AC 2011-967: LABORATORY DRIVEN EMC EDUCATION - DESIGN OF A POWER SUPPLY

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Abstract

This paper describes a practical approach to teaching electromagnetic compatibility (EMC) in the undergraduate curriculum. The elective senior level course discussed here combines aspects of both theory and applied engineering. In this course several laboratory assignments are devoted to the design of linear and switched-mode power supplies (SMPS), revealing the design tradeoffs vs. the EMC performance. Students are guided through a sequence of design steps that allow them to experience the effects of the component and topology choices and the resulting EMC performance. Several EMC phenomena are discussed and explained through these practical design activities facilitating students' understanding of this rather difficult topic.

Introduction

Methods, when combined in deliberate sequence, can build upon one another creating a powerful innovative problem-solving force as the output of one tool or technique becomes the input for the next[1]. In education, as one basic concept is introduced and allowed to cement itself in the student's understanding, additional depth and newer concepts can be added thereby increasing the student's overall knowledge. Each concept, then, becomes the building block for the understanding of the next.

Similar to most electrical engineering undergraduate schools Grand Valley State University has a two-course sequence in linear circuit analysis. Besides teaching the basics, these courses also present concepts that will be important to the subsequent study of electromagnetics. During this course of study students discover that most modern electronics require direct current (DC) to operate. Since distribution systems are alternating current (AC), students are taught early that they must first convert an AC feed to achieve a DC output.

In power supply selection students are taught that for a given application the transformer, and its regulation component, will be selected based on the current and voltage needs of the load and the need for tight or loose voltage and current regulation. As the mobile boom has increased hardware complexity while decreasing hardware size, combined with the nearly daily introduction of power eating applications, power supply requirements have increased. With mobile devices requiring longer battery life the designer does not have the luxury of developing large inefficient power supplies. A lot has to fit into a small space thereby creating electromagnetic interference (EMI) challenges for the designer.

In the last twenty years electromagnetic compatibility (EMC) problems have become more complex, as have their solutions[2]. Undergraduate level electromagnetics (EM) courses have traditionally focused on static electric and magnetic fields with limited coverage of time-varying fields[3]. With the increasing speed of digital devices a majority of the modern engineering applications involve the time-varying electromagnetic fields. As a result Adamczyk proposed a teaching approach that included time-varying fields with the expectation that it would provide the student a more thorough introduction to the issue of EMC[3]. Recognizing the validity of this approach, in the 2009 school year the university modified its EMC course content from a focus on electromagnetic fields to that based on applied electromagnetics.

Traditional Versus a Recommended Power Supply Teaching Methodology

Traditional power supply teaching methods present to the student the non-ideal behavior and susceptibility of individual components, such as wires, capacitors, resistors, and diodes, to radiated and conducted emissions[4]. At some point in the course a generic power supply model is presented to which a filter topology is introduced. If one is provided at all, a power supply laboratory supporting the book will be developed in which a filter is added to reduce EMI effects. Within this laboratory assignment before and after oscilloscope signatures will be compared. With this traditional teaching method it is expected that the student will conceptually recognize the importance of filters in reducing EMI.

This paper identifies a new way to study power supply EMI correction at the undergraduate level. As with the traditional method students are introduced to EMI as well as to the susceptibility of individual components to generate noise. When it comes time to develop power supplies, rather than just using computer modeling or creating one power supply, the student builds three simple power supplies with less than optimal component configurations. Oscilloscope signatures are acquired by the student as the quality of manufacture and the values of individual components are changed. Depending upon the type of power supply, within slightly more than a dozen steps the student is able to observe specifically how each component affects the signature in changing from one with high EMI to a signature that approaches the optimal condition.

This method is unique as the student is better able to understand the affect individual components have on power supply design while concurrently comparing the benefits and disadvantages of the three various power supply configurations. The power supplies selected include a linear power supply, a flyback switch mode power supply (SMPS), and a buck SMPS. For ease of construction, in all three labs the student mounts standard solid state components on a breadboard.

