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Analysis of the Effect of Supercapacitors on the Efficiency and Stability of Boost Converters in Photovoltaic Systems

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Abstract

This paper aims to demonstrate the energy efficiency improvements in a boost converter using supercapacitors and the Perturb and Observe (P&O) control method, particularly in the context of photovoltaic (PV) systems under partial shading conditions. Supercapacitors, known for their high energy density and rapid charge/discharge capabilities, are integrated into the boost converter circuit to mitigate voltage fluctuations and enhance energy storage efficiency. The PO control method is utilized to dynamically adjust the duty cycle of the MOSFET, ensuring the output voltage remains stable at the desired level of 70V, with an input voltage range of 30V to 60V. The study employs simulation techniques to evaluate performance improvements, focusing on energy efficiency and system stability when supercapacitors are used as filtering elements alongside advanced control strategies in PV systems experiencing partial shading. Simulation results indicate a significant reduction in voltage ripple and enhanced overall system efficiency, achieving a stable output voltage of exactly 70 volts. Specifically, the efficiency of the boost converter without a supercapacitor and Zener diode is 8.36%, while the configuration with a supercapacitor and Zener diode achieves 16.09% efficiency. Most notably, the configuration with a supercapacitor and without a Zener diode achieves an efficiency of 50.29%. The findings conclude that integrating supercapacitors and the PO control method in boost converters for PV applications substantially enhances energy efficiency and system stability, even under partial shading conditions

Keywords: Boost Converter, Perturb and Observe (P&O), Supercapacitor

1. Introduction

Solar panels are essential components for generating electricity from sunlight. This renewable energy source is highly favored because it can convert natural energy into electrical energy for daily activities. However, solar panels cannot operate independently; they require additional components such as maximum power point trackers (MPPT), batteries, and inverters. A boost converter is employed to increase the voltage so that the power output remains within specifications when delivered by the inverter. In a boost converter, pulse width modulation (PWM) signal control is required to increase the voltage, using a control method to achieve the desired set-point and provide an optimal PWM signal.

In this research, the boost converter's design is modified by replacing the traditional filter capacitor with a supercapacitor. This change aims to achieve a more stable output, ensuring the generated power can be optimized without excessive power loss during the voltage boosting process. Additionally, one of the key challenges in photovoltaic systems is partial shading, where portions of the solar panel array receive less sunlight due to obstructions such as clouds, trees, or buildings. Partial shading can cause significant fluctuations in the output voltage, leading to reduced efficiency and power losses. Traditional boost converters struggle to maintain voltage stability under these conditions, often resulting in suboptimal performance.

Existing boost converter designs often experience ripple in the output voltage, which can lead to power loss and instability for devices connected downstream. This paper proposes a new boost converter design that incorporates supercapacitors in place of conventional capacitors. The effectiveness of this new design is evaluated through simulations to compare its performance with traditional designs, especially under partial shading conditions. While previous studies have explored various methods to reduce voltage ripple and improve stability, including the use of advanced control algorithms and alternative passive components, the use of supercapacitors as a replacement for conventional capacitors in boost converters has not been extensively studied, particularly in the context of partial shading.

This research uniquely demonstrates that integrating supercapacitors not only enhances voltage stability but also significantly outperforms existing designs in terms of reducing voltage ripple and minimizing energy losses, even under partial shading conditions. By providing a comprehensive comparison with established methods, this study offers a novel approach that can be effectively utilized in practical applications, paving the way for more reliable and efficient energy systems. Additionally, there is a notable research gap in the integration of supercapacitors with the Perturb and Observe (P&O) control method, particularly in terms of improving system stability and power output. This study addresses this gap, showcasing the potential benefits of combining supercapacitors with advanced control techniques to optimize the performance of boost converters in photovoltaic systems, especially in scenarios involving partial shading.

2. System Design

2.1 Simulation Design

Block diagram of simulation for system can be seen in figure 1.

