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Closed Loop Control of SEPIC Converter Using dSPACE

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A B S T R A C T

DC-DC converters are used to increase (boost) or decrease (buck) battery voltages to accommodate the voltage needs of motors of electric vehicles and many other applications including communication equipment and power supplies for personal computers. Among the dc–dc converters, single-ended primary inductor converters (SEPIC) are widely used in applications where low ripple current is desired at the input and output terminals of the converter. The control actions needed to keep a specific variable of the converter under control, in this paper we are going to control the converter using dSPACE (digital signal processing and control engineer). The implementation of the proposed scheme is done using MATLAB/Simulink environment and the model will control the output voltage.

Keywords: *Proportional–integral (PI) control, single ended primary-inductor converter (SEPIC), sliding mode control (SMC)*

1. Introduction

A DC-DC converter is an electrical circuit that changes the amount of DC power. Modern electronic systems now require DC-DC converters because they are used to power a variety of devices, from tiny battery-powered gadgets to massive industrial uses. DC-DC converters are used for a variety of reasons, including voltage regulation, power conversion, isolation, and noise reduction. They can also be used to increase power system effectiveness, especially in battery-powered apps where getting the most out of the batteries is crucial. Using a switching circuit, DC-DC converters first transform the incoming DC energy into a high-frequency AC voltage. An inductor or transformer transforms this high-frequency AC voltage after which it is filtered to create the intended output voltage.

Based on their structure, or how the incoming voltage is converted into the output voltage, DC-DC converters can be categorised. The closed loop control of the SEPIC converter is described in this article."SEPIC converters are essential in regulating the power transfer between the battery and the drivetrain in electric cars. As needed for the motor driver and other components, they are used to scale up or step down the battery voltage. Electric cars that use SEPIC converters benefit from greater energy economy, longer battery life, and superior thermal control, among other things. Managing the elevated voltage of the battery pack is one of the major difficulties with electric cars. High power can be risky, particularly in the event of an accident or other emergency. SEPIC converters can help mitigate this risk by providing galvanic isolation between the battery and the motor controller. This can reduce the risk of electric shock and fire hazards. Another advantage of SEPIC converters in electric vehicles is their ability to regulate the output voltage even when the input voltage is greater than or less than the output voltage. This is important for maintaining the stability and reliability of the electrical system, especially when the battery voltage is fluctuating due to changes in load or temperature SEPIC converters also offer better noise immunity compared to other DC-DC converters, which is important in electric vehicles where noise can affect the performance of electronic components. Because closed loop control of SEPIC converters is crucial for ensuring stable and dependable power supply in electric vehicles, closed loop control of SEPIC converters is addressed in this article. A feedback loop is used in a closed loop control system to manage the converter's output voltage by changing the duty cycle of the switching circuit. This helps to compensate for any changes in the input voltage, load current, or other external factors that can affect the output voltage.In electric vehicles, closed loop control of SEPIC converters is necessary to maintain the stability and reliability of the electrical system.

2. Literature review

The CF-RSSMCC method is commonly used in power electronics to control the output current of DC-DC converters like Cuk converters, which are widely used due to their high efficiency and versatility. However, their nonlinear and time-varying nature presents challenges in regulating the output current. The CF-RSSMCC method addresses this issue by utilizing a sliding mode controller to regulate the current while reducing the switching frequency of the converter The CF-RSSMCC technique has two main stages: the inner current control loop and the outer voltage control loop. The inner loop regulates the current, while the outer loop regulates the output voltage. The sliding mode controller, which is a robust nonlinear control technique, is used in the inner loop to achieve accurate and fast current regulation. It works by forcing the system state to follow a sliding surface that is a function of the desired and measured output, and then uses the sliding mode to regulate the system state to the desired value while keeping the system on the sliding surface CF-RSSMCC is widely used in industrial automation, electric cars, and green energy systems. This is because it can efficiently step up or down the incoming voltage and maintain precise current regulation, even in the presence of parameter variations and disturbances. [1].

To decrease the output voltage ripple in sepic converters, an enhanced topology can be implemented by incorporating a coupled inductor in the converter circuit. This inductor can store energy, thereby reducing the voltage ripple on the output side of the converter. Furthermore, adjusting the converter's switching frequency using a control algorithm that is dependent on the input voltage can also minimize the output voltage ripple. By implementing these improvements, the sepic converter's performance can be more dependable and consistent. As a result, the power output can become more stable and reliable. [2].

