Design of a Rectifier and DC-DC Buck Converter

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***Abstract* — As the world's energy demands continually increase, the role of power electronics in reducing the variabilities and constraints on the power grid has become increasingly important. Key power electronics components, such as the power converter, are interfaced between a power source and load to control power parameters. Power converters, mainly rectifiers and DC-DC buck converters play important roles in transforming electrical energy from one form to another while minimizing losses. Rectifiers are key in converting alternating current into more stable direct current, as needed in systems that require constant DC power. On the other hand, DC-DC converters are instrumental in voltage regulation as they can step down (buck converters), step up (boost converters), or perform both operations (buck-boost converters). This paper details a comprehensive analysis of the design of a full-wave power rectifier and a buck converter and their performance. The core investigation involves theoretical calculations, simulation-based assessments, and the use of key components to meet predetermined specifications.**

Keywords — power electronics, power converters, rectification, full-wave rectification, buck converter, boost converter, buck-boost converter.

I. INTRODUCTION

Power electronics are essential components found in a variety of devices used today. They span nearly all devices, including automobiles, consumer electronics, and industrial applications such as battery chargers and motor drivers [1]. The field of power electronics has witnessed continuous growth and constant innovation, and the ever-increasing demand for energy-efficient solutions is a key factor driving this growth. Power converters are critical to the development of this field, as they aid in transforming electrical energy from one form to another while maintaining high efficiency and minimal losses. Among the numerous power converters are rectifiers and DC-DC buck converters, which are essential in power conversion in many applications [1].

Power rectifiers are converters responsible for converting alternating current (AC) into direct current (DC). Hence, this makes them vital in applications that require a constant DC source regardless of the type of power present. These applications include power supplies, battery chargers, and other industrial systems. One key characteristic of power rectifiers is their ability to rectify an AC input and provide a stable DC output. There are two main types of rectifiers: Half-wave rectifiers and Full-wave rectifiers. One major difference between a half-wave and a full-wave rectifier is that a half-wave rectifier allows only one half (either the positive or negative half) of the input AC waveform to pass through and blocks the other half. In contrast, as the name suggests, a full-wave rectifier rectifies both the positive and negative half of the input waveform, thus producing a more stable DC output [2]. The design of power rectifiers involves vital components such as transformers, capacitors, and diodes, with efficiency and total harmonic distortion (THD) being vital performance criteria; thus, selecting accurate components is essential for its operation.

On the other hand, DC-DC converters are power electronics converters that can efficiently step up or down the voltage of a DC power source, making it crucial for various applications, some of which include voltage regulation. Depending on their usage, DC-DC power converters can be classified as buck-converters, boost converters, or buck-boost converters. Buck converters step down DC voltages from higher to lower levels. The buck converter is typically used to distribute power in complex systems, e.g., broadband communication boards. They usually consist of one active switch, generally controlled by an integrated circuit, a rectifier, and filtering elements [3]. The boost converters step up DC voltages from lower to higher levels. Buck-boost converters, as the name suggests, combine the buck and boost converter's qualities, giving it the ability to either step down a DC voltage source or step up a DC voltage source. The design of DC-DC converters comprises inductors, switches, and control algorithms, all of which influence the overall performance, efficiency, and output ripple voltage [4].

This paper aims to present a detailed analysis of the design of a power rectifier and a buck converter. It encompasses the theoretical calculations with simulated values to design a buck converter and a power rectifier. The specifications under consideration are realized using real-world key components. Key parameters, such as the overall system's efficiency, are calculated to ensure that the specifications are being met.

II. LITERATURE REVIEW

A. Background of power rectifiers

The design of power supplies and the concept of power rectification plays a critical role in the scope of power electronics, which makes it possible to convert alternating current (AC) to direct current (DC), providing a stable DC power source for various applications. One of the premier rectifiers designed was the mercury arc rectifier discovered by Peter Cooper Hewitt in 1902 [5]. This type of rectifier follows the working principle of mercury vapor subjected to an electric arc. When an AC voltage is applied across the electrodes, the current flows through the mercury vapor, creating an arc between the electrodes. This process allows current to flow in only one direction, effectively converting AC to pulsating DC [5]. Some of the drawbacks of this design were its size, environmental hazards, and complexity.

