A CubeSat Power System Implementing a Zero Voltage Switching Resonant Buck Converter Design with Low Electronic & Radio Frequency Noise

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ABSTRACT

Noise from power systems can be a limiting factor in how well scientific instruments on CubeSats can perform. Instruments such as microwave radiometers which are on TROPICS, TEMPEST-D, and IceCube, or wide-band software defined radios such as those used on AERO/VISTA for Earth auroral hiss observations, or precipitation instruments used on RainCube are all affected by electronic and radio frequency (RF) noise. Current hybrid DC/DC converter technologies can also be prone to failure and anomalies during flight. The GRACE mission had the converter fail due to high temperatures, which caused a reduction in switching frequency. This research project will provide a way for CubeSat power subsystems to become more optimized and efficient by reducing the noise produced, enabling CubeSats to support a wider range of science missions. This paper presents a design for a CubeSat power subsystem that uses a phase-locking control scheme where the voltage ripple and RF noise can be significantly reduced so that the power converter does not affect the CubeSat instruments. CubeSats are now returning valuable scientific data and can improve temporal and spatial coverage. Optimizing CubeSat power subsystems enables its payload to become more effective.

INTRODUCTION

CubeSats are small satellites with lower Size, Weight, and Power resources and deployment cost. CubeSats allow for the testing new payload technologies, such as testing novel weather instruments. CubeSats also can be deployed in large numbers to improve temporal and spatial coverage. However, there is a need for power systems that are both efficient and low noise.

Motivation

In NASA's Strategic Plan for the years 2018-2021, it states, "A balanced science program proactively identifies potential technologies required to meet future mission requirements, conduct trade studies, assess development risks, and invests in new technologies well in advance of mission implementation. NASA is also expanding the use of lower-cost CubeSats and SmallSats to accomplish our science goals." [1] NASA has an interest in the development of CubeSats since they are cost effective ways of testing new and improved technologies. They are less expensive to build as well as launch. To be able to optimize the performance of CubeSats, we seek to better support payload instrument sensitivity. In the 2020 NASA Technology Taxonomy, it mentions "Remote sensing instruments and sensors include components, sensors, and instruments sensitive to electromagnetic radiation; particles (charged, neutral, dust); electromagnetic fields, both direct current (DC) and alternating current (AC)..." [2] Current hybrid converter technologies can generate RF noise and other electromagnetic interference (EMI). DC/DC converters can also have anomalies and failures. For example, the GRACE mission had reported converter failure due to high temperatures, which caused a reduction in switching frequency [3][4]. Other missions involving the International Space Station and Hubble Space Telescope have also reported converters having failed during flight [3]. This research project will provide a solution for a CubeSat power subsystem to become more optimized and efficient by reducing the noise produced. This will pave the way for CubeSats to support a wider range of missions.

Noise

Noise from power systems can be a limiting factor in how well scientific instruments on CubeSats can perform. Instruments such as microwave radiometers which are on TROPICS, TEMPEST-D, and IceCube, or wide-band software defined radios used on AERO/VISTA for Earth auroral hiss observations, or precipitation instruments used on RainCube are all affected by electronic and radio frequency (RF) noise.

An example of the difference between noise and a desired signal is shown in Fig. 1.

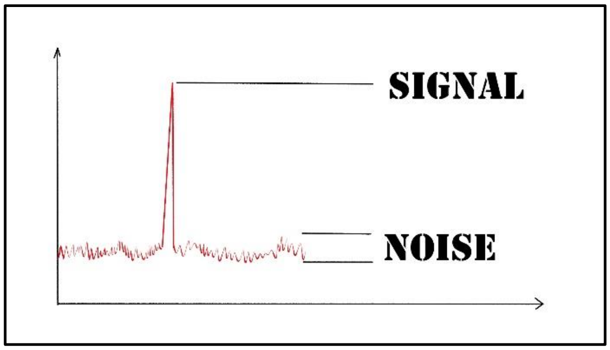


Figure 1: Noise vs. Desired Signal [5]

CubeSats currently use low-dropout (LDO) linear regulators to address this issue, but LDOs are limited in their ability to optimize power control, and perform unreliably in extreme temperatures. This is why a more optimized DC/DC power converter that has reduced noise is needed.

Noise does not just affect an instrument's measurement values but can also affect a camera sensor's imaging on a CubeSat. Fig. 2 [6] shows sample images collected with the Jet Propulsion Laboratory's (JPL's) AIRSAR P-band radar system.