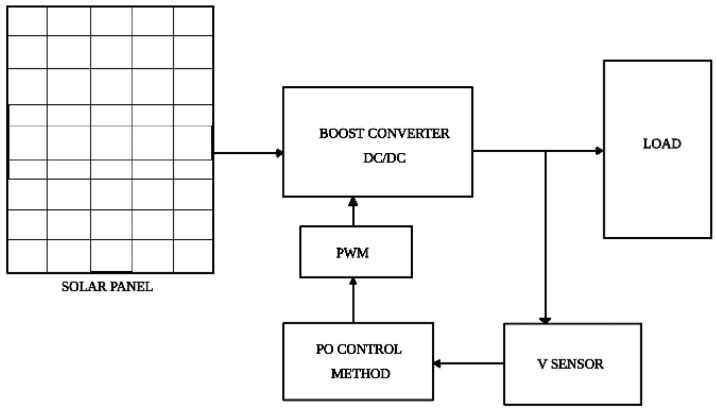

Figure 1. Block Diagram of Boost Converter System

Simulation of the system is conducted using the software with the specifications of the boost converter as shown in Table 1. The values of the components used in the system are calculated using formulas, such as those for the inductor and capacitor. These formulas aim to determine not the exact value of the component, but the minimum value required to ensure the system operates according to the desired specifications without unnecessarily increasing the component size.

Table 1. Specification of Solar Panel

Specification	Value
Number of solar cell	36
Maximum power (Pmax)	1000Wp
Maximum voltage (Vmax)	18V
Open Circuit voltage (Voc)	21,8V
Short Circuit Current (Isc)	6,05A
Maximum Current (Imax)	5,56A

Table 2. Boost Converter Specification

Specification	Value
Input voltage	20-72V_{dc}
Trigger Frequency	1Khz
Duty Cycle	10-90%
Load Resistance	400Ω
Inductor	30mH
Capacitor	300µF
Output voltage	70V
Output power	1000W

2.2 Boost Converter

The Boost Converter is a DC-DC voltage step-up circuit. The output voltage value can be increased by changing the duty cycle value in the switching of the boost converter circuit. One application of the boost converter circuit is in photovoltaic (PV) systems connected to the grid. The PV voltage is increased using the boost converter until it reaches a sufficient voltage level as the input voltage for the inverter. Subsequently, the inverter converts the DC voltage into AC voltage to be connected to the grid. the boost converter is connected to the solar panel for its source.

In this research, we compare systems with and without supercapacitors. The system with a supercapacitor can be seen in figure 4. Some supercapacitors cannot receive voltage above their specifications, so we compare the supercapacitor with and without a Zener diode. However, the difference is not significant, so it is tolerable for the supercapacitor to work with the voltage provided by the boost converter. Both systems, with and without supercapacitors, will receive feedback from the output to be optimized by the P&O control method, ensuring the output remains at 70V.

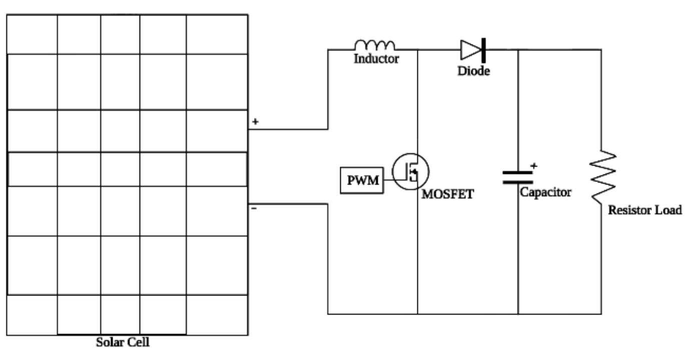

Figure 2. Boost Converter Circuit

The components that make up a boost converter include:

2.2.1 Solar Panels

The power sources for the circuit are solar panels, while batteries are used to supply power to the PWM control circuit and MOSFET driver.

2.2.2 Switch

The switching component used is the MOSFET. The selection of the MOSFET considers the voltage and current values of the converter. The MOSFET used is the IRFP4242PbF, which has a drain-source voltage (VDS) of 300 volts and a maximum drain current (ID) of 46 amperes. The IRFP4242PbF MOSFET is safe to use because the desired output voltage is 70 VDC, and the maximum supply current is 14.28 A.