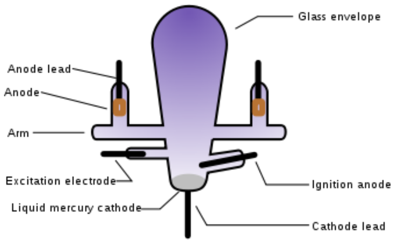

Fig. 1. The mercury Arc rectifier.

Concurrent improvement to the mercury arc rectifier over the years resulted in the discovery of the full-bridge and half-bridge rectifiers, which are dominantly used today.

III. POWER CONVERTER SPECIFICATIONS

A. Design Specifications of Power Rectifier to be met

In pursuit of this research endeavor, a set of precise design specifications were established for the design of an unregulated power supply. The power supply's input voltage is derived from a 230Vrms AC source with a frequency of 50Hz. The power supply will be designed to furnish a stable output voltage 48V DC with a permissible tolerance of ±10%. The output voltage is expected to yield a maximum ripple factor not exceeding 3.00%. Maintaining this ripple factor ensures a stable and reliable DC output. The power supply should be capable of providing a maximum output load current of 250mA. These design confinements serve as the basis for the development and assessment of the power rectifier, providing the grounds for achieving the intended objectives of this study.

B. Design Specifications of Buck Converter to be met

In the context of the buck converter design, the main objective was to engineer a system capable of producing a consistent output of 48V. This objective required the converter to facilitate a variable input source ranging between 150V and 210 in conjunction with managing a load that fluctuates between 65W and 100W. A crucial consideration was ensuring the converter's efficiency was greater than 90%.

IV. DESIGN METHODOLOGY

A. System diagram of the proposed solution for the Power Rectifier

Figure 2 illustrates the proposed solution for our unregulated power rectifier system.

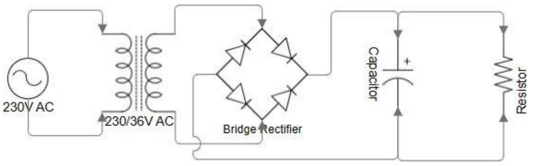

Fig. 2. System diagram for unregulated power supply.

The electrical circuit begins with a 230V AC voltage source and is first subjected to a voltage transformation process. This transformation involves using a 230/36V AC transformer to step down the voltage from 230V to a more manageable 36V AC level. This transformation is crucial to ensure subsequent circuit components operate within a safer and more appropriate voltage range.

Following the voltage transformation, the 36V AC source progresses into the subsequent stage of the circuit, where it undergoes the rectification process. This process involves using a full wave bridge rectifier, which converts the incoming AC signal into a more stable and unidirectional DC signal. As a result, the output from the bridge rectifier yields an approximate 50V DC source, providing a consistent voltage supply for electronic devices and components.

To further enhance the quality of the DC output and remove any residual AC fluctuations or ripples, a filtering component is introduced into the circuit. Typically, a capacitor is strategically positioned after the bridge rectifier. The primary function of the capacitor is to store and release electrical energy, effectively smoothing out the voltage waveform. Consequently, the output becomes a nearly ripple-free and steady DC source suitable for powering sensitive electronic equipment.

B. Proposed components to be used for the power rectifier

To fulfil the necessary voltage transformation while sustaining a maximum load current of 250mA, a DP-241-5-36L transformer was proposed. This transformer possesses an input voltage rating of 230V AC and a secondary voltage rating of 36Vrms @ 0.35A. Its selection was deemed appropriate due to its higher maximum current rating than the required load current. The 36Vrms output was considered ideal for rectification to achieve an output DC voltage of approximately 50V, which aligns closely to the desired output voltage.

