AN3725

Buck Converter Design and Feedback Controller Using Core Independent Peripherals

Features

- An Implementation of a PWM Feedback Controller for Buck Converters Using Core Independent Peripherals is Presented
- Hardware Design Guide for a Simple Buck Converter
- Component Value Calculations for Buck Converter
- Component Value Calculations for Error Amplifier
- Code Example is Available in Atmel START

Introduction

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Switch mode power supplies are more efficient at DC-DC conversion than typical linear voltage regulators but can often be overlooked because of the higher complexity and cost related to them. Dedicated controller ICs will typically only operate with predetermined voltage ranges and switching parameters, meaning that different designs have to be used in different use cases. Implementing the switching controller using the core independent peripherals of the AVR® DB family of microcontrollers makes for a highly flexible system, adding only passive components to the bill of materials, thereby reducing the number of more expensive ICs.

This application note shows how to implement a feedback switching controller for a buck converter using the core independent peripherals of the AVR DB family of devices. After the initial set-up, the core independent peripherals are independent of the CPU, allowing the microcontroller to do any other task in parallel.

In 2. Closed Loop Voltage Control using Core Independent Peripherals, a short overview of the feedback controller is given, as well as how to implement it using the core independent peripherals. The general design of the buck converter is covered in 3. Component Selection - Buck Converter. Setting the output voltage of the buck converter is covered in 4. Setting Output Voltage, while 5. Component Selection - Error Amplifier goes over the principles for PWM generation and design of the error amplifier compensation network. Finally, some measured characteristics of an example implementation are presented in 6. Results.

This application note does not go into detail on aspects like efficiency and time variance in current and voltage or layout considerations. Other application notes, linked below, go into more detail and can be used in conjunction with this application note to provide a deeper understanding of the subject.

- AN968 - Simple Sychronous Buck Regulator
- CIP Hybrid Power Starter Kit User's Guide

The available schematics of the CIP Hybrid Power Starter Kit can be used as a reference for layout and component selection.

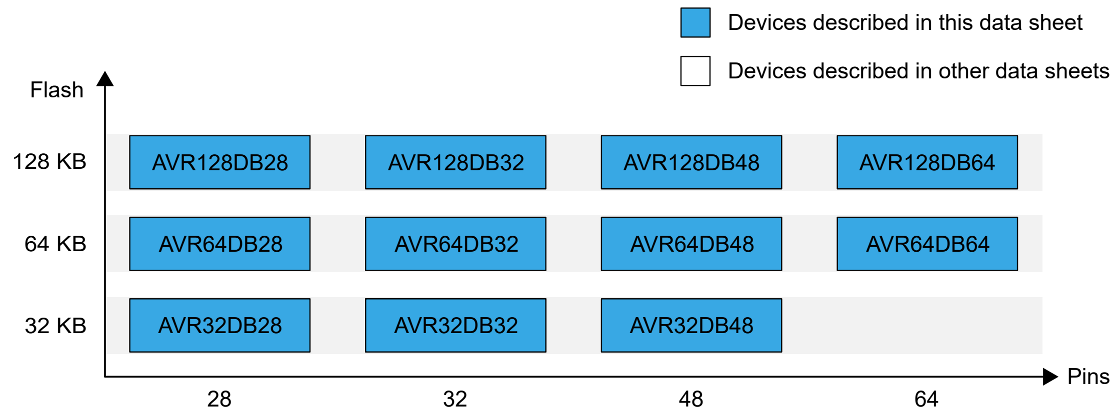
Table of Contents

1. Relevant Devices

This section lists the relevant devices for this document. The following figures show the different family devices, laying out pin count variants and memory sizes:

- Vertical migration upwards is possible without code modification, as these devices are pin-compatible and provide the same or more features
- Horizontal migration to the left reduces the pin count and, therefore, the available features
- Devices with different Flash memory sizes typically also have different SRAM and EEPROM

Figure 1-1. AVR® DB Family Overview



2. Closed Loop Voltage Control using Core Independent Peripherals

A buck converter uses periodic switching to step down the input voltage, V_{in}. This is achieved by controlling a power MOSFET using a PWM signal. The duty cycle of this signal decides the output voltage of the regulator, but, as the output voltage of the buck converter would naturally vary based on differences in load current, the PWM signal needs some kind of feedback regulated switching controller to compensate for this.