To attain power decoupling in a bridgeless cuk PFC rectifier, a control method can be employed. This technique utilizes a modified dual-loop control system that regulates both the input power factor and output voltage. The system consists of an inner current control loop and an outer voltage control loop. The voltage control loop adjusts the duty cycle of the converter to regulate the output voltage, while the current control loop ensures that the input current remains sinusoidal and in phase with the input voltage. By decoupling the power factor and voltage regulation, the system can attain high efficiency and low output voltage ripple. This control method is well-suited for high-power applications like electric vehicles and renewable energy systems, where optimal performance requires efficient power conversion. [3].

For high-power applications, a family of single-phase voltage double high power factor sepic rectifiers operating in DCM (discontinuous conduction mode) can be a viable option. These rectifiers double the input voltage and then rectify it to produce a DC output voltage. Operating in DCM allows for reduced switching losses and improved efficiency at light loads. A power factor correction (PFC) stage, integrated into the sepic converter, helps to achieve high power factor and low harmonic distortion. Additionally, a control circuit regulates the output voltage and ensures stable operation. These features make this family of rectifiers suitable for applications such as LED lighting, motor drives, and power supplies. By optimizing the design and improving the performance of these rectifiers, they can provide a cost-effective and reliable solution for various high-power applications. [4].

A sepic converter-based fast-acting DC electronic load can offer a cost-effective and efficient solution for safeguarding power supplies and batteries against overvoltage or overcurrent conditions. The sepic converter is utilized to convert the input DC voltage into a high-frequency AC signal that is rectified and used to drive a resistive load. The load can be tailored to provide precise and accurate current or power limiting, which prevents the output voltage of the power supply or battery from surpassing safe levels. One of the significant advantages of this load is its fast response time, which enables it to rapidly limit the output current or power in case of an overvoltage or overcurrent event. As a result, it safeguards the power supply or battery from any potential damage. Additionally, the load is easily integrated into existing test setups and can be remotely controlled through a computer or other interface. [5].

Nonlinear control techniques for sepic converters are a topic of active research, owing to their potential to enhance the performance of these converters. One such method is the sliding mode control, which offers robust and accurate control of the sepic converter across a wide range of operating conditions. In this technique, a sliding surface is defined to ensure that the converter operates within a desired operating region, while a sliding mode control law is utilized to ensure that the output voltage and current are regulated to their intended values. Another approach is the adaptive control, which can modify the controller parameters in real-time to compensate for variations and uncertainties in the converter parameters. This technique can boost the stability and efficiency of the sepic converter under diverse load conditions. In addition, intelligent control methods like fuzzy logic and neural networks can enable the sepic converter to learn from its operating conditions and adapt to changes in the load or input voltage. Taken together, these nonlinear control methods of sepic converters can enhance their performance, decrease their sensitivity to variations and uncertainties, and increase their reliability and efficiency. [6].

An advanced control method for regulating the output voltage and current of a sepic converter is the PWM integral sliding mode control with high-frequency operation. This method combines the benefits of PWM integral sliding mode control, which provides faster convergence and less chattering in the control loop, with the advantages of high-frequency operation, such as reduced component size and weight and improved efficiency. By using the PWM integral sliding mode controller, the output voltage and current of the sepic converter can be precisely regulated. Advanced control algorithms, such as digital signal processors or microcontrollers, can also be utilized to further improve the performance of the converter and enable precise control of its parameters. This technique can be particularly useful in applications where high efficiency and precise control are essential, such as in electric vehicles or renewable energy systems. [7].

The sliding mode control technique is commonly used for analyzing and controlling chaotic behavior in power electronic converters like the Sepic converter. This method involves defining a sliding surface that limits the chaotic behavior of the system and designing a controller that steers the system towards this surface. For Sepic converters, sliding mode control has proven effective in curbing chaos, minimizing output voltage ripple, and enhancing the converter's transient response. However, analyzing and designing sliding mode controllers for Sepic converters can be complex due to the converter's nonlinear characteristics. Despite this, the resulting improvements in stability and performance make the approach worthwhile. [8].

3. DC-DC CONVERTERS

3.1 BUCK CONVERTER

A buck converter is a type of DC-DC converter that is used to step down the input voltage to a lower output voltage. It is a popular converter topology because it is simple, efficient, and inexpensive.