For the bridge rectifier diodes, the MUR120 Series diode was proposed. These diodes boast a forward current of 1A, a forward voltage drop of 0.710V and a working peak reverse voltage of 200V. The choice of the MUR120 series diode was justified by several factors. Firstly, the peak inverse voltage (PIV) of the diodes significantly exceeds the peak voltage of the bridge rectifier (approximately 50V), making them highly capable of blocking all the voltage in reverse-biased conditions. Additionally, the current rating of the diodes substantially surpasses the maximum load current, ensuring reliable performance without overheating. Furthermore, the MUR120 series diodes offer fast reverse recovery times to help minimize switching losses and exhibit low forward voltage drops to minimize power losses.

Concerning capacitance, an initial calculation derived a minimum capacitance value of 481μF to attain a maximum ripple factor of 3%. Upon calculation, we had a capacitance of 486uF. To optimize the output and reduce the current ripple, a parallel combination of three 470μF capacitors was chosen, which elevates the total capacitance. In relation to the load resistance, calculations were conducted to ascertain the resistance value required to achieve a load current of 250mA. From computations, it was established that an approximate load resistance of 200Ω ensures the appropriate load current. Detailed calculations for the values of capacitances and resistances will be expounded upon in the subsequent section.

C. *Calculations for Proposed Solution for Power Rectifier and Simulink Design*

Calculations were made based on our design required to get the values of the components needed for our power rectifier.

For our system, the input voltage to the rectifier is 36Vrms.

$$Peak\ input\ voltage = 36\ \times \sqrt{2} = 50.911V$$

$$Max\ load\ current = \frac{50.911V - 2 \times V_{drop\ across\ D1}}{R_{load}}$$

To calculate the load resistance needed for a maximum load current of 250mA,

$$R_{load} = \frac{50.911V - 2 \times V_{drop\ across\ D1}}{Max\ load\ current}$$

$$R_{load}\ = \frac{50.911V - 2 \times 0.710}{0.25}$$

$$R_{load}\ = \frac{50.911V - 2 \times 0.710}{0.25}$$

$$R_{load}\ = 197.964\ \approx 200\Omega$$

To calculate the capacitance value needed for a maximum ripple factor of 3%,

$$Ripple\ factor = \frac{1}{4\sqrt{3}\ \times R_{load} \times f \times C}$$

$$C = \frac{1}{4\sqrt{3}\ \times R_{load} \times f \times Ripple\ factor}$$

$$C = \frac{1}{4\sqrt{3}\ \times 197.964\ \times 50 \times 0.03}$$

$$C =\ 486.07\mu F$$

To get a very small ripple at the output, we decided to use $C =\ 3 \times 470\mu F\ = 1410\mu F$

Figure 3 below shows our circuit implementation in Simulink.

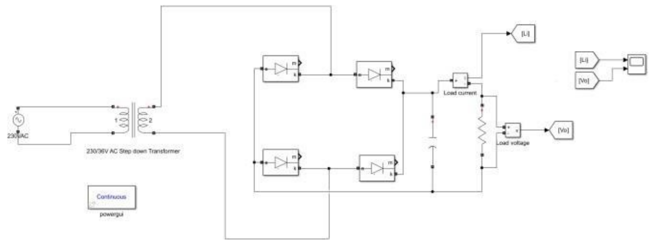

Fig. 3. Simulink model for unregulated power supply.

D. *System diagram of the proposed solution for buck converter*

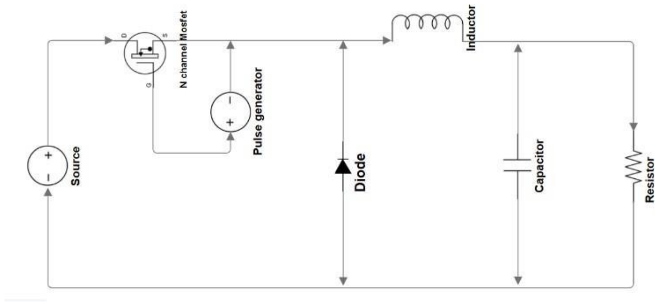

Fig. 4. System diagram for buck converter.

