Buck Converter

1st Yernazar Turlybek
yernazar.turlybek@nu.edu.kz

2nd Azamat Atikeyev
azamat.atikeyev@nu.edu.kz

3rd Symbat Nurgazy
symbat.nurgazy@nu.edu.kz

***Abstract*—A buck converter is a DC-to-DC converter that steps down voltage while increasing current. It operates by switching a transistor on and off at high frequencies, with an inductor and capacitor smoothing the output to reduce voltage ripple. Efficient and compact, buck converters are ideal for reducing voltage in applications like power supplies and battery chargers, offering high efficiency through careful component selection and control of the switching duty cycle.**

***Index Terms*—Buck converter, High-power electronics, Voltage regulation, Power conversion efficiency, Component selection, Simulation and modeling, MATLAB Simulink, Power Electronics, Switching frequency, Voltage ripple**

I. Introduction

In the realm of power electronics, buck converters play a pivotal role in voltage regulation across a wide array of applications, from renewable energy systems to electric vehicles and industrial machinery. These converters are prized for their efficiency and simplicity, providing a lower, controlled output voltage from a higher input voltage through pulse-width modulation (PWM) techniques. The burgeoning demand for energy-efficient and compact power conversion solutions has spurred extensive research into optimizing buck converter design for high-power applications. This paper focuses on the development and simulation of a high-power buck converter designed to step down a 420V input to a 340V output, operating at a 6kHz switching frequency to deliver 56kW to the load.

To address these challenges, this paper presents a methodical approach to the selection of the buck converter's components, including the duty cycle, inductor, and capacitor, based on theoretical calculations. These components are crucial for determining the converter's efficiency, output ripple, and response to load changes. Furthermore, we introduce a comprehensive simulation model developed in Simulink, which serves as a powerful tool for validating the theoretical design and analyzing the converter's performance in a controlled environment. The simulation results offer insightful data on the converter's efficiency, output voltage stability, and ripple characteristics, providing a robust foundation for further optimization.

II. Requirements and Theory

A. Requirements

The final design of the circuit was required to meet the following criteria:

- $V_{in} = 420$ V
- $f_{sw} = 6$ kHz
- $V_o = 340$ V
- Voltage variation $\Delta V = 3\%$
- $P_{load} = 56$ kW

B. Theory and Equations

This section goes into the theoretical understanding of buck converter [1] design, focusing on key parameters such as duty cycle, component selection, and performance analysis.

The duty cycle (D) of a buck converter, determined as the ratio of output voltage (V_o) to input voltage (V_{in})), governs the switching behaviour. It's calculated using Equation 1, where

$$D = \frac{V_o}{V_{in}} \tag{1}$$

This parameter controls the average output voltage by regulating the duration of transistor on/off states during each switching cycle.

Average current (I_o) flowing through the buck converter is estimated using Equation 2, where

$$I_o = \frac{P_{load}}{V_o} \tag{2}$$

representing the power delivered to the load.

The resistor (R) in the buck converter circuit plays a crucial role in load current determination and voltage regulation. Its value is calculated using Equation 3, where

$$R = \frac{V_o}{I_o} \tag{3}$$

The minimum required inductance (L_{min}) for continuous current flow through the inductor is determined by Equation 4, where

$$L_{min} = \frac{(1-D)R}{2f} \tag{4}$$

The product of inductance and capacitance (LC) is a parameter influencing the output voltage ripple and converter performance. Equation 5 provides the relationship between L and C, where

$$L \times C = \frac{1-D}{8(\frac{\Delta V_o}{V_o})f^2} \tag{5}$$

This equation ensures that the relation between inductance and capacitance is preserved while meeting the specified requirements for output voltage ripple.

III. Estimation of the RLC load

A. Estimation of resistor R

To calculate the value of R, first, we need to find the value of the duty cycle D by using (1):
$D = \frac{V_o}{V_{in}} = \frac{340}{420} = 0.81$
After that, we can find the average current I_0 that flows through the resistor by (2):
$I_o = \frac{P_{load}}{V_o} = \frac{56000}{340} = 164.7A$
Here, We consider the current and the voltage across the resistor to be purely DC as the peak-to-peak value is too small compared to the average value (3%).
Finally, resistor value R is found by (3):
$R = \frac{V_o}{I_o} = \frac{340}{164.7} = 2.064\Omega$