Here's how it works:

- The input voltage is applied to the buck converter circuit. This voltage is first applied to a switch (S1) in series with an inductor (L1) and a diode (D1).
- The switch (S1) is controlled by a pulse-width modulation (PWM) signal. The PWM signal turns the switch on and off at a specific frequency. When the switch is on, the input voltage is applied to the inductor (L1) and the inductor stores energy. When the switch is off, the inductor releases its energy to the output capacitor (C1) and a load (RL).
- When the switch is on, the inductor (L1) charges up and stores energy in the form of a magnetic field. The voltage across the inductor is equal to the input voltage. The current through the inductor increases linearly.
- When the switch turns off, the inductor releases its stored energy to the output capacitor and the load. The energy stored in the magnetic field of the inductor causes the current to continue flowing through the inductor, even though the switch is open. The voltage across the inductor reverses, and the current through the inductor decreases linearly.
- During the off time of the switch, the voltage across the output capacitor (C1) decreases due to the current flowing into the load. The voltage across the capacitor is also charged by the energy released by the inductor. The voltage across the capacitor is equal to the output voltage.
- The output voltage is regulated by controlling the duty cycle of the PWM signal that controls the switch. By varying the duty cycle of the PWM signal, the amount of energy transferred from the input to the output can be controlled.
- The buck converter is capable of producing an output voltage that is lower than the input voltage. The output voltage can be calculated using the following formula: Vout = Duty Cycle x Vin, where Vin is the input voltage, Vout is the output voltage, and Duty Cycle is the ratio of time the switch is on to the total switching period.

Overall, the buck converter is a useful DC-DC converter for applications where a regulated output voltage that is lower than the input voltage is required. It is widely used in a variety of electronic devices, such as computers, mobile phones, and power supplies.

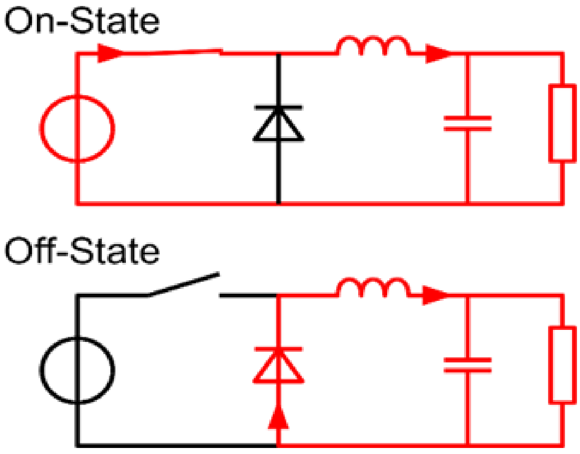

Fig 3.1 The two circuit configurations of a buck converter: on-state and off-state

3.2 BOOST CONVERTER

A boost converter is a type of DC-DC converter that is used to step up the input voltage to a higher output voltage. It is a popular converter topology because it is efficient and can provide a high voltage gain.

Here's how it works:

- The input voltage is applied to the boost converter circuit. This voltage is first applied to a switch (S1) in series with an inductor (L1) and a diode (D1).
- The switch (S1) is controlled by a pulse-width modulation (PWM) signal. The PWM signal turns the switch on and off at a specific frequency. When the switch is on, the input voltage is applied to the inductor (L1) and the inductor stores energy. When the switch is off, the inductor releases its energy to the output capacitor (C1) and a load (RL).
- When the switch is on, the inductor (L1) charges up and stores energy in the form of a magnetic field. The voltage across the inductor is equal to the input voltage. The current through the inductor increases linearly.

- When the switch turns off, the inductor releases its stored energy to the output capacitor and the load. The energy stored in the magnetic field of the inductor causes the current to continue flowing through the inductor, even though the switch is open. The voltage across the inductor reverses, and the current through the inductor decreases linearly.
- During the off time of the switch, the voltage across the output capacitor (C1) increases due to the energy released by the inductor. The voltage across the capacitor is also charged by the energy flowing from the input voltage source through the diode (D1) and the inductor (L1). The voltage across the capacitor is equal to the output voltage.
- The output voltage is regulated by controlling the duty cycle of the PWM signal that controls the switch. By varying the duty cycle of the PWM signal, the amount of energy transferred from the input to the output can be controlled.
- The boost converter is capable of producing an output voltage that is higher than the input voltage. The output voltage can be calculated using the following formula: Vout = Vin / (1 - Duty Cycle), where Vin is the input voltage, Vout is the output voltage, and Duty Cycle is the ratio of time the switch is on to the total switching period.

Overall, the boost converter is a useful DC-DC converter for applications where a regulated output voltage that is higher than the input voltage is required. It is widely used in a variety of electronic devices, such as LED drivers, battery chargers, and power supplies.