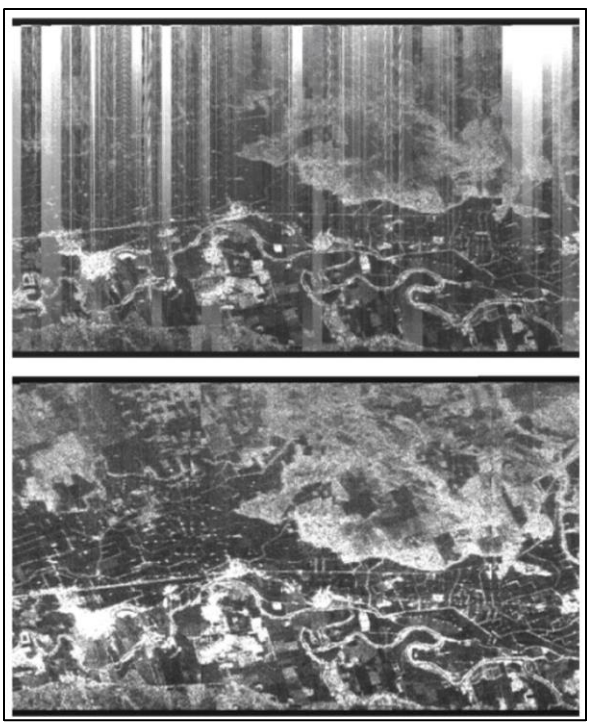


Figure 2: Sample images collected with the Jet Propulsion Laboratory's (JPL's) AIRSAR P-band radar system. [6]

The first image shows how the noise corrupts the pixels, causing the image to become disjointed and whited-out. The second image was taken after a noise mitigation technique was applied to the AIRSAR P-band radar system. Fig. 2 shows how important decreasing the amount of noise for instruments is as it affects its performance.

A noise evaluation study was done on a basic buck converter with a 200kHz switching frequency. RF probes and a spectrum analyzer were used. The results are shown in Fig. 3 [7].

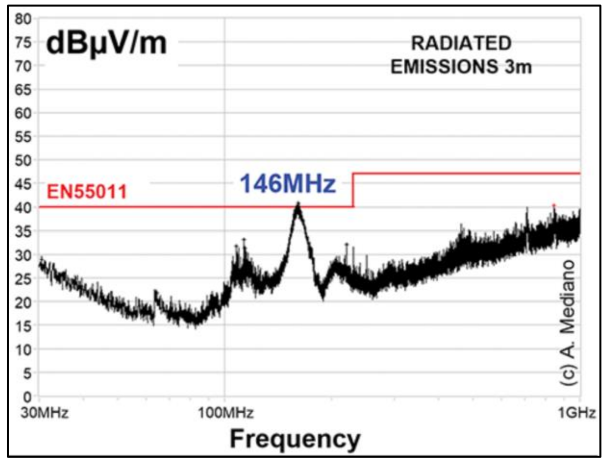


Figure 3: Test study of noise of a buck converter measured by near field probes [7]

Noise peaked at about 150 MHz for the output of the buck converter. This measurement is used as the baseline goal of the buck converter design. The goal is to be 150MHz or less to be able to provide the best results for the resonant buck converter. It is concerning that a 200kHz switching converter can have a noise peak at 150MHz. This shows why CubeSats need to address the noise issue of the power converter instead of simply integrating noise mitigation techniques in sensor instruments.

CubeSats currently use low-dropout (LDO) linear regulators to address the noise issue the buck converter creates, but LDOs are limited in their ability to optimize power control and perform unreliably in extreme temperatures. This is why a more optimized DC/DC power converter that has reduced noise is needed.

DC/DC POWER CONVERTERS

The DC/DC power converters, when regulating power in CubeSats, use switching voltages where one DC voltage level is converted to either a higher or lower DC voltage level. It switches at high frequency in the circuitry, effectively keeping the voltage at the panel constant by varying the current [5]. Although this method is power-efficient, it generates high amounts of noise due to harmonic frequencies from switching. This work focuses on the development of a DC/DC power converter design that will be applicable for all power converters in the electrical power system (EPS) for a CubeSat. An example of a typical CubeSat EPS layout and power converters is shown in Fig. 4 [8].

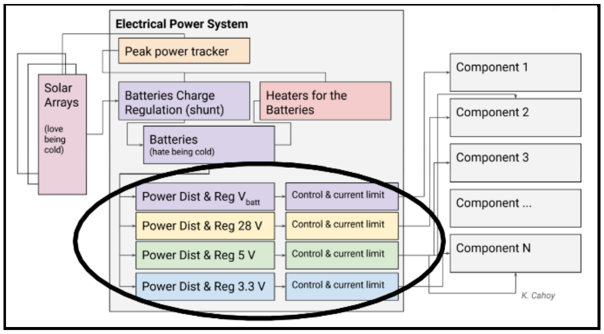


Figure 4: Block diagram of a typical CubeSat power system [8]

The typical electrical characteristics of a DC/DC power converter in the EPS of a CubeSat are shown in Table 1.

Table 1: Electrical Characteristics of a DC/DC Power Converter

Description	Conditions	Min	Typical	Max	Unit
Input Voltage		7.4	--	30	V
Output Voltage	5V Bus	4.95	5	5.05	V
	3.3V Bus	4.4	4.5	4.6	V
Switching Frequency	For 5V & 3.3V	150	175	200	kHz

The noise the power converter produces affects the scientific measurements being made. A solution to this problem is to design, build, and test a DC/DC power converter with a low-noise circuit design that reduces noise by phase-locking, and switches at high frequencies which will be discussed in the Future Work section of this paper. A simple buck converter schematic is shown in Fig. 5.

