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Self Tuning Buck Converter

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Abstract

Put in an abstract once the full report has been written.

Contents

Chapter 1: Introduction

I am very unsure on what I'm going to write here, if you have any suggestions that would be appreciated.

Switch-mode power supplies are commonly used in a wide variety of consumer and professional appliances to transform DC voltages with high efficiency. One such switch-mode supply is the buck converter, which steps down a DC voltage. The design of a buck converter is based around its tolerated inductor ripple, and will require specific components to design the output filter. These components can be difficult to purchase or accurately manufacture. This project will implement control systems to actively control with inductor ripple by modulating the switching frequency. This will allow engineers to design the converter directly for the inductor ripple, eliminating the need to design the output filter.

Chapter 2: Background

A literature research was performed to inform design decision made in this project, and to evaluate any existing research. It will discuss buck converter design factors and topologies, as well as the various different methods of PWM generation. In performing this literature research, the following terms were used to search for articles from Google Scholar, Engineering Village, and Te Waharoa:

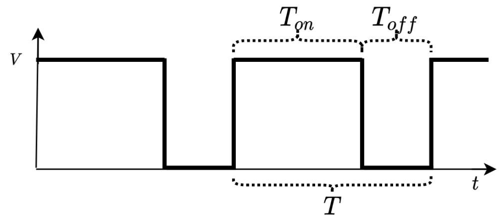
- Frequency Variable PWM
- Frequency-PWM converter
- Switching Frequency Converter

These searches returned no research relevant to the designs of this project, with the only related work focusing on the electromagnetic noise reduction using randomised frequency modulation [1, 2]. Because of this, research was instead performed to inform the design of the buck converter and the generation of PWM signals.

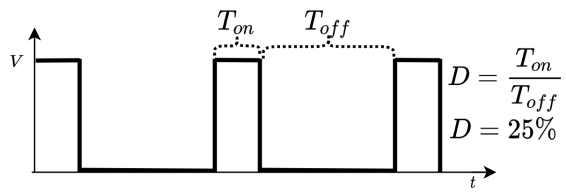
2.1 Pulse Width Modulated Signal Generation

Pulse width modulation (PWM) is a digital signal generation technique shown in Figure 2.1a, in which the Period T of the signal is held constant, while the ratio of its logic high period T_{on} to logic low period T_{off} is modulated. This ratio of high period to the low period is referred to as the duty cycle of the PWM signal and is often expressed as a percentage, this can be seen in Figure 2.1b.

PWM signals are used in a wide variety of applications for both digital and analogue electronics. PWM is often used to generate analogue signals from digital components by varying the average voltage of the digital PWM signal over time [3]. PWM is also used to control the switching elements contained within switch mode power supplies using this same principle, as discussed in Section 2.2. With regard to this project, we will be looking to generate a PWM signal that can be modulated in both duty cycle and frequency.



(a) Pulse width modulated signal



(b) Duty cycle calculation

Figure 2.1: Pulse width modulated signal characteristics

2.1.1 Analogue PWM Signal Generation

Designing a PWM signal generator using analogue components has three distinct stages required to generate the signal. These stages can be seen in Figure 2.2, and include clock generation, triangle wave generation, and signal comparator stages [4].

The clock generation stage generates a square wave clock signal at a set frequency. This is usually done using a quartz crystal oscillator, or another form of resonating oscillator circuit. The triangle wave generating state must take the clock signal from the previous stage, and produce a triangle wave of the same frequency. This stage is most often done using a standard op-amp integrating circuit with unity gain at the resonating frequency of the clock source. The final signal comparator stage will convert this triangle wave into a PWM signal. Using a comparator, a refrence voltage can be applied to the non-inverting input, and then the triangle wave can be applied to the inverting input. This will produce a pulse train with the same frequency as the clock source, where the period of T_{on} and T_{off} is set by the refrence voltage.