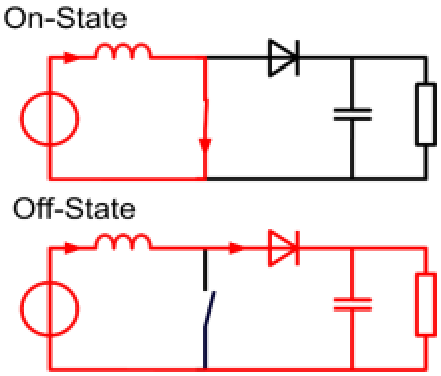

Fig 3.2 The two current paths of a boost converter, depending on the state of the switch S

3.3 BUCK-BOOST CONVERTER

A buck-boost converter is a type of DC-DC converter that can step down or step up the input voltage to a lower or higher output voltage, respectively. It combines the features of both the buck converter and the boost converter topologies. Here's how it works:

- The input voltage is applied to the buck-boost converter circuit. This voltage is first applied to a switch (S1) in series with an inductor (L1) and a diode (D1).
- The switch (S1) is controlled by a pulse-width modulation (PWM) signal. The PWM signal turns the switch on and off at a specific frequency. When the switch is on, the input voltage is applied to the inductor (L1) and the inductor stores energy. When the switch is off, the inductor releases its energy to the output capacitor (C1) and a load (RL).
- When the switch is on, the inductor (L1) charges up and stores energy in the form of a magnetic field. The voltage across the inductor is equal to the input voltage. The current through the inductor increases linearly.
- When the switch turns off, the inductor releases its stored energy to the output capacitor and the load. The energy stored in the magnetic field of the inductor causes the current to continue flowing through the inductor, even though the switch is open. The voltage across the inductor reverses, and the current through the inductor decreases linearly.
- During the off time of the switch, the voltage across the output capacitor (C1) decreases due to the current flowing into the load. The voltage across the capacitor is also charged by the energy released by the inductor. The voltage across the capacitor is equal to the output voltage.
- If the output voltage needs to be higher than the input voltage, the switch (S1) is connected to an additional inductor (L2) in series with the output capacitor (C1) and a diode (D2). During the off time of the switch, the inductor (L2) charges up and stores energy in the form of a magnetic field. The voltage across the inductor is equal to the output voltage. The current through the inductor increases linearly.
- When the switch turns on, the energy stored in the magnetic field of the inductor (L2) is released to the output capacitor and the load. The voltage across the inductor reverses, and the current through the inductor decreases linearly. The diode (D2) ensures that the inductor current flows through the load.
- The output voltage is regulated by controlling the duty cycle of the PWM signal that controls the switch. By varying the duty cycle of the PWM signal, the amount of energy transferred from the input to the output can be controlled.

- The buck-boost converter is capable of producing an output voltage that can be lower or higher than the input voltage, depending on the duty cycle of the PWM signal. The output voltage can be calculated using the following formula: Vout = Duty Cycle x Vin for step-down mode, and Vout = (1 / (1 - Duty Cycle)) x Vin for step-up mode, where Vin is the input voltage, Vout is the output voltage, and Duty Cycle is the ratio of time the switch is on to the total switching period.

Overall, the buck-boost converter is a useful DC-DC converter for applications where a regulated output voltage that can be higher or lower than the input voltage is required. It is widely used in a variety of electronic devices, such as battery chargers, LED drivers, and power supplies.

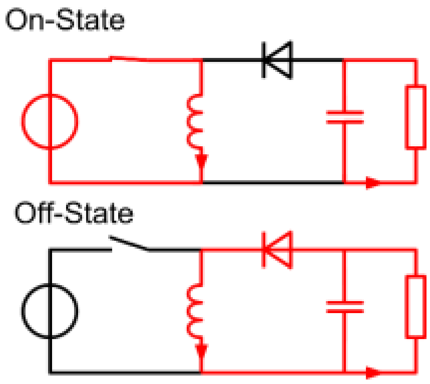

Fig 3.3 The two operating states of a buck–boost converter

3.4 CUK CONVERTER

The Cuk converter, which is a type of DC-to-DC converter, is known for its ability to minimize fluctuations in current. It achieves this by utilizing a shared capacitor and a single switching mechanism, making it a hybrid of a boost and buck converter. Like a buck-boost converter with an inverting configuration, a Cuk converter's output voltage can either be greater or lesser than the input voltage. In conventional DC converters, the inductor plays a major role in energy storage. However, in the Cuk converter, the capacitor is the primary energy-storage component.