Linear Power Supply

Linear power supplies tend to be the quietest (low electrical noise) of all power supply types[5]. One of their major drawbacks is the relatively large and weighty transformer needed to supply the output voltage. Due to its simplicity, large transformer, and relatively clean noise signature, as defined by low voltage ripple, the linear power supply is presented first in the lab.
The student is provided the schematic of the full-wave direct current power supply with capacitive filter and voltage regulator shown in Figure 1. This power supply is designed to provide a load current equal to 150 milli-amps at a voltage of 7.00 volts DC as measured across the fixed load resistor. R_2 provides an adjustable output voltage. Figure 2 provides the linear power supply output voltage waveform taken with an oscilloscope across load resistor R_L. In six simple steps the student observes that a relatively clean output voltage can readily be achieved with little or no EMI.

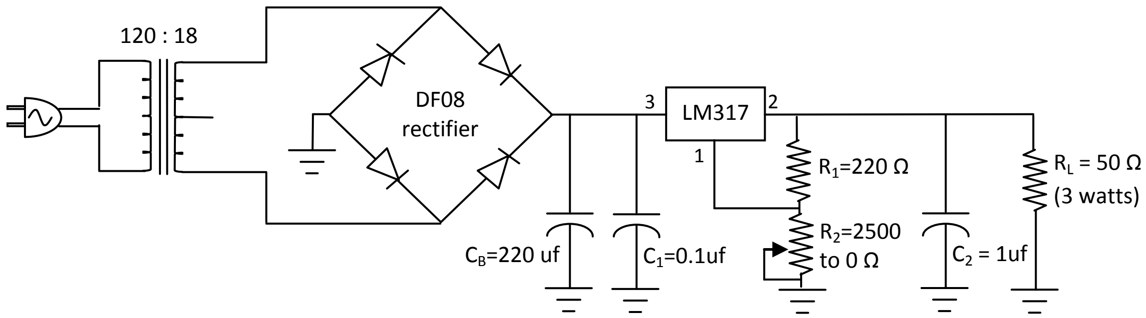

Figure 1: Full-wave direct current linear power supply.

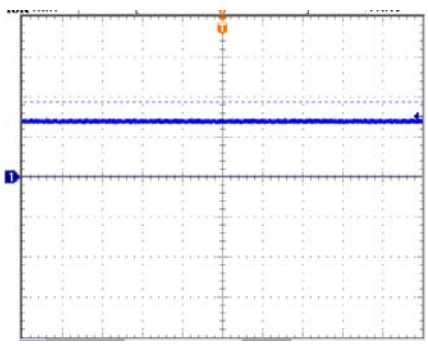

Figure 2: Linear power supply output voltage waveform. The oscilloscope data scales represent 5.00 volts per major division along the Y-axis and 100 micro-seconds per major division along the X-axis. The voltage signal is 7.60 volts.

Supporting the textbook and an associated course lecture, the laboratory instruction sheet identifies for the student that there are a number of paths through which interference can affect a power supply, including direct radiation, power lines, internally generated digital circuitry or rectifiers, the input cable, and the output cable. They are informed that one method to reduce noise voltage developed when designing a power supply is to reduce the internal inductance.

The instruction sheet also identifies the functions of the various components, such as the filter capacitor and the parallel load capacitor being used as a storage device which functions to improve the transient response. The laboratory has the student increase the lengths of various wires in an attempt to induce inductance. A step is provided in which a tantalum capacitor is placed just in front of the voltage regulator in order to cancel the inductive effects (and resulting high frequency oscillations) of wires and components feeding into the regulator, should they be observed.

Remembering that linear power supplies tend to be the quietest of all supply types, in developing the laboratory exercise we have had little success in achieving a noticeable noise in the output waveform. It is understood that the student should observe the same result. This is not perceived as a negative since a relatively clean output voltage with little or no EMI is desirable. The tradeoff, the student will observe soon enough, is that a clean signal from a linear power supply comes at the cost of having a large and weighty power supply transformer.

Switch Mode Power Supplies

Due to the higher frequency at which they operate, generally between 50Khz to 500 Khz and increasing, switch mode power supplies get by with a much smaller transformer[6]. They have become the power supply of choice due to their light weight, efficiency, and they are relatively inexpensive to build. Unfortunately switch mode power supplies are susceptible to EM noise generation. The flyback SMPS and the buck SMPS are next introduced in the laboratory since they present contrasting differences in topology, waveforms, and noise signatures.

Provided with the labs are appendices providing detailed SMPS design information[7 8], identifying the sources of ringing in the waveforms[9], and the use of snubbers[10].