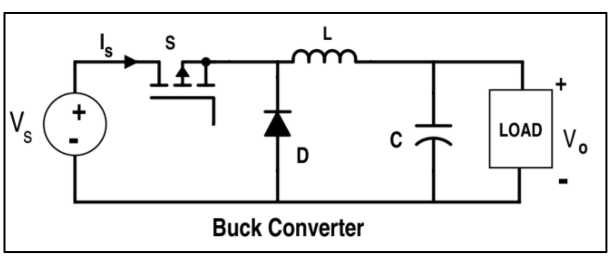


Figure 5: DC/DC Buck Converter Schematic [9]

Although this type of power converter is noisy, it is still widely used due to its compact and simplistic design and it is also inexpensive to manufacture and buy. The goal of the buck converter is to step-down the voltage from the input source to the output load.

The first two versions of the buck converter design were used to create a strong base for the resonant buck converter design. The basic buck converter needed to be tested to understand how much noise is being produced by the converter and where the noise is being produced. Version 1 will be used to make sure the buck converter is working and work out any issues. Version 2 will finalize the basic buck converter design and will be used for the base for Version 3 which is detailed in the Future Work section.

CAMERA SENSOR

A Raspberry Pi is a single board computer that consists of various systems-on-chip. Raspberry Pis are ubiquitous in CubeSats due to its simplistic design and being easily accessible at a low cost. Therefore, the test payload in this research will be a Raspberry Pi connected to a Raspberry Pi camera sensor which the developed DC/DC power converter and circuit will have to provide power to the Raspberry Pi to operate it.

Fig. 6 shows the connection between the buck converter, the Raspberry Pi, and the camera sensor.

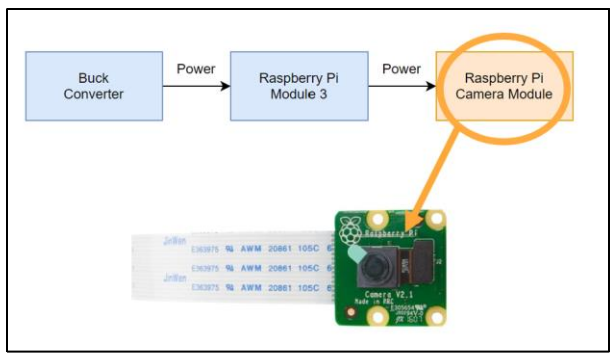


Figure 6: Block Diagram Highlighting Camera Sensor

The goal of the project is to measure the noise of a buck converter while powering the camera sensor. Instead of using the camera sensor to take pictures with a button press, a more consistent method was used to make sure the camera was running continuously while making the noise measurement. When the Raspberry Pi is powered on, the startup sequence includes the code to instantly turn on the camera sensor to do a video stream.

DESIGN OF BASIC BUCK CONVERTER

Fig. 7 shows the Version 2 of the buck converter PCB schematic.

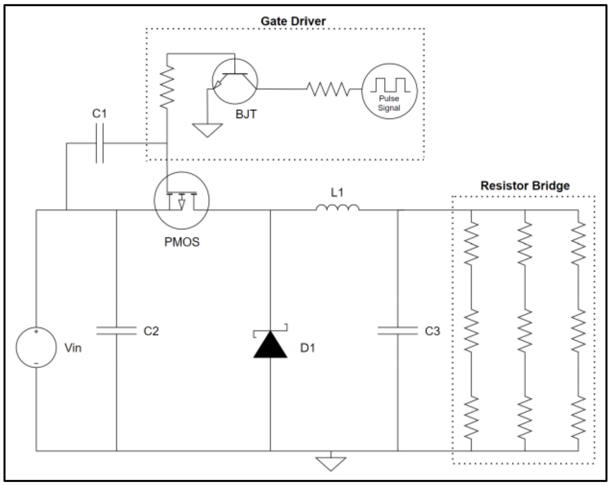


Figure 7: Buck Converter Design Schematic

The gate driver consists of an amplifier using an NPN BJT with a resistor connected to a PWM signal. The BJT drives the PMOS that then drives the diode to switch. The Version 1 buck converter schematic included a gate driver chip instead of the amplifier, but the chosen chip didn't work properly, so an amplifier circuit was used to drive the PMOS instead.

Table 2 shows the component values and specifications of the Buck Converter.

Table 2: Buck Converter Components & Specifications

Description	Value
Vin	12V
Vout	5V, 3A
C1	10uF
C2	50uF
C3	5uF
L1	20uH
Resistor Bridge	1.6 Ohms
Switching Frequency	200kHz

C1 and C2 act as capacitive filters to filter out the noise from the input voltage Vin coming from a power supply (battery, solar cells, etc.). The resistor bridge was chosen so that it would be able to withstand a higher wattage with a lower load resistance value, so that it outputs 5V and 3A. The resistor bridge is made up of nine 1.6 ohm resistors that can handle 3W each. The total wattage that the output of the buck converter can withstand roughly 20W.