The electrical circuit for the buck converter begins with an input voltage source that spans a range between 150V and 210V. Subsequently, this source is connected to an N-channel MOSFET. The output voltage of the MOSFET is intricately modulated by adjusting the duty cycle, a parameter meticulously controlled by a pulse generator circuit. This modulation facilitates the precise regulation of the output voltage emanating from the MOSFET.

The output from the MOSFET then passes through a low-pass filter comprising an inductor and a capacitor. The primary function of this filter is to attenuate or remove the higher-frequency components from the voltage signal. The capacitor within the filter circuit effectively shunts these high-frequency variations, ensuring that the output is a stable, direct current (DC) voltage.

The resultant DC voltage, now devoid of the rapid fluctuations inherent in the original input, is delivered to the load. The load can vary its power consumption within a range of 65W to 100W. This buck converter design enables efficient voltage conversion and regulation, making it suitable for applications where a stable and adjustable DC voltage supply is needed.

E. *Proposed components to be used for the buck converter*

The chosen power MOSFET for the buck converter is the BSC16DN25NS3, an N-channel MOSFET characterized by a Gate source voltage of ±20V, an ON-state maximum resistance of 165mΩ, a continuous drain current of 10.9A and a drain-source breakdown voltage of 250V. The selection of this MOSFET was informed by several key considerations. Notably, its low ON-state conduction losses contribute to higher efficiency. Additionally, the substantially higher drain current compared to the anticipated load currents (ranging between 1.35A and 2.08A) ensures reduced power losses due to heat, which consequently improves the system efficiency. Additionally, the breakdown voltage of the power MOSFET is much higher than the source voltage, which ensures effective blocking of voltage across the source during non-conducting states.

For the diode, the VS-E5TH1506-M3 hyperfast rectifier diode with a forward current of 15A, a reverse breakdown voltage of 600V and a forward voltage drop of 1.15V was proposed. The decision to opt for this diode was driven by its optimization for high-speed operation and the minimal forward voltage drop losses it incurs. Furthermore, its large reverse breakdown voltage ensures effective blocking of the source voltage when the diode operates in the reverse-biased mode.

Upon calculations, the determined values for the resistor, inductor and capacitor are 33.446Ω, 23.04Ω, 27.29uH and 2.82uF, respectively. These values were derived to optimize the performance of the buck converter in achieving the desired voltage regulation and efficiency.

F. *Calculations for Proposed Solution for Buck Converter and LTSpice Design*

Assuming a switching frequency of 500kHz

f = 500kHz

$$Vin_1 = 150V \qquad Vin_2 = 210V$$

The range of load power varies from 65W to 100W.

The output voltage should be 48V.

$$R_{load\_1} = \frac{Vo^2}{P_1} = \frac{48^2}{65} = 35.446\Omega$$

$$I_{load1} = \frac{P_1}{V_0} = \frac{65}{48} = 1.35A$$

$$I_{load2} = \frac{P_2}{V_0} = \frac{100}{48} = 2.08A$$

Calculating the range of duty cycles

$$D_1 = \frac{V_0}{Vin_1} = \frac{48}{150} = 0.32$$

$$D_2 = \frac{V_0}{Vin_2} = \frac{48}{210} = 0.23$$

To calculate the minimum inductance, we utilize the maximum load resistance and the minimum duty cycle.

$$L_{min} = \frac{(1-D)\,R}{2f} = \frac{(1-0.23)\times 35.446}{2\times 500000} = 27.29uH$$

The standard inductor value used was 47uH.

Assuming 0.5% voltage ripple,

$$C = \frac{1-D_2}{8L\frac{\Delta V_o}{V_o}f^2} = \frac{1-0.23}{8\times 27.29u\times\frac{0.5}{100}\times 500000^2} = 2.82uF$$

The standard inductor value used was 4.7uF

Figure 5 below shows our circuit implementation of the buck converter in LTSpice.

