, and because of that, designers often settle for cheaper solutions like diodes.

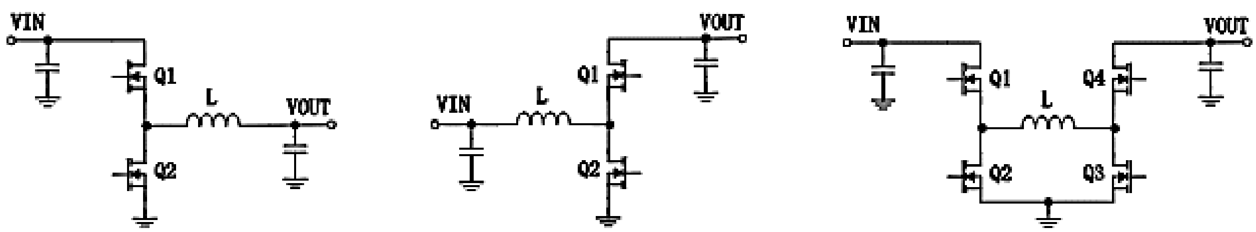
Additionally, testing all equipment inside of these converters can be expensive and time-consuming as well. Since they have extremely complex design, these converters naturally have much more potential fault points, compared to simpler converter designs.

# 4. BIDIRECTIONAL DC-DC CONVERTERS

Bidirectional DC-DC converters transfer power in both directions, and are essential for tasks like battery management systems in electric vehicles, energy storage, and regenerative braking. These converters function in both boost and buck modes, giving flexibility in power flow control.

Bidirectional converters can be of three main types: buck, boost, and buck-boost. Buck-boost converter can be implemented with 2 or 4 switches and are the most common bidirectional DC-DC converters. The three possible variations are represented in Figure 8. We understand how buck-boost converter can run in both directions, but how do buck or boost converters achieve that?

Buck converter can run as boost converter, but in opposite direction. Similarly, a boost converter can run as a buck converter in the opposite direction. [7]

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(Reference: Zhan, David (2018). "Design Considerations for a Bidirectional DC/DC Converter." Renesas Electronics Corp., Principal Engineering Manager, Industrial Analog & Power Group.)

## 4.1. Design

Bidirectional DC-DC converters can have two possible topologies. Supercapacitor backup system is used strictly with buck-boost converter, while battery charge/discharge system can be used with all three converter types.

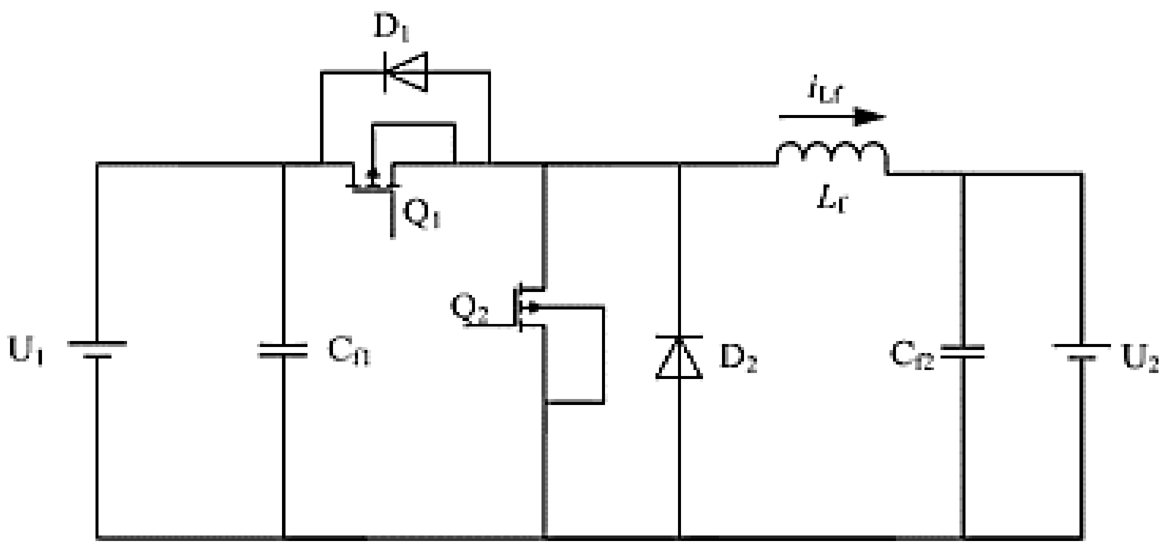



**FIGURE 9.** 2-Switch Bidirectional DC-DC Converter Circuit

(Reference: Lia, B. Y., Xu, C., Li, C., & Guan, Z. (2017). Working principle analysis and control algorithm for bidirectional DC/DC converter. Journal of Power Technologies, 97(4), 327–335.)