Fig 8 shows Version 1 of the buck converter design.

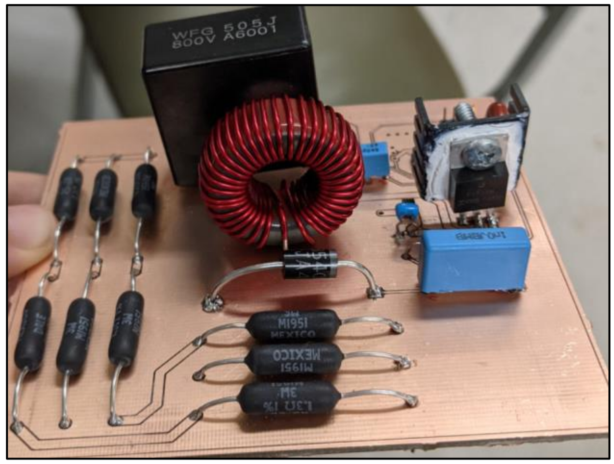


Figure 8: Version 1 Buck Converter PCB Top View

The problem with Version 1 is how big the board is. The board is not compact which will increase the amount of noise even without the noise output coming from the MOSFET switching. The thickness between the traces and the ground copper were not thick enough so areas around the gate of the MOSFET were accidentally shorted during soldering which led to the gate driver chip not functioning properly.

Fig. 9 shows the top view of Version 2 of the buck converter PCB with the soldered components.

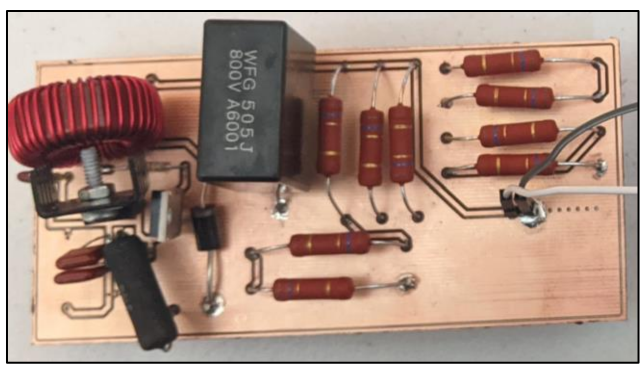


Figure 9: Version 2 Buck Converter PCB Top View

The PMOS (Infineon Hexfet) and Schottky diode were chosen to be able to handle the fast switching at higher frequencies to reduce loss and switching noise on the diode. The BJT was chosen to have a high amperage tolerance of 6A to be able to handle the high current and voltage needed to drive the PMOS.

A metallized polypropylene film capacitor was chosen for C3 because it is mostly used for automotive applications, where it performs well in switching DC/DC converters and high frequency and current circuits. The importance of selecting a capacitor that can handle a switching application has to do with the ESL and ESR values. ESR is the Equivalent Series Resistance and ESL is the Equivalent series Inductance.

A high ESR value will cause the capacitor to dissipate heat in high current applications. A low ESR values helps with filtration purposes which overall helps the performance of a circuit such as a buck converter.

A high ESL value will generate high amounts of noise at high frequencies. It will also cause the capacitor to malfunction. A voltage ringing will be generated, causing the circuit to perform oddly.

A toroidal choke inductor was chosen for L1 because it acts like a low pass filter for high frequency switching PWM signals. At such a high frequency, the inductor is still able to perform as an inductive component without concern about it turning capacitive.

The fabrication of the PCB was made as small as possible to be able to reduce the amount of noise travelling between the components' current paths. The paths were made as thick as possible to be able to handle the high amount of current being outputted by the converter.

RASPBERRY PI MODULE 3 & CAMERA

Fig. 10 shows a block diagram of the project setup

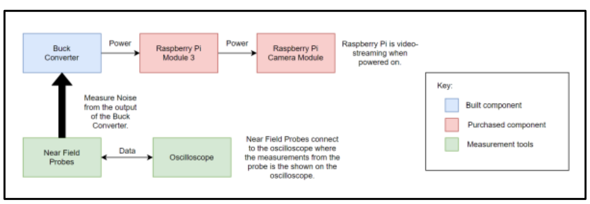


Figure 10: Block Diagram of Project Setup [Christine Page]

The buck converter is the only built component in this setup. The Raspberry Pi Module 3 and Raspberry Pi camera module were purchased. The near field probes and oscilloscope were acquired as measurement tools.

The goal is to have the buck converter connect to the Raspberry Pi Module 3 and power it. The Raspberry Pi Module 3 would then be powering the Raspberry Pi camera, acting as a connector between the buck converter and camera sensor. The connector is needed due to the buck converter not having controls to be able to regulate the voltage output to be able to power the camera sensor safely due to the time constraints of this phase of the project. When the Raspberry Pi Module 3 powers on, the camera sensor is coded to immediately turn on and to begin to start video-streaming.