A simple, but fully operational switch mode power supply is shown to students so that they can see the smaller footprint of the transformer. The SMPS labs, however, allow the switching signal to be supplied by a function generator. This makes it quick and easy for the student to maintain the fixed output voltage by varying the duty cycle and the rise and fall times of the gate signal. These laboratories are designed using larger components that operate close to their limiting range since in this state they provide classic EMI signatures on the oscilloscope. As such the student can easily see on the oscilloscope the effect that individual component changes make on the output waveform without having to spend a lot of time adjusting the oscilloscope settings.

The Flyback Converter Switch Mode Power Supply shown in Figure 3 is designed to provide a load current of approximately 150 milli-amps at a voltage of 7.00 VDC. The output voltage can be changed by varying the switching duty cycle or by changing the value of R_2. The overall goal in the flyback SMPS laboratory is for the student, by modifying component values and inserting new components, to reduce ringing and distortion of the output voltage waveform to more closely resemble a square-wave, as shown in Figure 4.

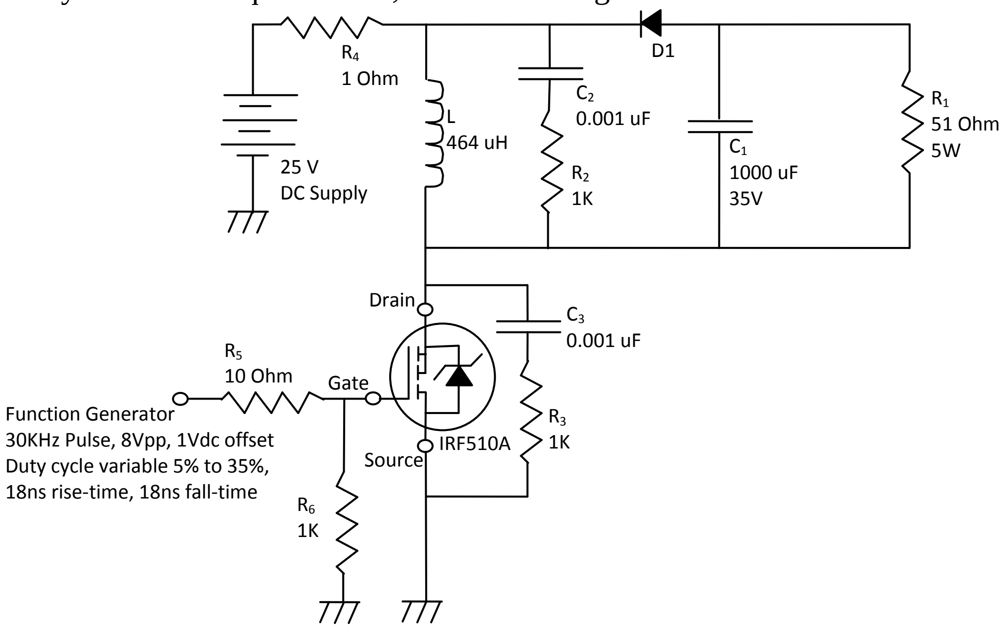

Figure 3: Flyback Switch Mode Power Supply

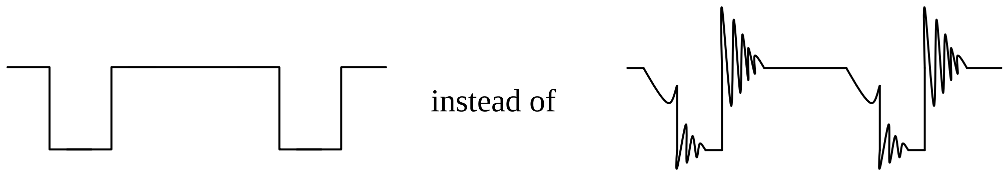

Figure 4: Ideal flyback SMPS waveform (left) compared to a distorted waveform displaying high EMI (right).

In order to provide variation and highlight additional concepts the buck SMPS in the third laboratory, with schematic as shown in Figure 5, is designed to provide a load current of 100mA at a voltage of 2.0 VDC. Voltage is also maintained by changing the percentage of the switching duty cycle. The overall goal of the buck SMPS laboratory is also to reduce ringing and distortion of the output voltage waveform, as shown in Figure 6, by modifying components.