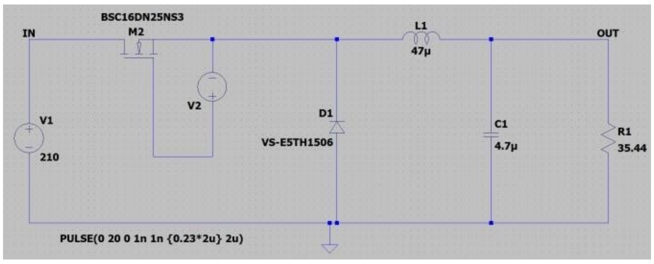

Fig. 5. LTSpice model for buck converter.

V. RESULTS AND DISCUSSION

A. *Output waveforms for unregulated power supply*

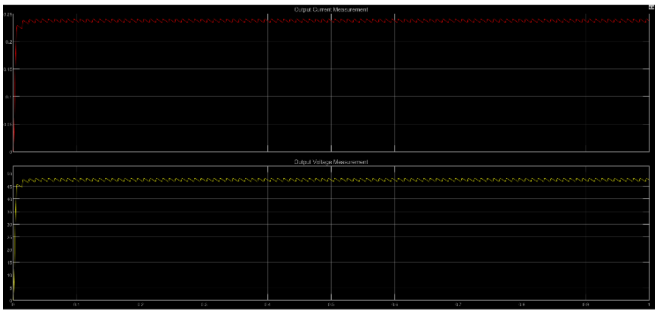

Fig. 6. Output voltage and current measurement across the load

From the graph, it is evident that the output voltage and current waveforms have a small amount of ripple, which is consistent with our expectations. The output of the bridge rectifier without the filter is a pulsating DC signal. However, as the rectified output traverses the filter capacitor, the capacitor charges during the peaks of the pulsating DC signal. Subsequently, during the troughs of the pulses, the capacitor discharges its stored energy into the load. This dynamic interaction serves to mitigate the ripple in the voltage, ultimately yielding a smoother and more consistent DC output.

To calculate the efficiency of our power supply,

$$n = \frac{DC\ output\ power}{AC\ input\ power}\times 100\%$$

From our simulation, $P_{DC} = 11.7975$W and $P_{AC} = 40.6$W

$$n = \frac{11.7975}{40.6}\times 100\% = 29.06\%$$

From the simulation, the efficiency of our power supply is 29.06%.

B. *Output waveforms for buck converter*

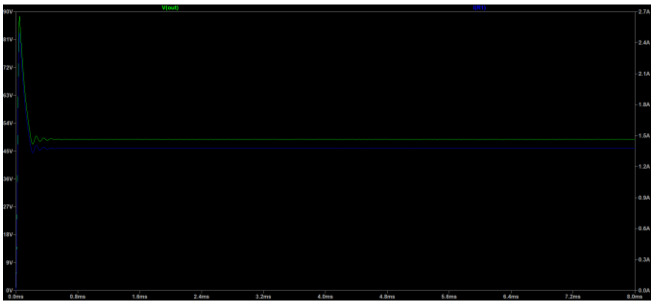

Fig. 7. Load voltage and current measurement for input voltage of 210V, load resistance of 35 Ω and duty cycle 0.23

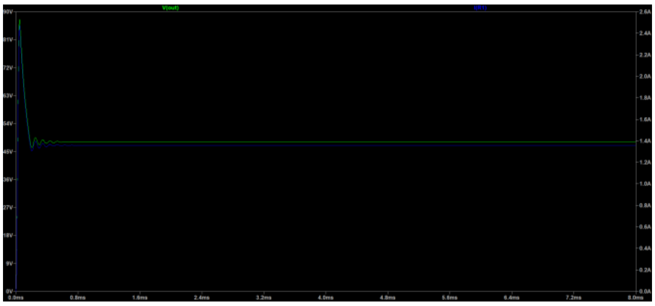

Fig. 8. Load voltage and current measurement for input voltage of 150V, load resistance of 35 Ω and duty cycle of 0.32