Fig. 11 shows the physical setup of the devices shown in Fig. 10.

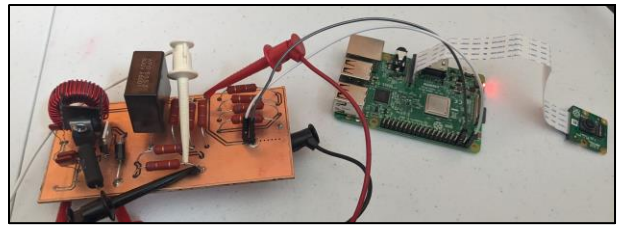


Figure 11: Physical Setup of Buck Converter Powering Camera Sensor

The buck converter does not have its own power supply, so a power supply is used to input 12V. The power supply is connected to the supply node of the MOSFET. A function generator is connected to drive the BJT that then drives the MOSFET. A multimeter is connected to the output of the converter to make sure the output is 5V as to not blow up the Raspberry Pi. The output is then connected to the input and ground of the Raspberry Pi. The red light indicates that the Raspberry Pi is powered up.

NOISE EVALUATION

Switching Noise on Oscilloscope

A visual way to see where most of the noise on the output is being generated is to use the oscilloscope and focus on the voltage waveform on the diode and the output.

The switching on the diode has ringing when the PMOS switches off, causing the noise on the output, as shown in Fig. 12.

Figure 12: Voltage Waveform of Diode & Output Load

The yellow waveform is the voltage waveform across the diode. The green waveform is the voltage waveform across the output (resistor bridge).

The ringing is caused by the current harmonics produced by the fast switching of the PMOS and diode.

Zooming in on the ringing on the diode switching and output is shown in Fig. 13.

Figure 13: Switching Noise Waveform of Diode & Output Load

The amount of noise due to the switching can be measured on the oscilloscope. The amount of switching noise caused by the diode is around 25 MHz when including the capacitive filters C1 and C2. Without the filters, the switching noise was 50 MHz.

The higher the switching frequency, the higher the amount of noise is expected. With a 200kHz switching frequency, roughly 150MHz of noise due to switching was expected based off a test case study [9]. By carefully selecting components that had noise reduction and making the board layout as small as possible, the amount of noise produced was reduced by 87% of the expected.

Increasing the capacitive filter size and moving to surface mount components (SMD) to reduce board size in the Resonant Buck Converter design will be able to reduce these switching harmonics even more to decrease the noise on the output.

Near Field Probe Test

There are two types of near field probes: H-Field and E-Field. H-Field probes measure magnetic fields caused by current changes while the E-Field probes measure electric fields caused by voltage changes. To measure RF noise, the H-Field probes are more commonly used as they are sensitive to the switching current harmonics.

The H-Field probes can show where RF noise is on a PCB by moving along the current paths. An example of how to use them is shown in Fig. 14 [10].

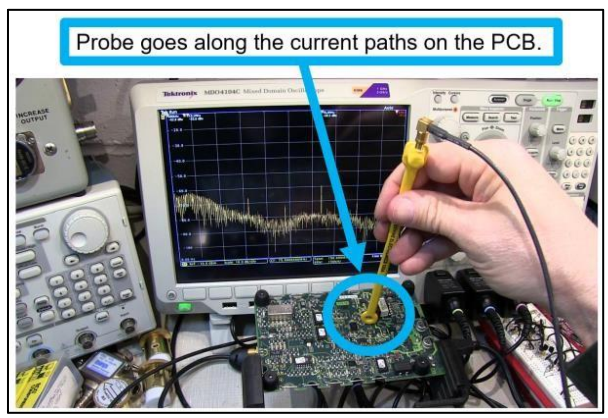


Figure 14: H-Field Probe Applications [10]

Normally, before being able to use the probes, they need to be calibrated first by using a probe factor (PF). To find the PF, the probe is connected to a vector network analyzer (VNA), which is used as the receiver. The output of the VNA is connected to a 50-ohm microstrip, which acts as the load. A setup of this procedure is shown in Fig. 15 [11].

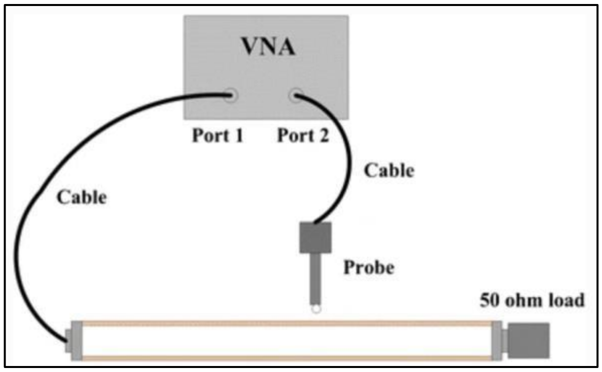


Figure 15: H-Field Probe Setup [11]

The probe is fixed to be directly above the microstrip at exactly the center of the microstrip. Then, the probe should move from left to right along the microstrip. The magnetic field at the center of the microstrip should be the largest [11]. The PF can then be obtained using Equation (1).

$$PF = \frac{H_{respond}}{V_{out}} \quad (1)$$

For the probes that were used, calibration was not necessary. The probes connected directly into the oscilloscope via a connector. The probes can also connect directly into a spectrum analyzer. Due to COVID, there wasn't easy access to a spectrum analyzer, so an oscilloscope was used instead.