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2.2.3 Diode

The diode used is the NTE5826. This diode is chosen because it is designed for high power applications. The NTE5826 diode has a maximum voltage capability of 400 volts and a current rating of up to 50 amperes, making it safe to use in the boost converter.

2.2.4 Inductor

The inductor used is a solenoidal inductor made from copper wire wound around a ferrite core. The inductance can be calculated using the following equation:

$$L_{min} = \frac{D_{min}(1 - D_{min})^2 R}{2f}$$
$$= \frac{0.1(1 - 0.9)^2.400}{2.1000}$$
$$= 16{,}2mH$$

In Continuous Conduction Mode (CCM), the inductance created must be greater than the minimum inductance. Therefore, the inductance used is 30 mH.

2.2.5 Capacitor

The capacitor functions as a filter to limit the output voltage ripple of the converter. The capacitor used in the design of this boost converter has a ripple of 1%. The capacitance value can be calculated using the following equation:

$$C_{min} = \frac{D_{max}}{\%V_r.R.f}$$
$$= \frac{90\%}{1\%.400.1000}$$
$$= \frac{0.9}{0{,}01.400.1000}$$
$$= 225\mu F$$

This converter is widely used for solar power generation and wind turbine applications. Its main components consist of MOSFETs, diodes, inductors, and capacitors. When the MOSFET switch is closed, current flows through the inductor, causing the energy stored in the inductor to increase. When the MOSFET switch is open, the current from the inductor flows to the load through the diode, causing the energy stored in the inductor to decrease. The ratio between the output voltage and the input voltage of the converter is proportional to the ratio between the switching period and the switch-off time.

2.2.6 Supercapacitor

The supercapacitor is used as a replacement for a capacitor. Both the supercapacitor and the capacitor have the same function, which is to filter the output that will be delivered from the

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boost converter. The difference between a supercapacitor and a regular capacitor lies in their operational durability and stability in providing output. The supercapacitor used in this research has a working voltage of 3 Volts, a capacitance of 100F, and can deliver a current of 11.7A. Since no supercapacitor specification can provide a voltage of 100V, the supercapacitors will be connected in series to achieve a working voltage of 70V. A total of 24 supercapacitors will be connected in series to achieve a working voltage of 70V as per the desired specifications

3. Simulation Result

3.1 Simulation Result

Boost converter system simulation was performed by measuring the output voltage of the boost converter and the ripple that occurred on the output. The circuit diagram of the boost converter used to simulate the system can be seen in figure 7.