Figure 2-1 shows the basic layout of such a controller. It is implemented using an error amplifier, analog comparator and a ramp signal to adjust the duty cycle of the switch on the buck converter based on feedback from the output. With the introduction of the op amp peripheral of the AVR® DB family of microcontrollers, it is possible to implement this control system using only core independent peripherals with some external resistors and capacitors. By combining the voltage regulation of a system with the microcontroller, the cost of the system, as well as complexity, can be reduced by eliminating the need for a dedicated controller IC. The controller also adds the ability to adjust the output voltage in software, making it a practical solution for digitally adjustable power supplies and fine adjustment to compensate for tolerances in external components.

Figure 2-1. Closed Loop Voltage Control With Type 3 Error Amplifier

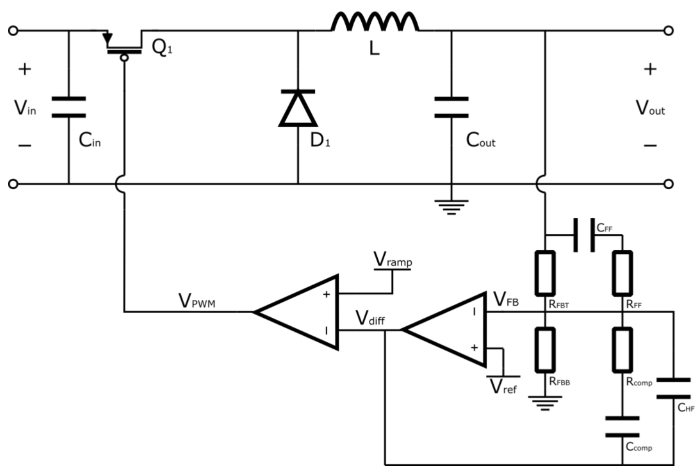


Figure 2-2 shows the internal and external connections on the AVR DB to implement this controller. The code for the configuration of the peripherals is available through Atmel START. Additional components, as seen in Figure 2-3, are needed to achieve proper amplification and phase compensation through the error amplifier, as well as a simple RC-filter, which is used to shape the square wave output of the timer to be used as the ramp voltage for PWM-generation.

Figure 2-2. Closed Loop Voltage Control Using Core Independent Peripherals

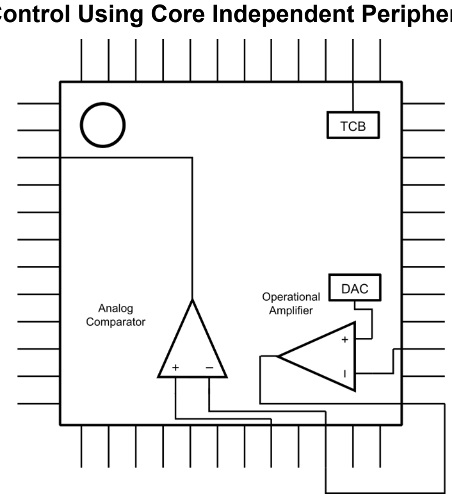
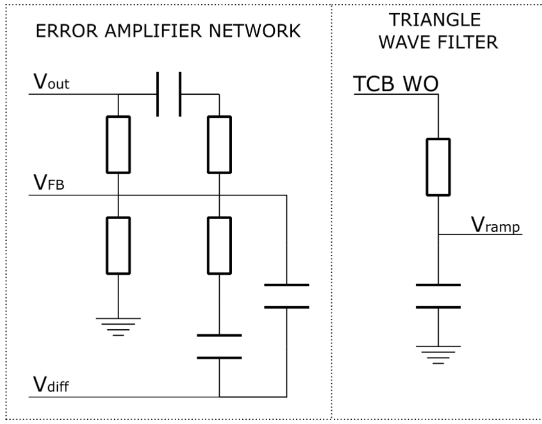


Figure 2-3. Error Amplifier Compensation Network and Ramp Generator



2.1 Peripheral Configuration

Some of the important considerations when configuring the peripherals are mentioned below. For a complete setup, see the code example on Atmel START.