Two H-field probes were used. These two probes are shown in Figure 16 [11].

Figure 16: H-Field Probe Used [11]

The probe with the circular loop end is used to narrow down where on the PCB board the most EMI is being emitted. The probe is held so that the loop is perpendicular to the board and follows the current paths (traces) of the board. The oscilloscope is observed to see the RF noise level.

Once the area of EMI emission is identified, then the probe with the straight end will be used to figure out which node is causing the RF noise output.

RESULTS

There were two buck converters used for the Near Field Probe test.

DC/DC Buck Converter Version 2

By using the RF probes, the highest EMI emissions were coming out of the gate of the MOSFET and the output load of the Buck Converter. Fig. 17 shows the RF noise output on the gate of the MOSFET on the oscilloscope.

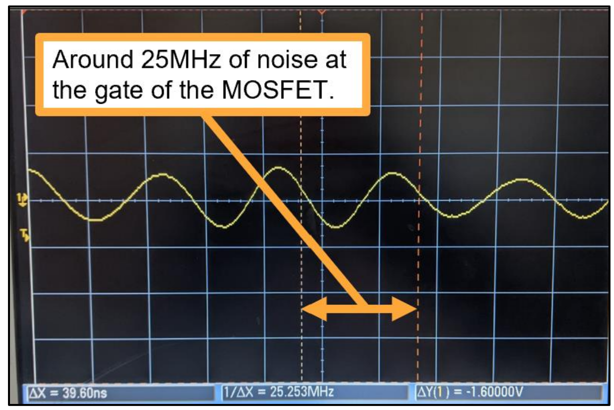


Figure 17: MOSFET Gate Noise Output of the Version 2 Buck Converter Measured at Zero-Crossing

Measuring at the zero-crossing, the noise is measured to be around 25MHz. Fig. 18 shows the RF noise was measured on the output of the converter.

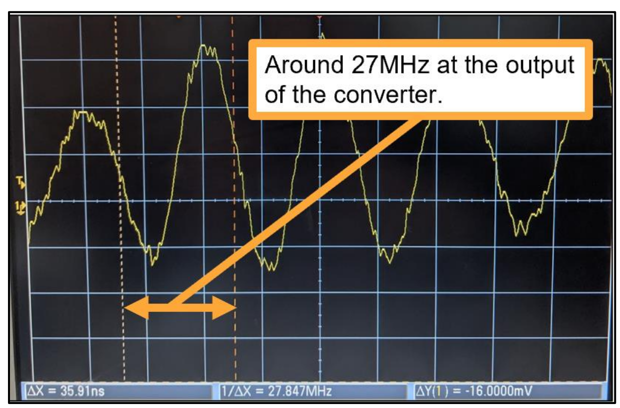


Figure 18: Output Noise of the Version 2 Buck Converter Measured at Zero-Crossing

Measuring at the zero-crossing, the noise is measured to be around 27MHz. It is expected that the RF noise coming from the MOSFET will be similar to the output RF noise of the output load since the hard-switching on the MOSFET is the cause of the noise on the output as shown in the voltage waveforms in Fig. 12 and Fig. 13.

Amazon Buck Converter 5V/3A

The amazon buck converter is detailed to be able to handle a max output of 5V and 3A to be able to power a Raspberry Pi. The switching frequency is stated to be at 500kHz. The amazon buck converter is 1/3 the size of Version 2 of the buck converter that was designed for the project. The amazon buck converter also uses all SMD components. The amazon buck converter was used to compare its RF noise output to the Version 2 buck converter design.

Fig. 19 shows the setup of the amazon buck converter powering the Raspberry Pi and camera sensor.

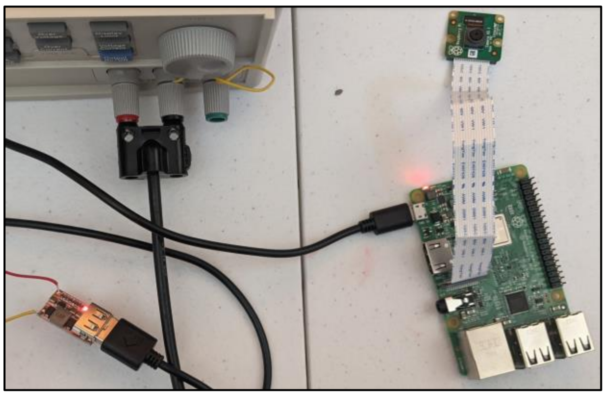


Figure 19: Physical Setup of Amazon Buck Converter Powering a Raspberry Pi and Camera Sensor

The setup is similar to Fig. 11 with the Version 2 buck converter. The power supply is connected to the buck converter and supplies 12V in. Then a USB connector on the output connects to the input of the Raspberry Pi module to power it which is indicated in the red light.