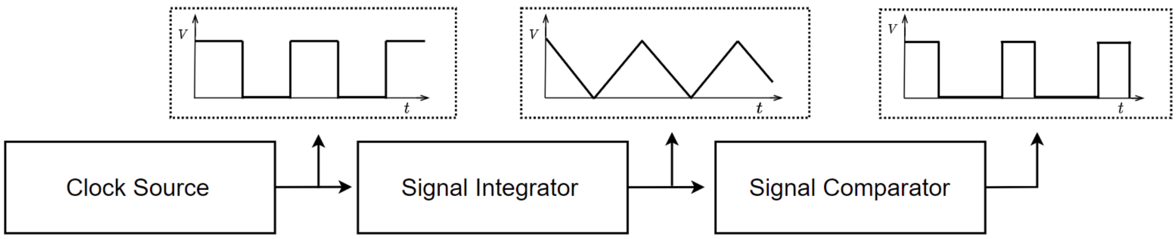


Figure 2.2: Stages of analogue PWM generation

2.1.2 Digital PWM Signal Generation

Designing a PWM signal generator with digital components is far more simple than the method described in 2.1.1, and can be done using either a microcontroller or a Field Programable Gate Array (FPGA). By using an internal timer that is continually incrementing at a known period we can set a period for our PWM. Then by toggling a digital I/O when a compare variable is equal to the value of the timer. we are able to generate a PWM signal with a variable duty cycle [5]. This can be achieved on most microcontrollers, however the maximum frequency and duty cycle accuracy will be dependant on individual clock speed a and internal register sizes.

2.2 Buck Converters

The buck converters is a variant of a switch mode power supply that steps down a DC input voltage to a DC output voltage. They are commonly used in a wide variety of consumer and professional appliances such as laptops, phones, and chargers due to their high efficiency compared to other DC-to-DC step down converters such as linear regulators [6].

The basic operational components of a buck converter can be seen below in Figure 2.3. From this we see that a buck converter has three main elements, the input voltage source, two switching components, and an output filter across the load. In the case of Figure 2.3, the first switching component is an actively controlled switch such as a MOSFET or transistor, and the second a passive switching diode. This configuration of an active and a passive switch is known as the non-synchronous buck converter topology, if the passive diode were to be replaced with a second active switch the topology would be considered synchronous. Although both topologies function under the same fundamental principles, the non-synchronous topology is easier to implement with the drawback of higher losses and therefor lower efficiency.

It can also be seen from Figure 2.3 that a buck converter has two operating states that are controlled through the activation of these switching components. By toggling these switching components at high speed though the use of PWM, we can control the current flowing through the inductor of the output filter. By controlling this current we are also able to directly control the current through, and voltage across the output load of the converter. Using this, buck converters will often have a feedback control system in their design to be able to actively control and regulate the output voltage during usage. This controller will vary the duty cycle of the the switching PWM signal, thereby varying the output voltage of the buck converter as shown in Equation 2.1.

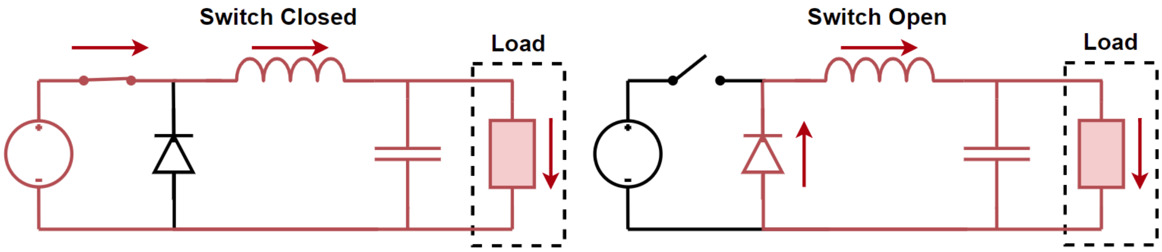


Figure 2.3: Operating states of a buck converter

2.2.1 Buck Converter Design

The design of a common buck converter has two primary considerations, the output voltage of the converter V_0, and the inductor current ripple of the converter Δi_L. These considerations can be specified by designing the buck converter using Equation 2.1 & Equation 2.2 [7, 8].