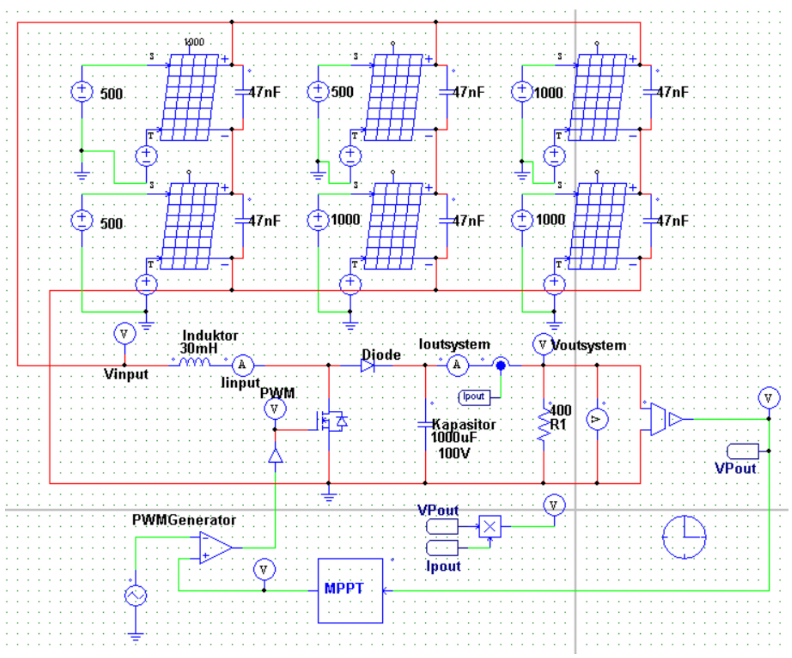

Figure 3. Boost Converter Before Supercapacitors Integration

Figure 3 illustrates the schematic of a boost converter, detailing the critical components and their operational interaction. The converter functions by stepping up the input voltage, storing energy in the inductor during the switch-on phase, and releasing it during the switch-off phase, thereby achieving a higher output voltage. This elevated voltage is essential for the efficient charging of the supercapacitor and for meeting the voltage requirements of downstream circuits.

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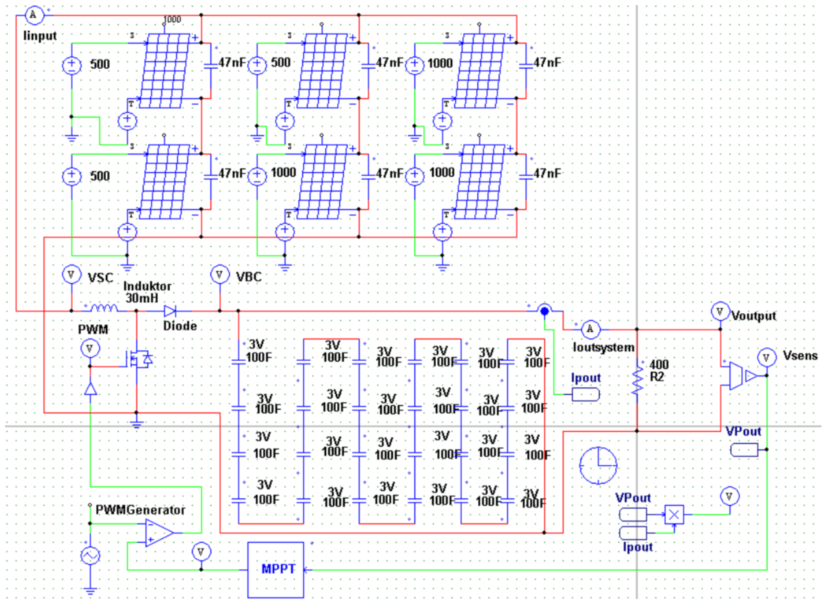

Figure 4. Boost Converter with Integration Supercapacitors

Figure 4 presents the configuration of a boost converter integrated with a supercapacitor, demonstrating the process of voltage step-up and subsequent energy storage. The converter efficiently charges the supercapacitor by elevating the input voltage, thereby enhancing energy storage capability and ensuring a stable power supply to the load during periods of increased demand.

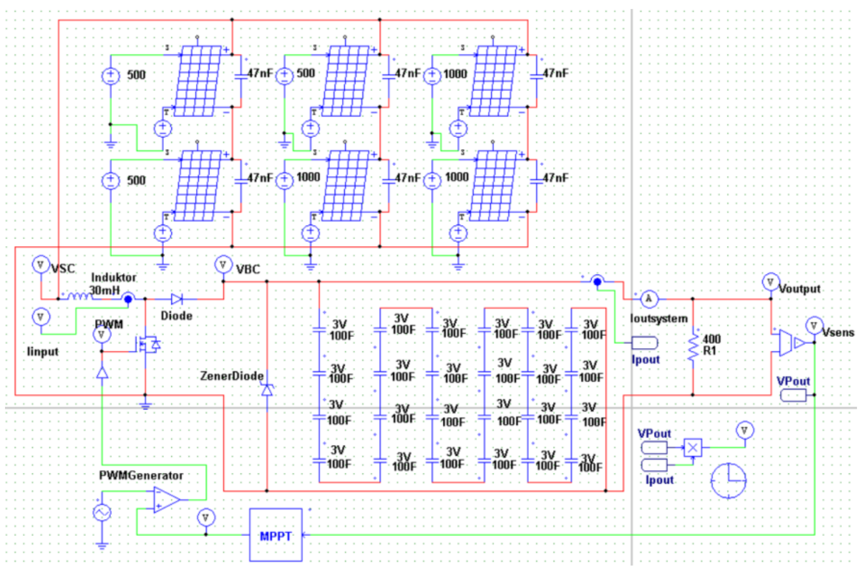

Figure 5. Boost Converter with Supercapacitors Integration and Zener Diode as Voltage Regulator