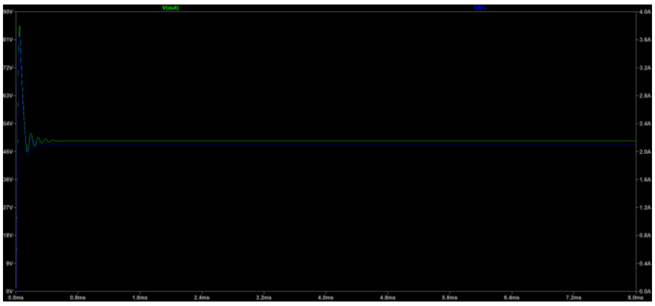

Fig. 9. Load voltage and current measurement for input voltage of 210V, load resistance of 23.04 Ω and duty cycle of 0.23

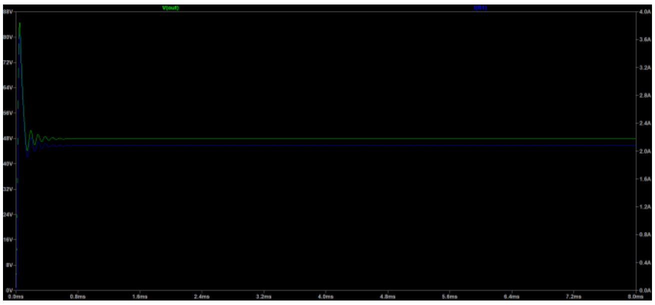

Fig. 10. Load voltage and current measurement for input voltage of 150V, load resistance of 23.04 Ω and duty cycle of 0.32

From the graphs above, it was observed that the output voltage consistently maintained a value of around 48V as the input voltage varied between 150V and 210V, and the duty cycle fluctuated in the range of 0.23 to 0.32. Concurrently, the load current varied within the anticipated range of 1.35A to 2.08A, aligning with our calculated expectations.

In the context of theoretical efficiency calculations, it was assumed that the power supplied to the source equaled the power delivered to the load. Consequently, if the minimum output power is 65W, the minimum input power is also considered 65W. Similarly, for the scenario where the maximum output power is 100W, the corresponding maximum input power is 100W, resulting in an overall efficiency of 100%.

Upon simulation, for an input power of 65W and a load resistance of 35 Ω, the calculated resistance value is 35 Ω. With an input voltage of 210V, load resistance of 35Ω, and a duty cycle of 0.23, further analysis and calculations can be performed to derive additional insights into the performance and efficiency of the buck converter system. If more specific details or calculations are required, they can be provided based on the available data and parameters.

$$P_{in} = 73.2249\text{W} \qquad P_{out} = 68.3367\text{W}$$

$$Efficiency = \frac{P_{out}}{P_{in}} \times 100\%$$

$$Efficiency = \frac{68.3367}{73.2249} \times 100\% = 93.32\%$$

Alternatively, using the same input power for an input voltage of 150V, load resistance of 35 Ω and a duty cycle of 0.32,

$$P_{in} = 70.27\text{W} \qquad P_{out} = 66.42\text{W}$$

$$Efficiency = \frac{P_{out}}{P_{in}} \times 100\%$$

$$Efficiency = \frac{66.42}{70.27} \times 100\% = 94.52\%$$

For an input power of 100W, the resistance is 23Ω. For an input voltage of 210V, load resistance of 23 Ω and a duty cycle of 0.23

$$P_{in} = 110.374\text{W} \qquad P_{out} = 103.00\text{W}$$

$$Efficiency = \frac{P_{out}}{P_{in}} \times 100\%$$

$$Efficiency = \frac{103.00}{110.374} \times 100\% = 93.32\%$$

Alternatively, using the same input power for an input voltage of 150V, load resistance of 23 Ω and a duty cycle of 0.32,

$$P_{in} = 106.25\text{W} \qquad P_{out} = 100.50\text{W}$$

$$Efficiency = \frac{P_{out}}{P_{in}} \times 100\%$$

$$Efficiency = \frac{100.50}{106.25} \times 100\% = 94.59\%$$

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