All peripherals are set up to run in Standby sleep mode to allow the microcontroller to enter its most power-efficient sleep mode available while still regulating the buck converter.

2.1.1 Op amp and DAC

The op amp is configured as a standalone general purpose operational amplifier. As the error amplifier configuration needed for proper feedback regulation in buck converters is specific for this use case, there is no internal functionality for this. To implement the external feedback network, the negative input of the op amp is configured as a pin input, and the output needs to be enabled. The positive input is internally connected to the DAC output.

The regulation process is active, meaning that the peripheral needs to be configured in “always on” mode.

The DAC is used to set the reference voltage for the error amplifier. The value for this voltage is set to provide good headroom in both directions in the op amp. A good starting point is to set it close to half of the supply voltage of the microcontroller.

2.1.2 Analog Comparator

The Analog Comparator (AC) is configured to compare voltages on external inputs. As the AC generates the PWM signal used to control the switching transistor, the output is routed to a pin. The comparator must have a fast response time. As a result, the power profile setting with the shortest response time and highest power consumption is chosen as a tradeoff since the power profile setting controls the current through the comparator.

2.1.3 Timer Counter B

The Timer Counter B (TCB) peripheral is chosen over the Timer Counter A (TCA) as it has a lower power consumption. The peripheral is configured in 8-bit PWM mode with a duty cycle of 50%, and the output is filtered through an RC-filter, shaping the signal so that the comparator can use the resulting triangle wave to generate the PWM signal. The frequency of the waveform generated by this peripheral will set the switching frequency, f_{SW}, of the controller.

3. Component Selection - Buck Converter

Components chosen in the buck converter, shown in Figure 3-1, have to be correctly dimensioned based on the needs of the rest of the system. As Switch mode regulation is inherently imperfect for generating a constant stable output voltage, some variation is to be expected in regards to the output voltage and current. Table 3-1 shows the parameters that must be specified to calculate the values of the components in the circuit. Based on the needs of the system, the designer decides the accepted limits for these variations, along with the operating voltages and power ratings.

Figure 3-1. Buck Converter

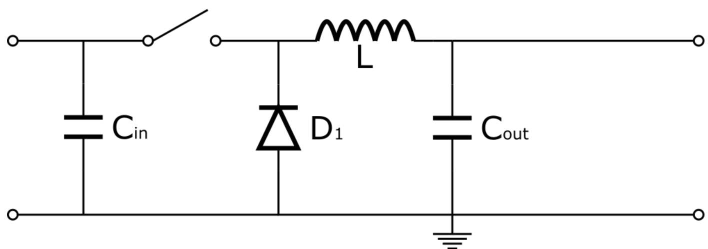


Table 3-1. Power Supply Parameters

Input voltage	V_{in}
Output voltage	V_{out}
Maximum power	P_{max}
Output voltage ripple	ΔV_{out}
Inductor current ripple	ΔI
Switching frequency	f_{SW}

3.1 Inductor and Input/Output Capacitor

The first choice of components is the inductor, L, which is used in conjunction with the output capacitor, C_{out}, for filtering the output voltage, stabilizing it around the targeted output voltage. The main consideration for this component is to limit the current ripple in the regulator, and its value is, therefore, based on the specified inductor current ripple, ΔI:

$$L = \frac{V_{in} - V_{out}}{\Delta I} \cdot \frac{D}{f_{SW}}$$

Where $D = V_{out}/V_{in}$ is the duty cycle of the switch. In situations where a range of input voltages is required, the inductor is dimensioned for the highest rated voltage, as this is when the ripple current is largest.