This figure presents the configuration of a boost converter integrated with a supercapacitor,

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demonstrating the process of voltage step-up and subsequent energy storage. The converter efficiently charges the supercapacitor by elevating the input voltage, while a Zener diode is incorporated to limit the output voltage to 70V, thereby enhancing energy storage capability and ensuring a stable power supply to the load during periods of increased demand.

at the simulation output voltage will be mainly observed too see and compare the output between with and without supercapacitor and testing the output with feedback with optimization using PO method. Result of the simulation can be seen in figure 5.

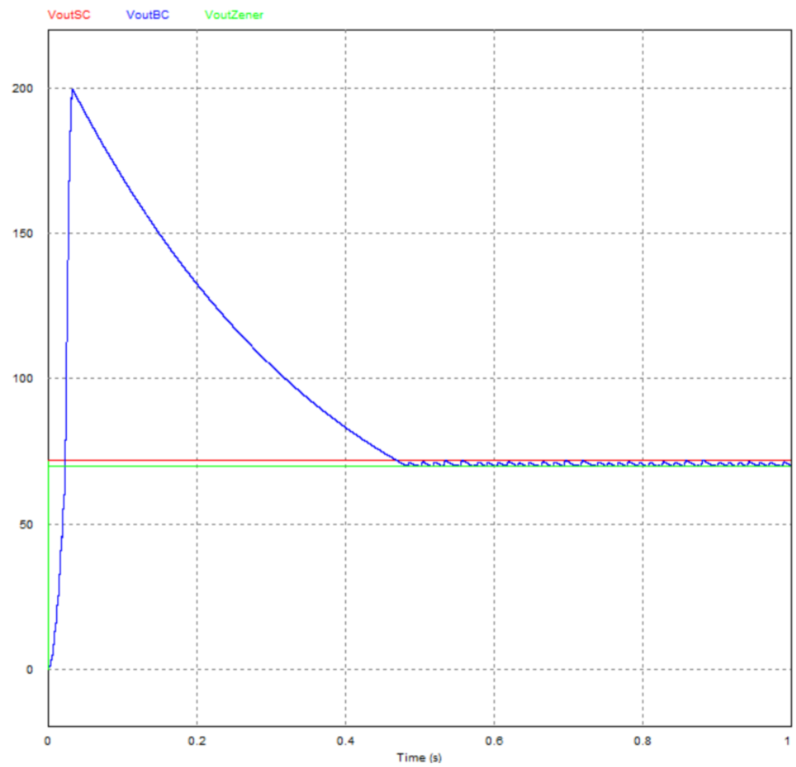

Figure 6. Output of Three Different Method

Figure 6 shows different result of simulaton which is blue graph for conventional boost converter, red graph for boost converter with supercapacitor integration and green graph for boost converter with superacapacitor integration and zener diode.

The three configurations of the boost converter show distinct characteristics in terms of output ripple and stability. The blue graph represents a conventional boost converter without supercapacitors, resulting in the highest ripple among the configurations. This high ripple is likely due to the absence of any additional energy storage, making the output more susceptible to fluctuations in input and load conditions. Consequently, this setup may be less suited for applications requiring a stable DC output, as it lacks the means to buffer against sudden changes.

In contrast, the red graph illustrates the boost converter with integrated supercapacitors, which significantly reduces ripple and enhances stability. Supercapacitors, serving as supplementary energy storage, effectively smooth out the output by quickly absorbing or releasing charge in response to variations, thus maintaining a more stable voltage. This setup is more advantageous for applications needing consistent power with minimal fluctuations.