Fig. 20 shows the noise measured at the output of the amazon buck converter.

Figure 20: Output Noise of the Amazon Buck Converter Measured at Zero-Crossing

Roughly 28MHz of noise is measured on the output of the amazon buck converter. These results are similar to the 27MHz of noise on the output of the Version 2 buck converter designed for the project.

Considering that the amazon buck converter is working at a much higher frequency, it makes sense that the results are similar. Even though the amazon buck converter is smaller and uses SMD components, it is operating at more than twice the switching frequency. However, there was speculation that the switching frequency is lower than advertised, but there is no way to check it without doing research on the SMD components used to create the amazon buck converter.

Testing the amazon buck converter verifies that even with developing a buck converter on a smaller board and with SMD components, the high switching frequency along with the hard switching creates a limitation that a regular buck converter can’t overcome.

FUTURE WORK

COTs

Texas Instruments has developed “low-noise DC/DC switching regulators” (TPS62912 and TPS62913) which use an integrated ferrite-bead compensation as a filtering noise technique. This also reduces the voltage ripple out by around 30dB. These are good results, but one of the issues is that the device is only being tested with frequencies up to 100kHz. A CubeSat EPS, as shown in Table 1, needs the buck converter to have a minimum switching frequency of 150kHz.

The buck converter also doesn’t come with an incorporated L-C filter. The L-C filter must be added on after-the-fact. Up to two L-C filters were tested and used.

The output voltage waveform of the first L-C filter is shown in Fig. 21 [12].

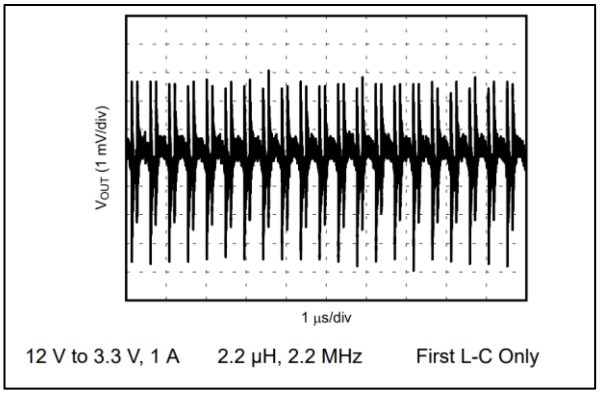


Figure 21: Vout Ripple After the First L-C Filter [12]

The figure clearly shows that the output is still being affected by the hard-switching of the buck converter device even with the L-C filter. Without a resistive load to dampen this, it becomes clearer in this image that the hard-switching is an issue that causes high RF noise and output voltage ripple even with an L-C filter to try and decrease it.

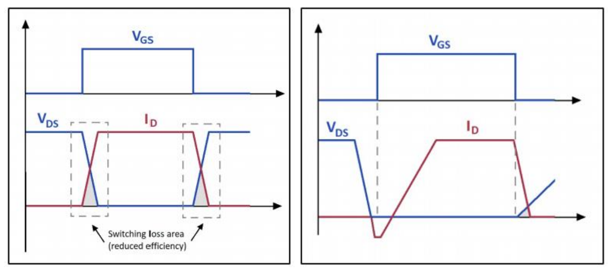
This also shows that without the L-C filters added onto the buck converter, the noise output caused by the high frequency switching hasn't been resolved. There is only a way to filter or mitigate it by using L-C filters which works, but does not fix the underlying problem that the hard switching causes.

Another feature of the TPS62912 is that it has a fixed switching frequency at 2.2MHz. Having the switching frequency fixed makes it so that the pulse width modulation will have to modify the duty cycle which will determine how long the device stays on or off. With a variable switching frequency, there is a way to control how many times a device turns on and off per second as well as being able to control which creates a cleaner output. This is beneficial to be able to power various loads that CubeSats are required to have onboard. A fixed frequency limits the number of loads that it can power effectively with less noise and higher efficiency. This is why a power converter design that can tackle the RF noise output without compromising the efficiency with a variable frequency (being able to change the switching frequency) is needed.

Electronic & Radio Frequency Noise Reduction

There are two schemes used to regulate power: Pulse width modulation (PWM) and resonance. PWM regulates power by varying the duty cycle to control the interruption of current flow through the power switch. Due to inductive switching, implemented PWM schemes have hard switching on both turn-on and turnoff, which causes high switching power loss but with better conduction efficiency. With a power converter operating at a frequency lower than resonance, a resonance scheme operates with zero-current (soft) turn-off and, when a sudden increase in current occurs after switching, the implemented resonance scheme has a sudden increase in current (hard turn-on) which results in higher conduction losses but with less switching power losses. Typical power converters in CubeSats use a basic buck converter with a PWM control scheme where hard-switching causes harmonics that produce noise.