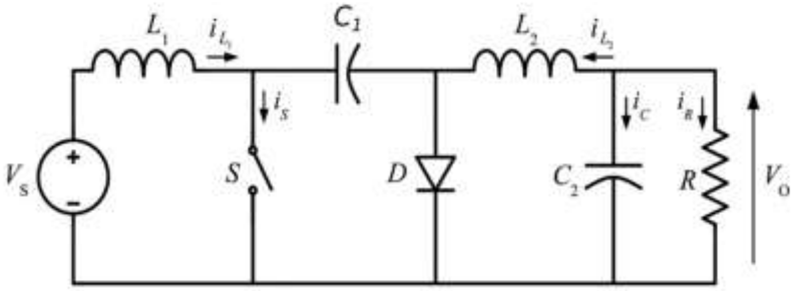

Fig 3.4 CUK Converter Circuit Diagram

There are several variations of the Cuk conversion that differ from the typical setup. For example, if the coils share a single magnetic core, output fluctuations can be reduced and efficiency can be increased. The capacitor enables constant power transmission and as a result, this type of converter produces low EMI. The Cuk converter uses a switch and a diode to enable energy transmission in both directions. Since it is an inverting converter, the output voltage has an opposite polarity to the input voltage. The converter's primary advantage is the steady currents at the input and output. However, the switch's excessive current stress is its main drawback.

3.5 SEPIC CONVERTER

A SEPIC converter (Single Ended Primary Inductor Converter) is a type of DC-DC converter that can step up, step down or invert an input voltage. It is a non-isolated converter, which means that there is no electrical isolation between the input and output. The SEPIC converter is designed to maintain a constant output voltage, regardless of changes in the input voltage or load current. It achieves this by regulating the duty cycle of a switch in a switching circuit, which in turn controls the amount of energy transferred from the input to the output. The SEPIC converter uses an inductor to store energy when the switch is on and release it when the switch is off. The inductor is connected in series with the input voltage source and a capacitor, which acts as an energy storage device. The output voltage is taken from the capacitor and the load, which is connected in parallel with the capacitor.

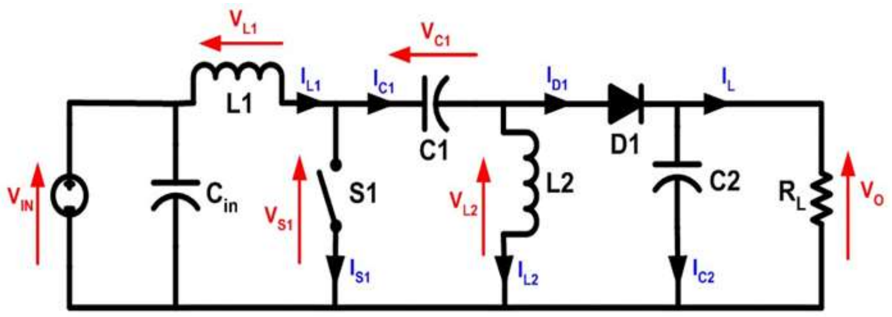

Fig 3.5 Schematic Diagram of SEPIC Converter

CIRCUIT OPERATION:

The SEPIC converter operates by using an inductor to store and transfer energy between the input and output stages of the converter. Here are the basic steps of how it works: During the first stage, the switch in the converter is turned on, which connects the input voltage source to the inductor. The inductor charges up with energy from the input voltage. Once the inductor has charged up, the switch is turned off. This causes the inductor to release the energy it has stored, which creates a voltage across the output capacitor and load. This voltage is lower than the input voltage, as the inductor effectively "steps down" the voltage. If the output voltage is lower than the desired value, the control circuit in the converter adjusts the duty cycle of the switch to increase the voltage transfer from the input to the output. This can be achieved by increasing the amount of time the switch is on, which allows more energy to be stored in the inductor before it is released to the output. Similarly, if the output voltage is higher than the desired value, the control circuit adjusts the duty cycle of the switch to decrease the voltage transfer from the input to the output. The output voltage is regulated by a feedback loop that continuously monitors the output voltage and adjusts the duty cycle of the switch accordingly. This ensures that the output voltage remains stable, even as the input voltage or load current varies. Overall, the SEPIC converter is a versatile and efficient DC-DC converter that can be used in a wide range of applications. Its ability to step up, step down or invert the input voltage, along with its stable output voltage regulation, make it a popular choice in many industries.