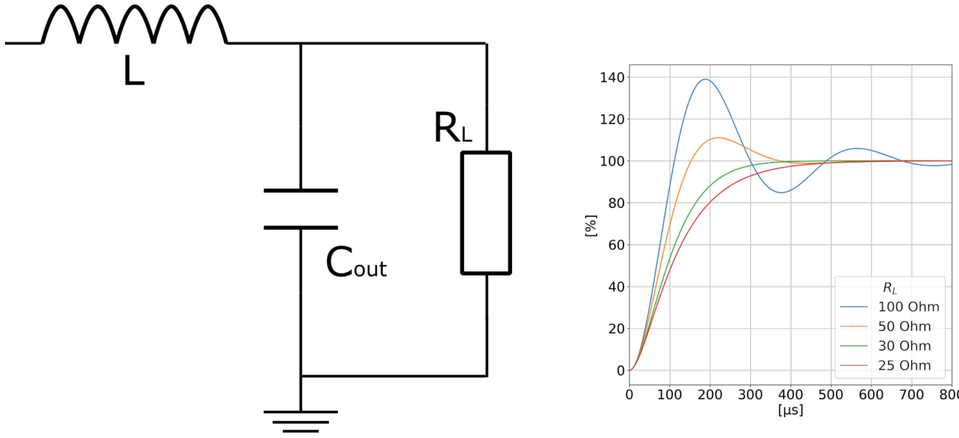
C_{out} is chosen next to complete the output filter. The charge in the capacitor will counteract the output voltage ripple and, therefore, its value is decided according to the maximum output voltage ripple, ΔV_{out}. Its minimum value can be calculated using the following equation:

$$C_{out} = \frac{\Delta I \cdot D/f_{SW}}{\Delta V_{out}}$$

Add an input capacitor to stabilize the voltage further. This value can be calculated in the same way as the output capacitor, but for most applications, a 10 µF ceramic capacitor will suffice.

The duty cycle used in the calculations above does not take into consideration the changes in the load resistance, R_L, which affect the step response of the output filter, as seen in Figure 3-2. A margin of 10-20% may be added to the maximum duty cycle to make sure the components are within specs for the full operating range.

Figure 3-2. Step Response of RLC-Filter



Note: In addition to choosing components based on calculated values and desired characteristics, all components must be dimensioned to handle the maximum current and voltage in the circuit.

3.2 Rectifier and Switch

Choosing the rectifying diode and switching transistor is done in such a way that they exhibit as close to ideal switch behavior as possible. The following is a few points to take into consideration when choosing the switching transistor:

Switching Transistor

- Low figure of merit
- Low ON-resistance
- High switching speed
- V_{DS} rating to handle voltage spikes
- Ability to switch using the logic level of the controller

If the input voltage of the buck converter is higher than the logic level of the microcontroller, additional circuitry is needed to achieve reliable switching. The figures below show two such options for switching circuitry that always satisfies the requirement of operating the switching transistor using the logic level of the switching controller. An N-channel MOSFET will typically have a lower on-resistance than a P-channel MOSFET, meaning that Figure 3-4 will have a higher efficiency than Figure 3-3, but at the cost of some additional complexity in the supporting circuit.

Figure 3-3. Buck Converter With PMOS-Switch

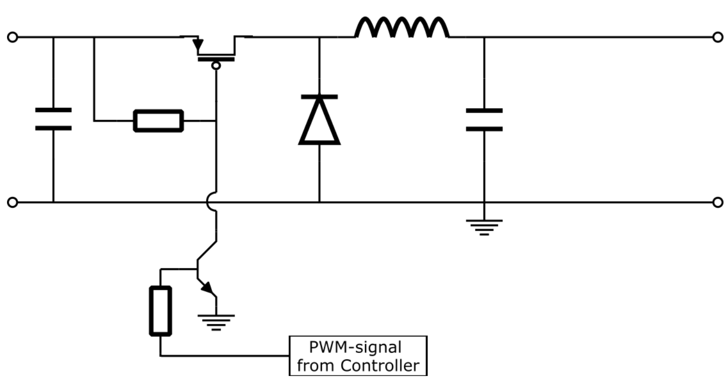
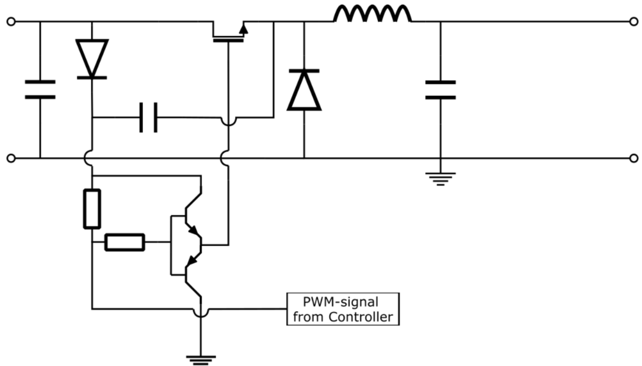