B. Estimation of LC value

To the given requirement for the design of the buck converter, it is not possible to find L value and C value one by one. Instead, We will try to find $L \times C$ value. Inductor and capacitor values can be chosen from the acceptable range of values, but the relation has to be conserved. Changing one of them and adjusting the other one does not influence the average output voltage, peak-to-peak output voltage and the average current. Thus, LC value is found by (5):
$L \times C = \frac{1-D}{8(\frac{\Delta V_o}{V_o})f^2} = \frac{1-0.81}{8 \times 0.03 \times 6000^2} = 2.2 \times 10^{-8} H \times F$
The minimum value of inductance L, so that the current is continuous, is found by (4):
$L_{min} = \frac{(1-D) \times R}{2f} = \frac{(1-0.81) \times 2.064}{2 \times 6000} = 3.2 \times 10^{-5} H$

IV. Simulink Model Design

The Simulink model is designed to simulate a Buck converter. The Simulink model is composed of the following components:

- DC Source: This component acts as the power supply for the Buck converter, providing a constant DC voltage input.
- MOSFET: The Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) serves as a switch within the circuit. By turning on and off in response to a control signal, it regulates the flow of energy through the converter.
- PWM Generator: The Pulse Width Modulation (PWM) Generator creates a control signal for the MOSFET. By adjusting the duty cycle of this signal (the ratio of the on-time to the total cycle time), the PWM Generator controls the average power delivered to the load.
- Inductor: The inductor stores energy in the form of a magnetic field when current flows through it. In a DC-DC converter, it serves to smooth out the current waveform, aiding in the reduction of voltage ripple on the output.
- Capacitor: Capacitors store energy in an electric field, providing a smoothing effect on the output voltage.
- Resistor: This component is used to simulate the load on the Buck converter in the Simulink model.
- Diode: The diode allows current to flow in only one direction, providing a path for current when the MOSFET is off. It prevents the reverse flow of current from the load back into the converter.

V. Simulation Results

The simulation was conducted to validate the calculations, confirming the resistance $R = 2.064\,\Omega$ and the inductance-capacitance product $LC = 2.2 \times 10^{-8}\,\mathrm{H} \cdot \mathrm{F}$. According to the results (Fig. 2), the mean or the average value of the output voltage is 342.2 V, the peak-to-peak voltage is 10.18V and the RMS of the output voltage is 342.2V. Here, voltage variation ΔV_o equals $\frac{peak-to-peakvoltage}{averagevoltage} = \frac{10.18}{342.2} = 2.97\%$ as in the design requirements. To verify power absorbed by a load:
$P_load = I_{RMS} \times V_RMS = 166.2A \times 342.2V = 56873.6W$
where $I_{RMS} = 166.2$ by Figure 3.
As can be seen, all the design requirements were met by configuring the values of R,L and C.

References

[1] D. W. Hart and D. W. Hart, *Power electronics*. McGraw-Hill New York, 2011, vol. 166.