Lastly, the green graph represents the configuration with both supercapacitors and a zener diode, which further stabilizes the output with low ripple. The addition of a zener diode helps in voltage regulation, maintaining output within a narrow range by clamping any excess voltage. This configuration offers the most stable output among the three, with minimal ripple, making it highly suitable for sensitive applications requiring precise voltage control and smooth power delivery.

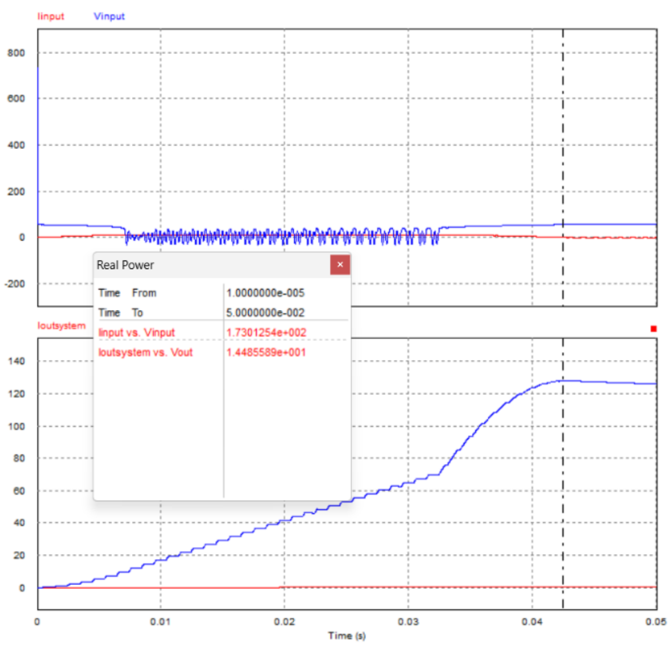

Figure 7. Voltage and Current Graph of Input and Output of Boost Converter Without Supercapacitors Integration

Figure 7 shows graphs of the input and output voltage, current, and power values. The power values are used to calculate efficiency, as depicted in Figure 7. The efficiency can be calculated using the following equation:

$$\eta = \frac{P_{out}}{P_{in}} X100\%$$

$$\eta = \frac{14,48}{173,01} X100\%$$

$$\eta = 8,36\%$$

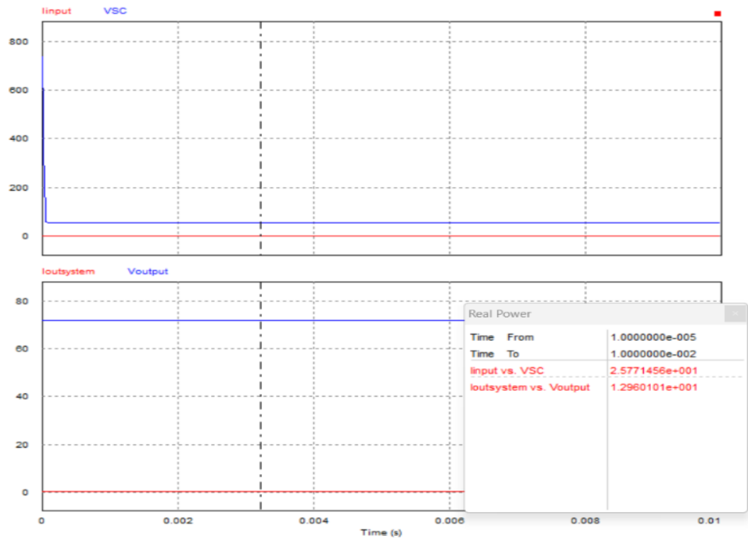

Figure 8. Voltage and Current Graph of Input and Output of Boost Converter with Supercapacitors Integration