Figure 3-4. Buck Converter With Bootstrapped NMOS-Switch



The diode choice is made to minimize the forward voltage, as the power loss in the diode is proportional to the forward voltage and driving current, meaning that the power loss can become substantial for regulators delivering higher currents. Typically, a good diode choice will be a Schottky diode with low forward voltage and sufficient power rating.

For applications that require smaller losses in the rectifying circuit, a synchronous solution can be implemented by replacing the diode with a MOSFET. As the switching transistor and the rectifying MOSFET can never be turned on at the same time, additional logic has to be added to introduce dead time control. However, only the most basic solution with a simple diode is outlined in this application note.

4. Setting Output Voltage

Figure 4-1. Constant Output Buck Converter Network

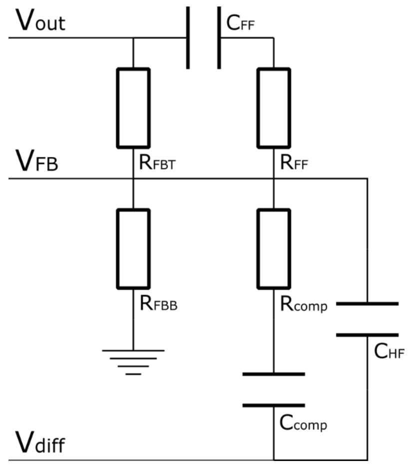


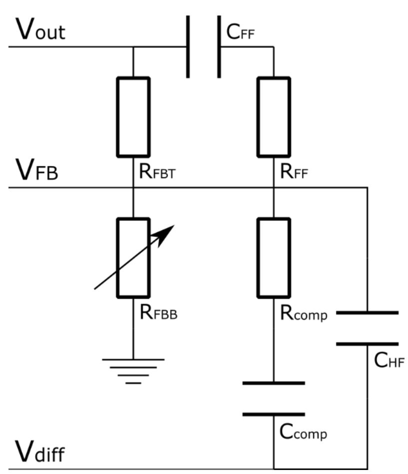
Figure 4-1 shows the complete feedback network needed. As the capacitors block DC voltages, the feedback resistors R_{FBT} and R_{FBB} will set the feedback voltage, V_{FB}, by attenuating the buck converter output voltage, V_{out}. Knowing this, the V_{out} of the buck can be set. The resulting feedback voltage, V_{FB}, of this voltage division will equal the internal reference voltage V_{ref} when V_{out} is at the desired level. The resulting relation between the resistors and the reference voltage is given by:

$$V_{out} = V_{ref} \cdot \frac{R_{FBT} + R_{FBB}}{R_{FBB}}$$

$$\Rightarrow R_{FBT} = R_{FBB}\left(\frac{V_{out}}{V_{ref}} - 1\right)$$

This feedback controller uses the internal DAC as the reference voltage, meaning that the output voltage can be adjusted in software. It does, however, not allow for very large adjustments, as the amplifier might have undesired characteristics closer to its supply voltage.

Figure 4-2. Variable Output Buck Converter Network With Variable Resistor



For applications using an adjustable output regulator, the bottom resistor R_{FBB} is replaced by a variable resistor, such as a potentiometer, as seen in Figure 4-2. This is important as the top resistor R_{FBT} is a part of the phase compensation network in the error amplifier, while R_{FBB} does not affect the poles of the system.

Note: Typical values for these resistors fall in the range of 20-200 kΩ. Higher values than this can affect the stability of the op amp, while lower values will draw unnecessary amounts of current, resulting in lower efficiency.