VI. Appendix

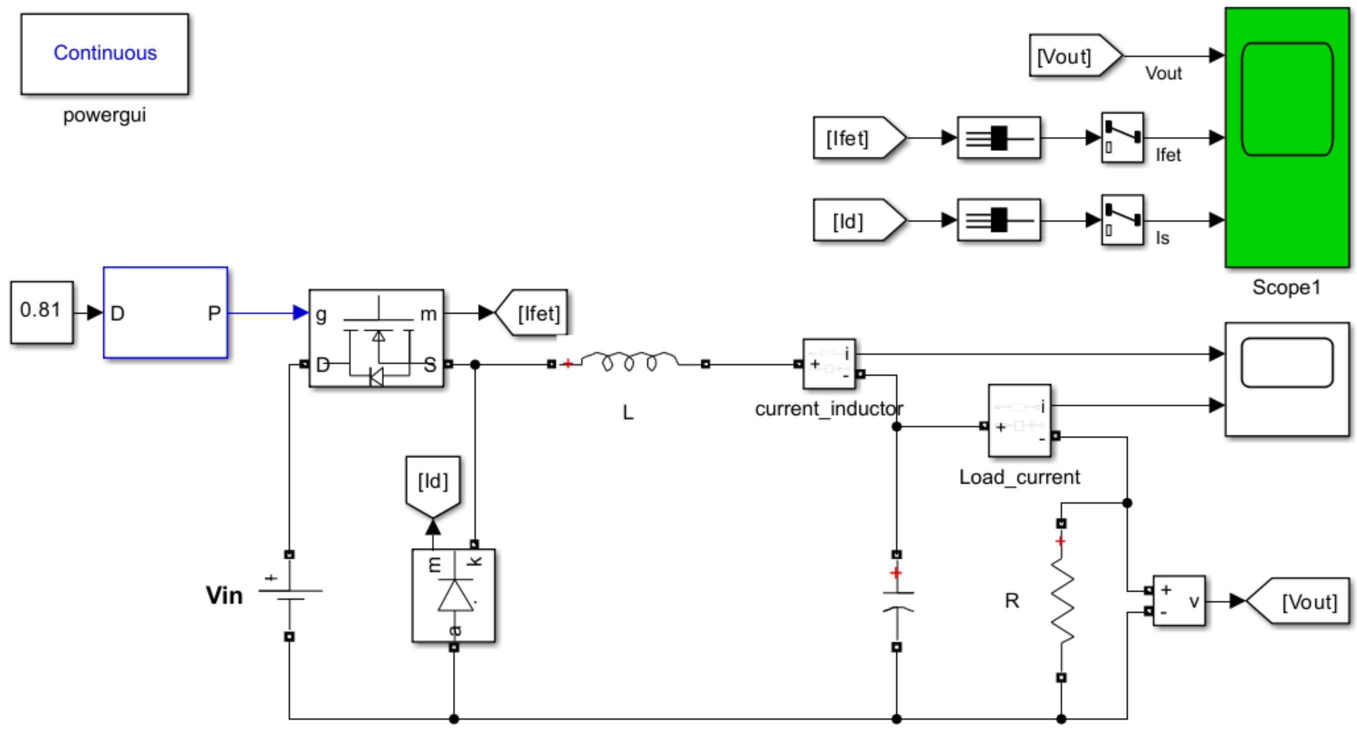

Fig. 1. Simulink model

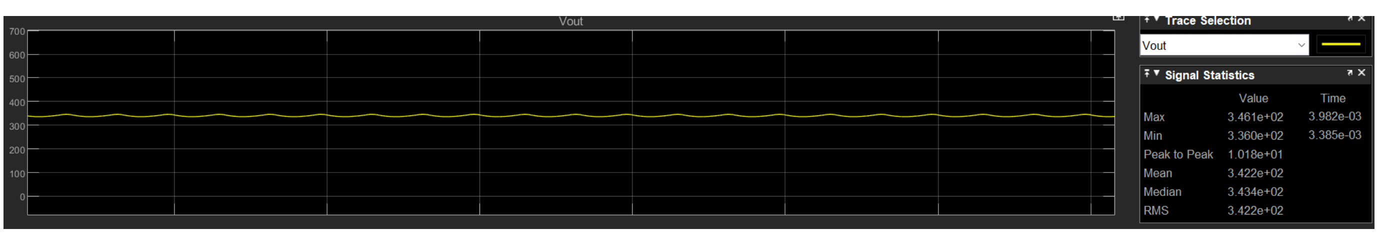

Fig. 2. Output voltage signal statistics