Figure 8 shows graphs of the input and output voltage, current, and power values. The power values are used to calculate efficiency, as depicted in Figure 8. The efficiency can be calculated using the following equation:

$$\eta = \frac{P_{out}}{P_{in}} X100\%$$

$$\eta = \frac{12{,}96}{25{,}77} X100\%$$

$$\eta = 50{,}29\%$$

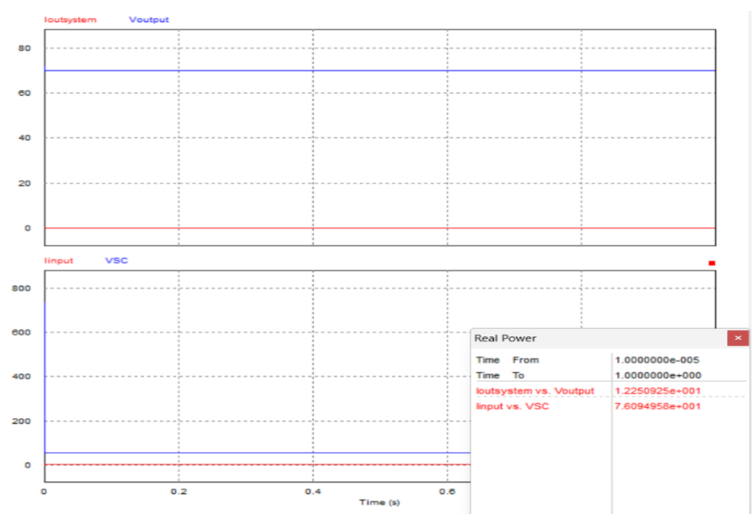

Figure 9. Voltage and Current Graph of Input and Output of Boost Converter with Supercapacitors Integration and Zener Diode as Voltage Regulator

Figure 9 shows graphs of the input and output voltage, current, and power values. The power values are used to calculate efficiency, as depicted in Figure 9. The efficiency can be calculated using the following equation:

$$\eta = \frac{P_{out}}{P_{in}} X100\%$$

$$\eta = \frac{12{,}25}{76{,}09} X100\%$$

$$\eta = 16{,}09\%$$

4. Discussion

Most notably, in the boost converter with a supercapacitor but without a Zener diode, the output voltage gradually decreases from 72 volts to 70 volts. While no ripple is present, the output voltage initially exceeds the desired design. This occurs because the boost converter's cycle is too fast, causing the supercapacitor to store voltage at 72 volts, which then slowly decreases as the duty cycle decreases until reaching the optimal value of 70 volts. Despite this initial overshoot, this configuration achieves a significantly higher efficiency of 50.29%. The absence of ripple and the efficient energy storage capability of the supercapacitor contribute to this remarkable improvement, demonstrating the potential of supercapacitor integration in enhancing boost converter performance.

Figure 7, 8, 9 presents the power comparison of input versus output for the three configurations, providing further insight into the efficiency percentages. The data shows that the configuration without a supercapacitor and without a Zener diode exhibits significant power losses, with a low output-to-input power ratio, corresponding to its 8.36% efficiency. The configuration with a supercapacitor and Zener diode shows a modest improvement in power output, leading to its 16.09% efficiency. The most efficient configuration, with a supercapacitor and without a Zener diode, demonstrates the highest output-to-input power ratio, corresponding to its 50.29% efficiency. This data confirms that the supercapacitor's role in reducing power losses and enhancing voltage stability is crucial for optimizing boost converter performance.

In summary, the analysis reveals that while both configurations achieve the desired output voltage, the use of a supercapacitor particularly without a Zener diode provides substantial benefits in terms of efficiency and voltage stability. The configuration with a supercapacitor and without a Zener diode stands out with an efficiency of 50.29%, far surpassing the other configurations, making it the most effective design for minimizing power losses and optimizing energy conversion in boost converters

5. Conclusion

In conclusion, the study shows that adding a supercapacitor to a boost converter, especially without a Zener diode, greatly improves efficiency and voltage stability. The setup with only the supercapacitor achieves a high efficiency of 50.29%, much better than other configurations, by reducing power losses and keeping the output voltage steady without ripple. Other setups, either without the supercapacitor or with a Zener diode, have lower efficiency and more power losses. This result highlights the advantage of using a supercapacitor without a Zener diode in boost converters to reduce power loss and keep voltage stable, making it a better choice for efficient energy conversion.

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