5. Component Selection - Error Amplifier

5.1 Importance of Poles

The function of the error amplifier is to output a signal relating to the deviation between the output voltage and a reference voltage. To use this principle in a switching controller, however, we also need to compensate for phase effects in the output filter. This ensures that the switch reacts in phase with the voltage on the input on the buck converter filter and not the output voltage, V_{out}. Identifying the poles and zeroes generated by the output filter, as well as the bandwidth, is the first step in designing this compensation network and is given by:

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

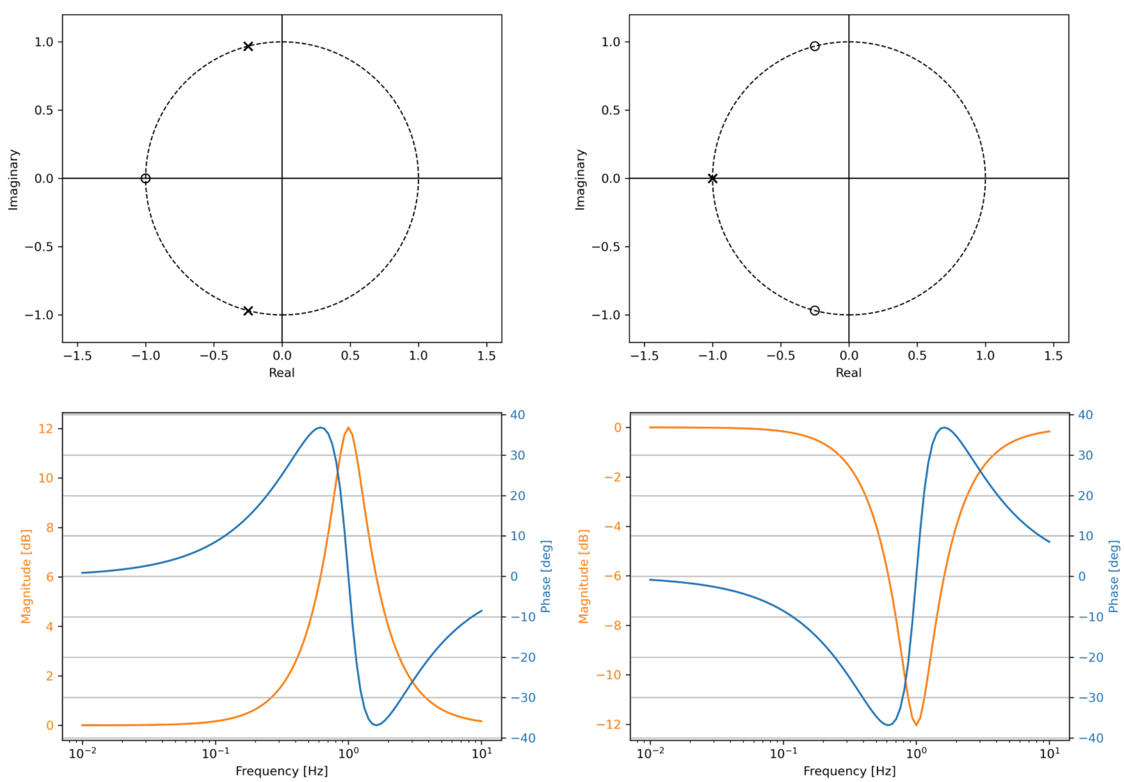
$$\omega_Z = \frac{1}{R_{ESR} \cdot C_{out}}$$

$$\omega_c = 2\pi \cdot \frac{f_{SW}}{10}$$

where ω_0 is the pole given by the LC output filter. ω_Z is given by C_{out}, where R_{ESR} is the equivalent series resistance of the capacitor. The bandwidth, ω_c, is given by the switching frequency, f_{SW}.

The effects of poles and zeros of the output filter will be canceled out by setting the amplifier zeros equal to output filter poles and amplifier poles equal to output filter zeros. Figure 5-1 shows the poles and zeros as well as the Bode plot of two complementary systems to illustrate the effects of the different parts of this system. The complementary poles and zeros to the output filter of the buck converter are added to the system by the resistors and capacitors in the feedback network, Figure 2-3.