When designing a buck converter the first design specification that must be met is the output voltage. In Equation 2.1 the output voltage can be directly related to the input voltage V_{in} and the switching duty cycle D. Using this equation it is possible to directly set the output voltage of the buck converter by varying this duty cycle.

$$V_o = D \cdot V_{in} \tag{2.1}$$

Once the output voltage has been specified, the inductor current ripple can be calculated and specified with Equation (2.2). This equation allows for the inductor current ripple to be directly related to the inductor size L, and the PWM switching frequency f_s. This allows the the specification of the inductor current ripple through the varying of these two values.

$$\Delta i_L = \frac{V_o \cdot (1 - D)}{L \cdot f_s} \tag{2.2}$$

These two equations will be used to inform the designs and specifications of this project, and will be discussed in detail in Section 3.1.

Chapter 3: Work Completed

This chapter will discuss the work that has been completed so far on this project. It will begin by discussing the projects requirements', using them to design and justify the final specifications of the system. Once the specifications are outlined, the architecture and design of the final system will be discussed. Finally the design and current implementation of the PWM signal generator will be specified.

3.1 Defining & Justifying System Specifications

- Discuss the requirements that were laid out in the project proposal for the evaluation of the system.
- Discuss how these system requirements needed to be translated into a set of quantitative system requirements that can be used to define and design the system.
- Discuss the system requirements that are required to effectively design the system (PWM frequency & duty cycle step size), and then outline how they were calculated.
- Discuss how these requirements will affect the design of the system

3.2 System Architecture & Design

To achieve the requirements that have been outlined in Section 3.1, it is important to design the system architecture around them. In Figure 3.1 an overview of the system architecture can be seen, with three main design sections outlined. These sections each represent a significant segment of work that must be completed for the final artefact of this project to be achieved.

The first section of work that must be completed is the design of the PWM generation, denoted 1 in Figure 3.1. This PWM generator will be used to control both the output voltage and the inductor current ripple, and as such must be able to modulate both the duty cycle and the frequency of the PWM to the precisions required.

The second section of work is the design of the sensing elements required by the system, denoted 2 in Figure 3.1. These elements will be used to measure both the output voltage and the inductor current ripple, and therefor must be able to achieve the required precisions and sampling rates.

Finally the third section of work is the design and implementation of the two control systems, denoted 3 in Figure 3.1. These control systems will be responsible for maintaining the desired output voltage and inductor current ripple of the buck converter. This system will therefor be responsible for facilitating the final functionality of the project, combining sections 1 & 2.