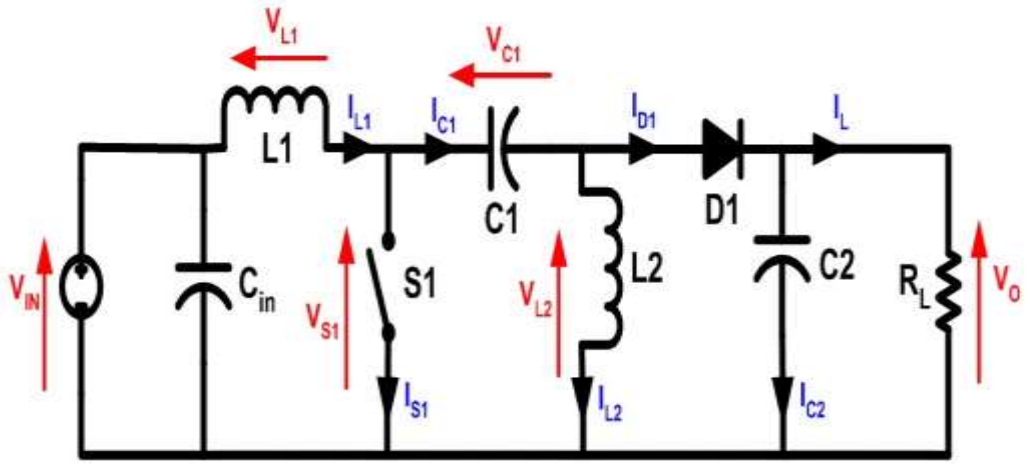

Fig 3.5 Schematic Diagram of SEPIC Converter

Continuous mode of operation:

Under continuous mode operation, the SEPIC converter works as follows:

- The input voltage is applied to the SEPIC converter circuit. This voltage is first applied to an inductor (L1) in series with a switch (S1). The switch can be a MOSFET or a BJT transistor.
- The switch (S1) is controlled by a pulse-width modulation (PWM) signal. The PWM signal turns the switch on and off at a specific frequency. When the switch is on, the input voltage is applied to the inductor (L1) and the inductor stores energy. When the switch is off, the inductor releases its energy to a capacitor (C1) and a load (RL).
- When the switch is on, the inductor (L1) charges up and stores energy in the form of a magnetic field. The voltage across the inductor is equal to the input voltage minus the voltage drop across the switch. The current through the inductor increases linearly.

- When the switch turns off, the inductor releases its stored energy to the load and the capacitor. The energy stored in the magnetic field of the inductor causes the current to continue flowing through the inductor, even though the switch is open. The voltage across the inductor reverses, and the current through the inductor decreases linearly.
- During the off time of the switch, the voltage across the capacitor (C1) decreases due to the current flowing into the load. The voltage across the capacitor is also charged by the energy released by the inductor. The voltage across the capacitor is equal to the output voltage.
- The output voltage is regulated by controlling the duty cycle of the PWM signal that controls the switch. By varying the duty cycle of the PWM signal, the amount of energy transferred from the input to the output can be controlled.
- The SEPIC converter can step up or step down the input voltage depending on the duty cycle of the PWM signal. If the duty cycle is greater than 50%, the output voltage will be greater than the input voltage. If the duty cycle is less than 50%, the output voltage will be less than the input voltage.

Overall, the SEPIC converter is a useful DC-DC converter for low-power applications where a regulated output voltage is required. Continuous mode operation is desirable because it allows for a smoother transfer of energy from the input to the output, resulting in less output voltage ripple.

Dis continuous mode of operation:

In the discontinuous mode of operation, the SEPIC converter operates in a similar way as it does in the continuous mode, but the inductor (L1) is allowed to fully discharge before the switch (S1) turns on again.

Here's how it works:

- Initially, the switch (S1) is turned on, and the inductor (L1) starts storing energy from the input voltage. The current through the inductor increases linearly.
- When the current through the inductor reaches a certain level, the switch is turned off. At this point, the inductor discharges its stored energy into the output capacitor (C1) and the load (RL). The current through the inductor decreases linearly to zero.
- Once the current through the inductor reaches zero, the switch (S1) turns on again, and the cycle repeats. The inductor begins to store energy again, and the current through it increases linearly until the switch is turned off.
- Because the inductor fully discharges during each cycle, the output voltage experiences more ripple compared to the continuous mode. However, the discontinuous mode can be more efficient for low-power applications because it allows the inductor to discharge completely, reducing losses.
- The output voltage can be controlled by adjusting the duty cycle of the PWM signal that controls the switch. By increasing the duty cycle, the output voltage can be increased, and by decreasing it, the output voltage can be decreased.

Overall, the SEPIC converter can operate in either continuous or discontinuous mode, depending on the application and design requirements. The discontinuous mode can be more efficient for low-power applications, but it may produce more output voltage ripple compared to the continuous mode.