Figure 5-1. Pole-Zero Plot and Bode Plot for Complementary Pole-Zero Systems

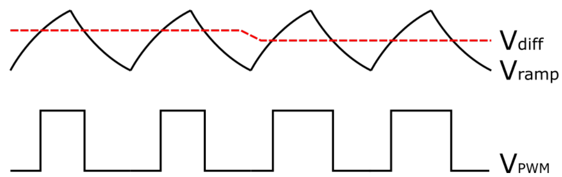


5.2 PWM Generation

The PWM signal is generated using the error amplifier and the voltage ramp generated by the filtered waveform output of the TCB. As seen in Figure 5-2, the error voltage, V_{diff}, on the output of the op amp sets the duty cycle in relation to the voltage ramp, V_{ramp}. This means that to achieve good regulation, the amplification factor must therefore be set in relation to the amplitude of the ramp signal generated by the TCB waveform generator and filter. Taking into account the effects of ω_c and ω_0, the amplification factor A_{VM} can be set:

$$A_{VM} = \frac{\omega_c}{\omega_0 \cdot V_{in}} \cdot V_{ramp}$$

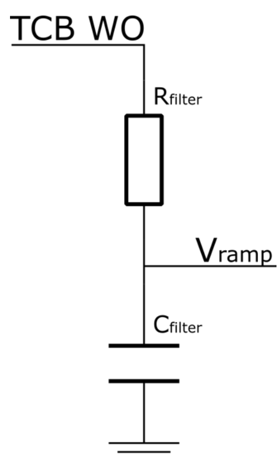
Figure 5-2. PWM Generation



Generating the ramp signal, V_{ramp}, is done by filtering the square wave output of the timer with an RC-filter. The amplitude of the signal is decided based on the accuracy and responsiveness of the op amp in the controller, meaning the better characteristics in the op amp will allow for lower amplitudes, which will lead to a more efficient system. Knowing this, the components for the triangle wave filter can be set using the equation for charging a capacitor in the RC circuit, seen in Figure 5-3, like this:

$$C_{filter} = -\frac{1}{f_{sw} \cdot R_{filter} \cdot \ln\left(1 - \frac{V_{ramp}}{V_{cc}}\right)}$$

Figure 5-3. Triangle Wave Filter



where V_{CC} is the supply voltage of the microcontroller. The switching frequency, f_{SW}, is set as the frequency in the TCB, as described in 2.1.3 Timer Counter B.

5.3 Component Selection

Knowing the poles, zeros and the appropriate amplification factor, the rest of the components in the compensation network can be calculated.

The gain is set by the ratio between R_{comp} and R_{FBT}. As R_{FBT} and A_{VM} are set previously, R_{comp} can be calculated as the product of these:

$$R_{comp} = A_{VM} \cdot R_{FBT}$$

Setting the first zero of the amplifier is done using C_{comp} and R_{comp}, while the other is set by C_{FF} and R_{FBT}. These will fall on the output filter poles, resulting in the following capacitor values:

$$C_{comp} = \frac{1}{\omega_0 \cdot R_{comp}}$$

$$C_{FF} = \frac{1}{\omega_0 \cdot R_{FBT}}$$

The first pole of the amplifier is set by the combination of C_{HF} and R_{comp}, and the second is set using R_{FF} and C_{FF}. Setting the pole resulting from C_{HF} and R_{comp} equal to half the switching frequency, f_{SW}, and the pole resulting from C_{FF} and R_{FF} equal to the zero generated by the output capacitor and its series resistance gives the following equations for C_{HF} and R_{FF}:

$$C_{HF} = \frac{1}{2\pi \cdot f_{SW}/2 \cdot R_{comp}}$$

$$R_{FF} = \frac{1}{\omega_Z \cdot C_{FF}}$$

Note: The calculated values typically fall outside standard values for the components. In this case, the closest available standard value may be chosen. Larger deviations from the calculated components can result in slower switching response as the phase of the input and regulation signals fall out of sync. The system will typically still handle the regulation, but lower efficiency and higher output ripple is to be expected.