The difference between hard-switching PWM scheme and a ZVS switching scheme is shown in Fig. 22 (a) [15] and Fig. 22 (b) [15] respectfully.



(a) Hard-Switching **(b) ZVS Switching**

Fig. 22. Hard Switching vs. ZVS Switching [13]

Combining these two schemes will be beneficial in creating a type of power converter that has better conduction efficiency and less switching loss. Creating a quasi-resonant power converter that can incorporate both PWM and resonance schemes will eliminate the vulnerabilities of the two schemes and reduce the noise of the overall system.

An example of a quasi-resonant buck converter is shown in Fig. 23 [14].

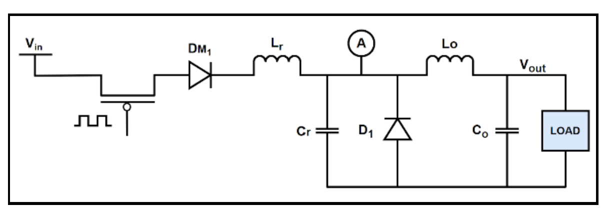


Figure 23: Quasi-resonant buck converter with ZVS switch (Version 3) [14, modified by Christine Page]

The design will have all components on a single board as a fully integrated solution to efficiently process DC power at a reduced cost. Its high frequency design offers small-sized passives and a higher quality factor (Q) inductor. An all-mode power converter will use inductors that depend on the Q of the inductor to achieve higher efficiency. The design will feature a tunable Q factor by using a fixed frequency and variable capacitance values which will create a variable resonance to control the amount of the output voltage.

The control scheme proposed is a phase-locking control scheme designed to minimize the voltage ripple of the output, which will reduce noise. The power converter can use the phase-locking technique to reduce the RF frequency. Two voltage-controlled oscillators will be implemented into the design, with one of the oscillators being a reference. A phase frequency detector (PFD) will determine if the other oscillator produces a waveform at a slower frequency compared to the reference source, as shown in Fig. 24 [14].

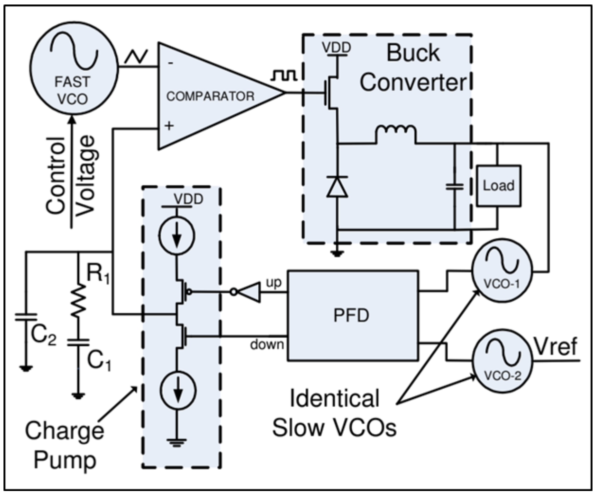


Figure 24: Phase-locking control scheme to reduce the output control ripple [14]

The PFD compares the rising edges of the two waveforms and produces up-signals that have a larger pulse width to pump more current into the sources to the filter. This will increase the duty cycle by also increasing the voltage at the output, which will then match the frequency and waveforms produced by the two sources, locking the power converter to a desired or set output voltage, reducing voltage ripple.

Maintaining Efficiency

The proposed power converter will incorporate a quasi-resonant switch design that combines both PWM and resonance schemes to create a phase-locking control scheme to improve the switching behavior of the semiconductor devices when regulating power. A quasi-resonant converter will ensure less conduction and switching loss by combining PWM and resonance schemes to support each other's weaknesses by regulating power using zero current (PWM switch) and zero voltage (resonance switch) switching. Eliminating the ringing from the switching behavior will reduce the power loss from switching, making the power converter more efficient.

A CubeSat's design is driven by power limitations where every mW counts. This means that maintaining the overall power subsystem efficiency leaves more power for other payload operations. The development of this proposed DC/DC power converter will allow a CubeSat to be more power efficient.

CONCLUSION

Noise is present in anything instruments are used for and is the unwanted effect on a signal measurement. Instruments are extremely sensitive to noise, and noise can corrupt and affect the data of instruments used on CubeSats like microwave radiometers, wideband software defined radios, and precipitation instruments. Although mitigation techniques are integrated in instruments and LDOs are being used to combat the noise issue, addressing the noise due to the hard switching in the power converter itself is the first step to decreasing the overall noise a CubeSat's EPS must deal with.

The results of the noise evaluation for Version 2 of the buck converter show potential. The noise was measured at around 25MHz which is significantly lower than the expected 150MHz from the reviewed study. Although the results were decent, discovering that most of the noise was generated from the hard switching of the MOSFET means there will be a limitation to how much the noise can be decreased. The next step is to eliminate the hard switching and make the buck converter a resonant buck converter to be able to do a soft switching scheme that will bypass the limitations that the hard switching buck converter scheme has presented.

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