4. MATLAB SIMULATIONS AND RESULTS OF SEPIC CONVERTER

4.1 MATLAB Simulink model

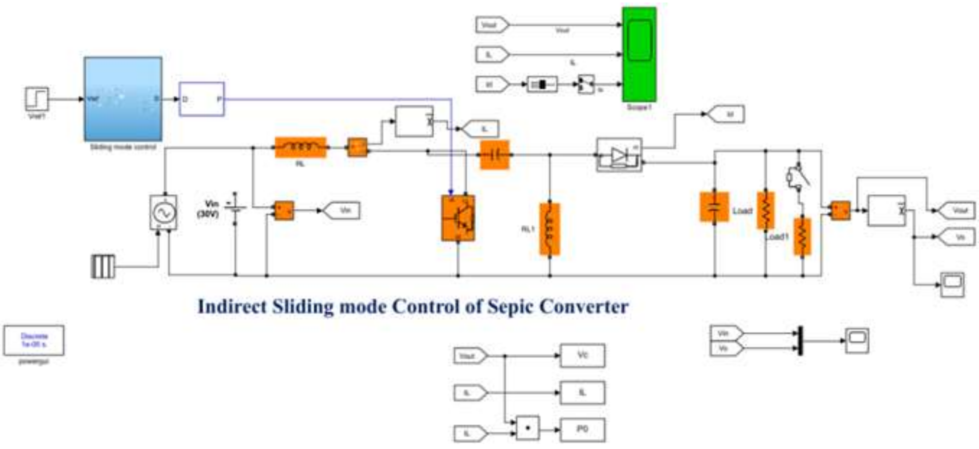

Fig 4.1 MATLAB Simulink model

4.2 MATLAB SIMULATION RESULTS:

PERFORMANCE AT CONSTANT LOAD AND CONSTANT VOLTAGE

The figure 4.2.1 illustrates the steady-state results of the input voltage (Vin), output voltage, and inductor currents in both the buck and boost modes, with a load resistance of 100. It is apparent from the graph that the output voltage is fixed at 48 V, indicating that the controller maintains the output voltage at its reference value. Furthermore, the figure demonstrates that the recommended control technique efficiently achieves both buck and boost modes of operation.