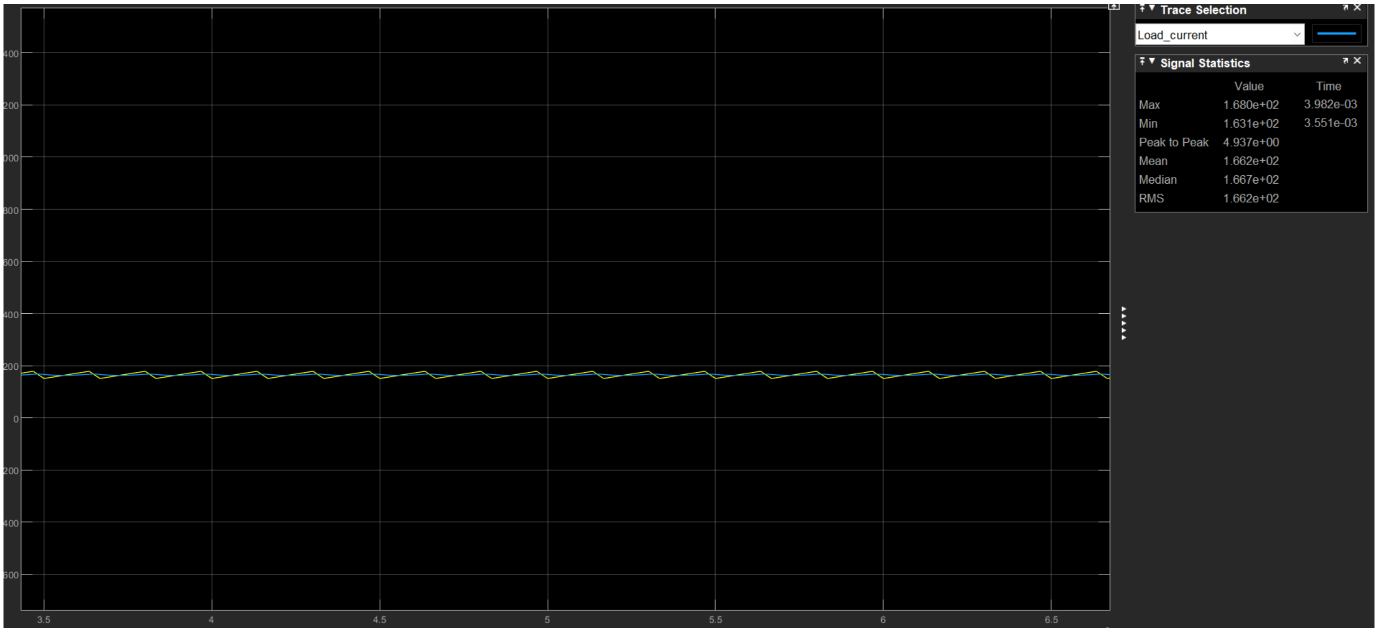

Fig. 3. Output current signal statistics

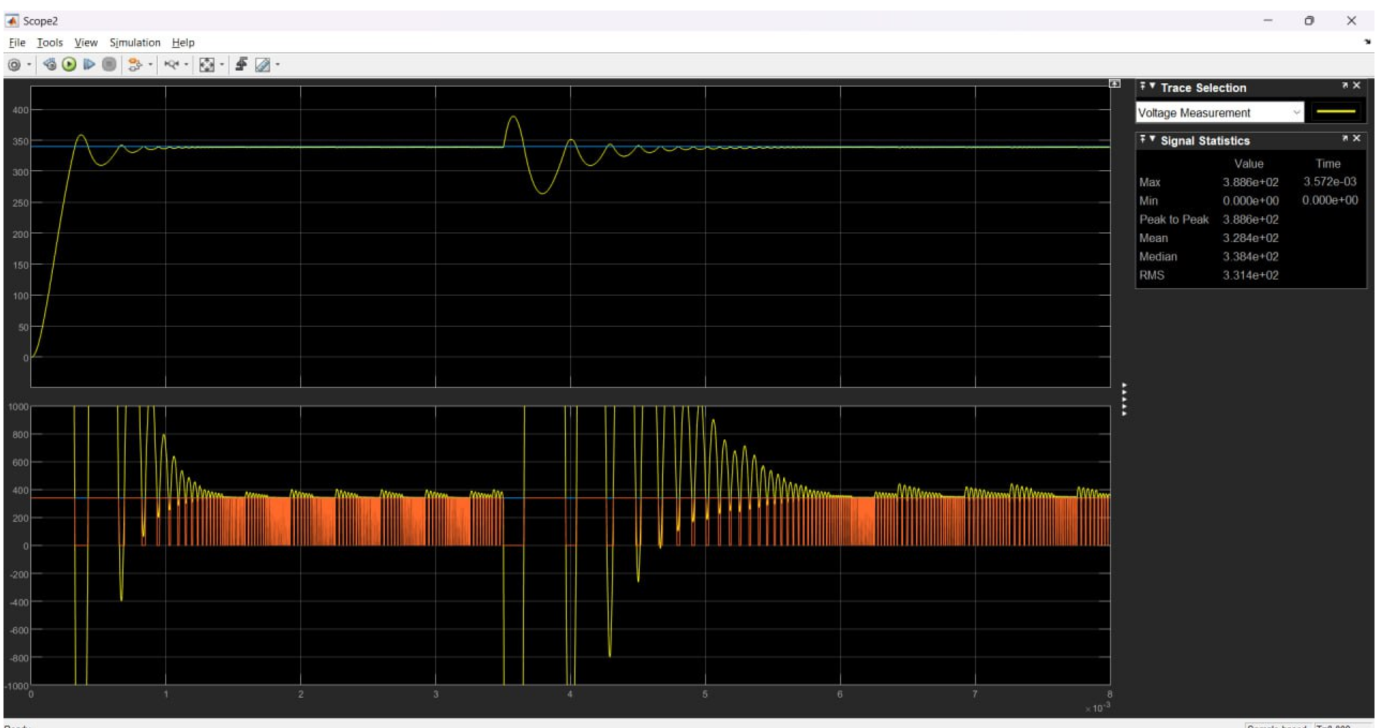