6. Results

The test results provided in this application note are meant only as indications of the capabilities of a system like this. Several factors as layout, switching frequency, component accuracy, and more will influence the final result. Layout considerations and component accuracy was purposefully not optimized in the testing to give a better starting point for less experienced designers, which means it will be possible to achieve higher performance by optimizing the design to reduce loss and increase stability.

Table 6-1. Power Supply Specifications

Input voltage	V_{in}	5-24V
Output voltage	V_{out}	5V
Maximum power	P_{max}	5W
Output voltage ripple	ΔV_{out}	50 mV
Inductor ripple current	ΔI	215 mA
Switching frequency	f_{sw}	100 kHz

Table 6-2. Components

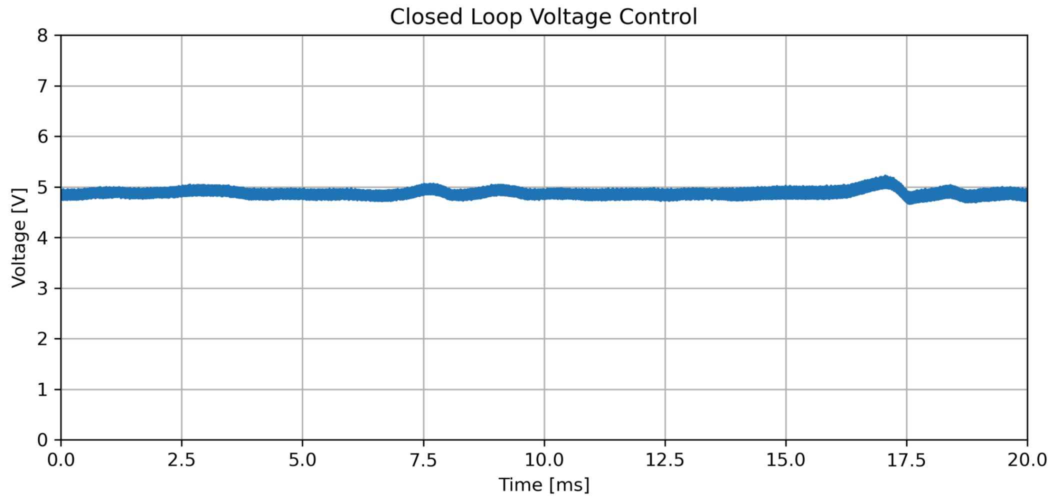
	Ideal Value	Used Value
L	220 µH	220 µH
C_{out}	10 µF	10 µF
R_{FBT}	3.31 kΩ	3.3 kΩ
R_{FBB}	1 kΩ	1 kΩ
R_{comp}	84.9Ω	85Ω
C_{comp}	552.6 nF	600 nF
R_{FF}	105.8Ω	100Ω
C_{FF}	14.2 nF	15 nF
C_{HF}	37.5 nF	40 nF

A bootstrapped ILB88721 N-channel MOSFET was used for switching in conjunction with a 1N4007 rectifying diode, which both are rated for more power than P_{max}.

6.1 Output Voltage Characteristics

The output voltage maintains a stable level for input voltages ranging from 5.5V to 24V while driven with 3W on the load. While some larger ripples can be seen in Figure 6-1, most noise is high-frequency switching noise, which can be eliminated using decoupling capacitors or other simple filtration methods. The average output voltage is slightly below the target voltage of 5V, though if higher accuracy is needed, this can be tuned using R_{FBB} or adjusting the op amp DAC-reference.

Figure 6-1. Output Voltage - Buck Converter using AVR128DB Voltage Controlled Feedback Regulation



6.2 Maximum Ratings

As mentioned in 6.1 Output Voltage Characteristics, the power supply was tested to a maximum input voltage of 24V and remained stable on the output. The theoretical maximum input voltage is decided by the target output voltage and the minimum duty cycle of the PWM signal.

The power supply was also tested to a maximum output power of 5W at an input voltage of 12V. While under this load, the output voltage remained stable. In a less than optimal system, there will be quite substantial switching losses in the transistor, meaning that good heat dissipation is important. These losses reduce efficiency in the circuit. For better performance, chose a switching topology with low on-resistance and fast switching

7. Revision History

Doc. Rev.	Date	Comments
A	11/2020	Initial document release

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