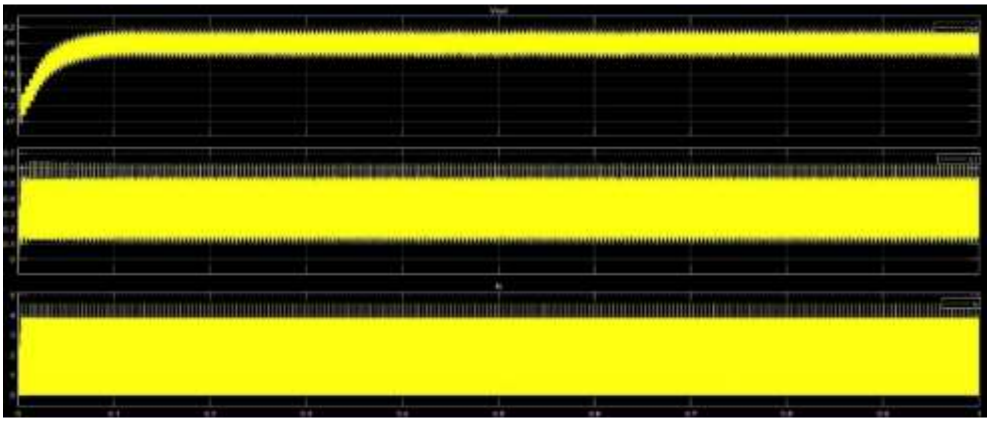

Fig 4.2.1 Performance with constant voltage and load

PERFORMANCE WITH CHANGE IN INPUTVOLTAGE

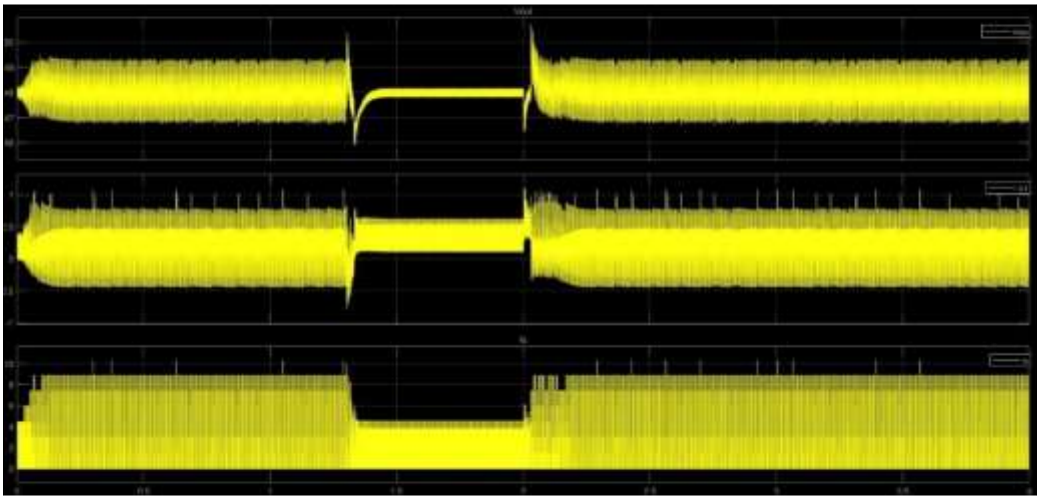

Fig 4.2.2 Performance with constant change in input voltage

Figure 4.2.2 shows fluctuations in the input voltage ranging from 60 V to 30 V and vice versa. It's worth noting that the converter operates in the buck mode when the input voltage is 60 V initially. However, as the input voltage drops from 60 V to 30 V, the converter switches from the buck mode to the boost mode. Similarly, when the input voltage increases from 30 V to 60 V, the converter switches back to the buck mode from the boost mode. To maintain a constant power supply to the load, the input current is adjusted in response to these mode transitions. The output voltage is efficiently regulated at 48 V, following its reference voltage.

Performance with changing load

Under 100% load variations, the suggested management strategy's effectiveness is also evaluated. when V_{out} = 48 V, there is a sudden shift in the load impedance. The weight was changed from 100 to 50 and then back to 100. The dynamic reactions as a result of these load variations are shown in Fig. 4.2.3.

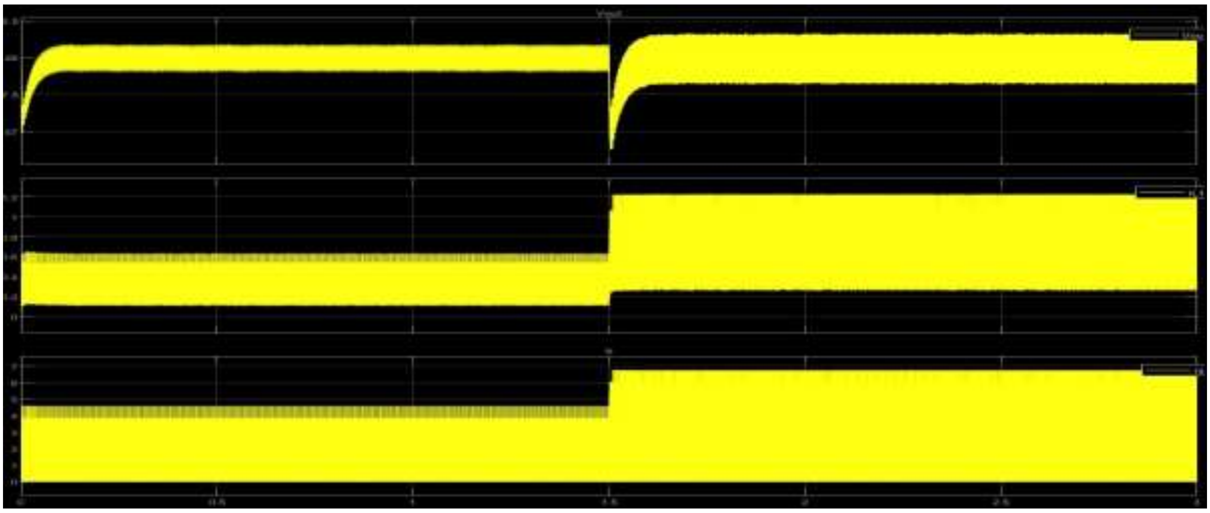

Fig 4.2.3 Performance with constant change load

CONCLUSION

A new method for controlling the output voltage of dc-dc SEPIC converters was proposed using an indirect sliding mode control (SMC) approach with a simplified sliding surface function that is dependent on the input current error. This method was shown to reduce design complexity and implementation costs. The area of the sliding mode's existence was determined for different PI gains, and a PI regulator was used to generate the input current reference. The proposed SMC technique was evaluated on a laboratory prototype converter operating in both buck and boost modes. The results demonstrated that this technique effectively regulated the output voltage, even under sudden changes in input voltage and load impedance. Theoretical issues were also considered.

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