Since they are the most common type of bidirectional DC-DC converter, because of their ability to both step up (boost) and step down (buck) the voltage when needed, Buck-Boost Converters are used as practical example to explain operating principle of bidirectional DC-DC converter systems.

Additionally, switches are implemented in a form a MOSFET, or in a form of a MOSFET and a Diode. The combination of the two is used when we need to achieve high power density at low frequency. Additionally, Inductor is used for storing energy, while the Capacitor is placed in parallel to the output, so it can smooth it out.

Supercapacitor stores energy statically, allowing for much higher capacitances and energy amount to be stored inside of it. We are operating either in in boost mode for traction operation, or in buck mode for regenerative braking. [8]

Finally, since this is a buck-boost converter, an inverter is placed at the load. This inverter, alongside the buck-boost converter makes Powertrain of a system, which is responsible for managing the conversion and flow of electricity.

## 4.2. Operation

### 4.2.1. 4-Switch Bidirectional Converter

When talking about 4-switch bidirectional buck-boost DC-DC converter, its operating modes depend on the relationship between the DC bus voltage $V_{IN}$ and the battery voltage $V_{OUT}$. This circuit is observed in Figure 8-C.

Initially, the DC bus voltage will be higher than the battery voltage. The converter will thus operate like a synchronous buck converter. Switch $Q_4$ is turned on, while $Q_3$ is turned off. Switches $Q_1$ and $Q_2$ are directly linked to the duty cycle. This situation enables the converter to step down the higher input DC voltage, so the batteries gets charged effectively.

Naturally, in buck-boost converters, there comes a cycle when $V_{IN}$ is lower than $V_{OUT}$. The converter will operate as a boost converter. $Q_1$ is on, while $Q_2$ will be off. The duty cycle will control $Q_3$ and $Q_4$. In this case, the lower DC input voltage is stepped up, so the battery gets charged effectively.

The DC input voltage can get relatively close to the battery voltage. $Q_4$ and $Q_1$ switches are controlled the reversed way, compared to the buck state. This enables the converter accordingly step up or step down the input voltage in order to match the battery voltage.

We thus observe three possible relations between the input and output voltages. Input voltage can be greater, lower or equal to the output voltage. Switch states can be adjusted accordingly if there is a need for coming back to a certain state. This happens if the battery (output) voltage value is not the desired one. [9]

Inductors store the energy in the form of magnetic field when current flow through them. When there is a cycle where no current flows, this energy is released so the output has stable current.

Capacitors in this circuit store the energy during period of high voltage and release it when that voltage drops. The capacitor placed in parallel to the output removes voltage fluctuations and ensures a smooth and stable output voltage waveform. They also act effectively as filters, filtering out any potential ripples and noise that might occur in the circuit.

#### 4.2.2. 2-Switch Bidirectional Converter

The 2-switch bidirectional converter consists of two switches $Q_1$ and $Q_2$, along with two diodes $D_1$ and $D_2$. During the high state of voltage input, switch $Q_1$ controls the flow of electricity. The appropriate circuit is shown in Figure 9, which was already discussed earlier.

During the low state of voltage input, switch $Q_2$ controls the flow of electricity. When $Q_1$ is on, $Q_2$ will be off, and the converters will be in buck mode. The current flows through $Q_1$ and diode $D_2$, stepping down the voltage value.

When $Q_2$ is on, $Q_1$ is turned off, and the converters will be in boost mode. The current flows through $Q_2$ and diode $D_1$, stepping up the voltage value. The voltage value is boosted.

However, as in synchronous converters, some sort of timing control is required for us to ensure that the two switches are not on at the same tame. This concept is known as dead time and is made to prevent potential short circuit faults. [5]

This inductor current flows through $Q_2$ to the load, maintaining output voltage. The inductor stores energy while $Q_1$ is on and releases it as soon as $Q_1$ turns off. It makes sure that load is constantly provided with a steady current.