Fig. 4. Output signal when using pid controller

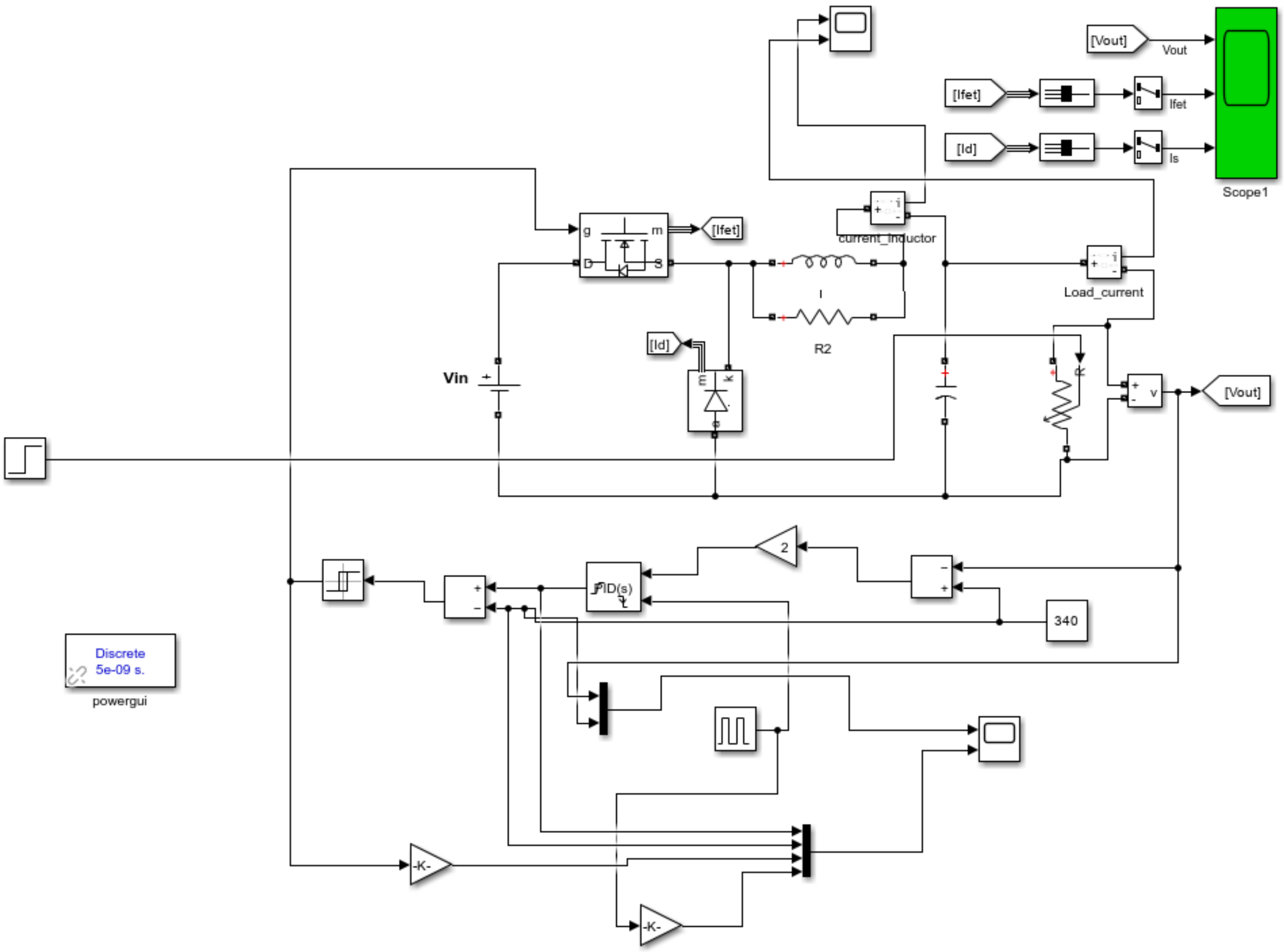

Fig. 5. Simulink model for controlling duty cycle