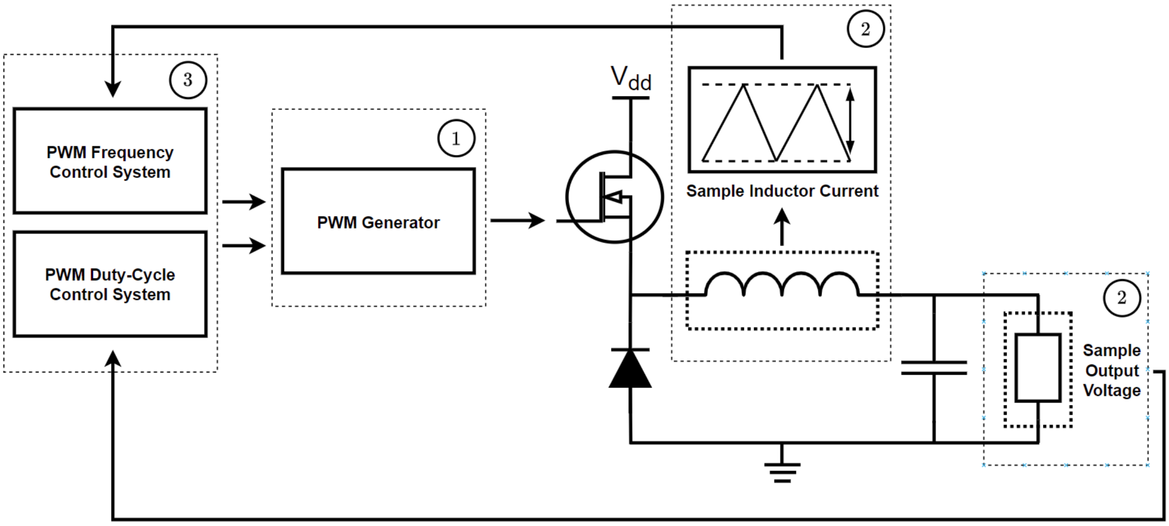


Figure 3.1: High level system overview

3.3 PWM Generation Design

- Discuss the different PWM generation methods outlined in chapter 2. Talk about each of their specific design implication, their advantages, and their disadvantages. This will be included in three different sections, analogue, microcontroller, FPGA.
- Discuss why I have selected a microcontroller for the PWM generation. And discuss how the design of this implementation affected the microcontroller selection.
- Discuss how the final design of the PWM generation was implemented, and what it's capabilities are. Show some images of it functioning, and attach the esp32 code in the appendix.

Chapter 4: Future Plan

4.1 Work to be Completed

- Discuss what work I still have to do before beginning the evaluation of the system.
  - Select sensors to measure peak-to-peak ripple current
  - finalise the circuit design for the project, this includes selection all other components needed for it's operation.
  - Create a final PCB for the design
  - Design the controller that will control both output voltage and inductor ripple

4.2 System Evaluation

The evaluation of this project will be based upon meeting the following selection of specifications. All evaluations of the design will be conducted using a 10Ω output load, with an input voltage of 12V DC.

- The buck converter will be able to take input voltages up to 12V DC
- The buck converter maintains basic functionality of $V_{out} = D \times V_{in} -$ effeciency
- The buck converter will output voltages between 3V and 10V DC
- The output voltage accuracy will be within ±5% of the target output voltage
- The user will be able to define the inductor ripple between 20% and 50%, with increments of 5%.
- The inductor ripple accuracy will be within ±5% of the defined inductor ripple
- The buck converter will have a switching frequency range of 1kHz to 100kHz

4.3 Project Timeline

- Create another Gant chart that now more accurately breaks down the required tasks into the remaining time. Discuss this chart and why it is set out the way that it is.

Feedback

- I want to ask for some suggestion on evaluating the final artefact. The evaluation described within my proposal has not changed, and it seems to be very simple at the moment.

Bibliography

[1] J. R. Roman, "PWM regulator with varying operating frequency for reduced EMI," Mar. 2001.

[2] Y. L. Familiant and A. Ruderman, "A Variable Switching Frequency PWM Technique for Induction Motor Drive to Spread Acoustic Noise Spectrum With Reduced Current Ripple," *IEEE transactions on industry applications*, vol. 52, no. 6, pp. 5355–5355, 2016.

[3] W. Tareen, M. Aamir, S. Mekhilef, M. Nakaoka, M. Seyedmahmoudian, B. Horan, M. A. Memon, and N. A. Baig, "Mitigation of power quality issues due to high-penetration of renewable energy sources in electricgrid systems using three-phase apf/statcomtechnologies: A review," in *Power Electronics in Renewable Energy Systems* (T. Suntio and T. Messo, eds.), 2019.

[4] J. Caldwell, *Analog Pulse Width Modulation*. texas instruments, June 2013.

[5] S. Colley, "Pulse-width modulation (pwm) timers in microcontrollers." Online, Feb. 2020.

[6] N. Mohan, *Power Electronics: A First Course*. Don Fowley, Oct. 2011.

[7] N. Mohan, *Power Electronics a First Course*, ch. 4: Switch Mode DC-DC Converters: Switching Analysis, Topology Selection and Design, pp. 38–68. Don Fowley, 2012.

[8] B. Hauke, "Basic Calculation of a Buck Converter's Power Stage," tech. rep., Texas Instruments, Aug. 2015.