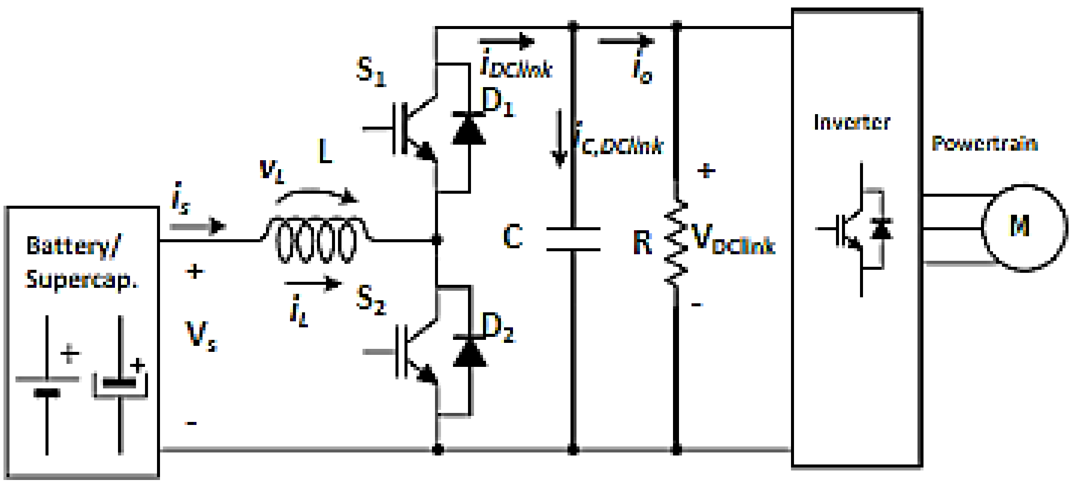
The capacitor is parallel to the load and it removes fluctuations from the output. It stabilizes the input voltage, giving the circuit a smooth supply. The output voltage is filtered by the capacitor. It makes the output stable and reduces any ripple.

As observed, the circuit in Figure 9 is similar to the one in Figure 5, which is synchronous DC-DC converter. This proves what we already know, and that is the fact that a bidirectional converter often has similarities to synchronous DC-DC converters. These converters often have complementary functionalities and advantages. However, Figure 9 implements diodes, while Figure 5 does not have diodes placed in parallel to both synchronous MOSFETs.

Additionally, a slightly different representation of circuit in Figure 9 is shown in Figure 10. This implementation includes BJT's (Bipolar Junction Transistors) and Supercapacitor.

The inverter is coupled with the converter itself to make the powertrain. It controls power flow and specific power values inside a system.

PWM and Supercapacitors can often be used to regulate the voltage values. Supercapacitors are capable of storing great amounts of energy. [4] PWM regulates the duty cycle based on the desired converter's behavior. This ensures efficient operation in both buck and boost modes.

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## 4.3. Waveforms

According to the 4-switch bidirectional buck-boost DC-DC converter, shown in Figure 8-c, the following waveforms can be shown. They are depicted in Figure 11.

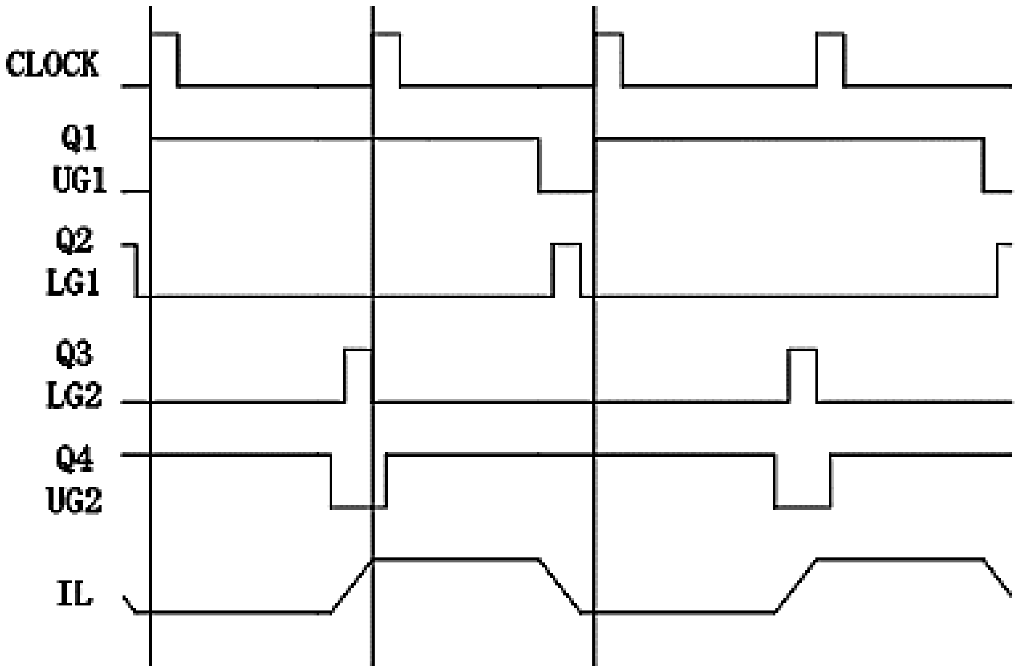


**FIGURE 11.** 4-Switch Bidirectional DC-DC Converter Waveform

(Reference: Zhan, David (2018). "Design Considerations for a Bidirectional DC/DC Converter." Renesas Electronics Corp., Principal Engineering Manager, Industrial Analog & Power Group.)

Initially, the clock signal is low, $Q_1$ and $Q_3$ are low, while $Q_2$ and $Q_4$ are high. Two pairs of switches maintain a continuous state for two clock cycles, meaning that every two clock cycle they change their state from on to off, or from off to on.

Moreover, every clock cycle, one pair of switches changes their state, either, $Q_1$ and $Q_2$ or $Q_3$ and $Q_4$. Both pairs cannot conduct at the same time, otherwise there will be a short circuit.

Inductor current becomes zero eventually after the end of switch-off. It is in continuous state. [10]

$I_L$ is the inductor current, which stores energy inside of its magnetic field for one duty cycle, and it releases it during the other. During a short clock cycle it either increases energy storage linearly, or decreases it, meaning that it began releasing energy to the load.

### 4.4. Real-Life Applications

Bidirectional DC-DC converters are used in applications where power needs to flow bidirectionally. The applications are found in storage systems, electric vehicles, grid inverters, as well as renewable energy systems. Battery charging applications are especially common.

There are data centers which require constant data flow without interruptions, and the use of bidirectional converts will often be suitable for those applications, even more than synchronous DC-DC converters. Additionally, power backup is something that is essential as well.

These converters allow the energy to be efficiently transferred between different voltage levels and storage devices. Power backup is extremely important as well, and we have already mentioned backup modes in bidirectional DC-DC converters. If certain voltage needs to be additionally lowered or increased, we can do it easily.

### 4.5. Advantages and Disadvantages

Bidirectional converters with both boost and buck modes manage energy flow according to the dynamic needs of energy systems. They offer flexibility in power flow direction. They are suitable for applications like energy storage systems, electric vehicles, and renewable energy setups, where power needs to flow bidirectionally.

Energy storage devices manage charge and discharge processes separately, each with its own powertrain. However, there are applications where rapid changes of state are required. Additionally, using diodes will increase conduction losses significantly. That is why, the use of MOSFET is much better since they have the feature of synchronous rectification. [11]

Bidirectional converters are usually more complex, requiring additional electronic components and control systems, which can increase both the complexity and cost of the system. However, in general, it is hard to determine whether or a bidirectional converter is advantageous our not, since it depends on the specific application.

# 5. CONCLUSION

This seminar paper provides a detailed analysis and discussion regarding the synchronous and bidirectional DC-DC converters, focusing on their actual operating principles alongside implementations in real life. Firstly, we had do dive into the general concepts of DC-DC converters. This was done to have a basic understanding of these devices.

Synchronous converters, using MOSFETs, offer improved efficiency by minimizing conduction losses, particularly at low output voltages. They have fast transient response, excellent voltage regulation, and compact design, making them ideal for small and portable applications. However, challenges like complex equipment design, expensive MOSFETs, and potential fault points are constraints to their wider implementation.

On the other hand, bidirectional converters play a crucial role in facilitating bidirectional power flow, crucial for applications like energy storage systems, electric vehicles, and renewable energy systems. Diodes can be used in these circuits, but their implementation increases conduction losses significantly. During the analysis of the two converter types, despite their clear differences, it was easily concluded that they have certain similarities and complementary features.

Since bidirectional converters require efficient power conversion in buck and boost modes, the implementation of synchronous rectification improves their performance by minimizing losses and improving overall efficiency. Combining bidirectional and synchronous functionalities in DC-DC converters creates systems that are both highly efficient and flexible.

While offering flexibility in power flow direction, bidirectional converters require additional electronic components and control systems, increasing cost and complexity.

The application of synchronous or bidirectional converters depends on specific application requirements, alongside factors such as efficiency, complexity, and cost to achieve optimal performance in modern energy systems.

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