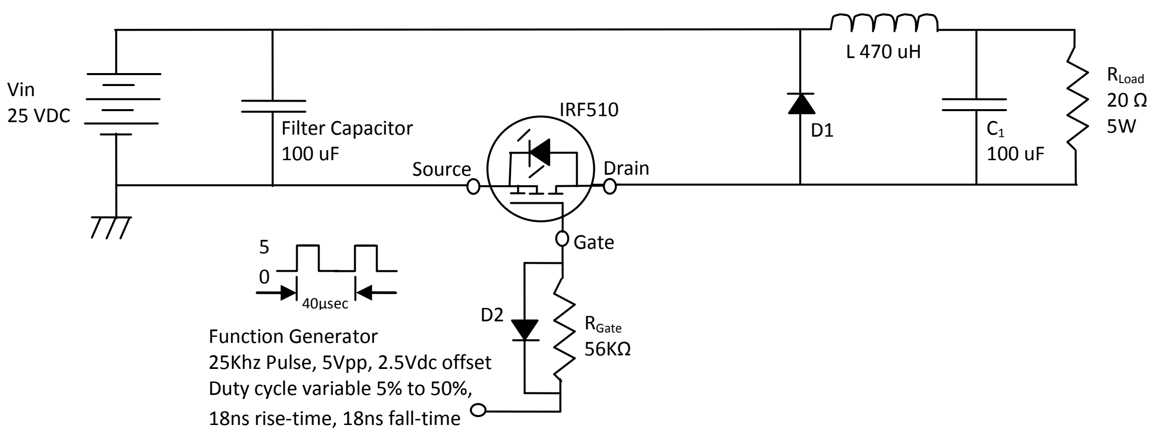

Figure 5: Buck Switch Mode Power Supply.

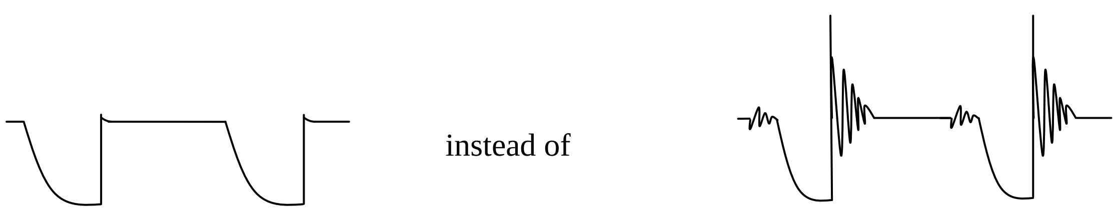

Figure 6: Ideal buck SMPS waveform compared to a distorted waveform displaying EMI.

Figure 7 and Figure 8 provide the flyback and buck SMPS starting waveforms along with that of their switching signals. The input switching signal is a short duty cycle square wave with minimal rise and fall times, as dictated by the precision of the signal generator. Figure 9 provides a close-up of the buck waveform showing the classic ringing signature indicative of EMI.

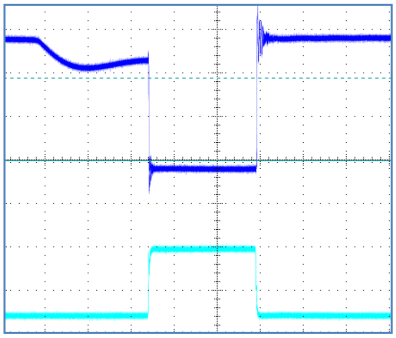

Figure 7: Flyback SMPS signature on top with associated switching signal on bottom. The switching duty cycle is set at 15%. The oscilloscope data scales represent 10.00 volts per major division along the Y-axis and 2.00 micro-seconds per major division along the X-axis. The voltage measured across the load resistor with a multi-meter is 4.4 volts DC.

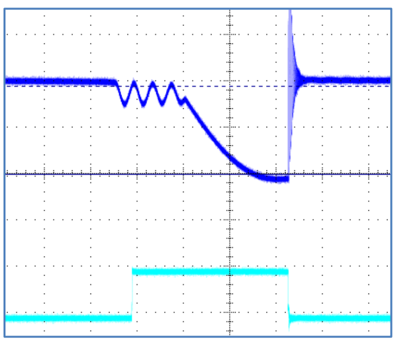

Figure 8: Buck SMPS signature on top with associated switching signal on bottom. The switching duty cycle is set at 33.7%. The oscilloscope data scales represent 10.00 volts per major division along the Y-axis and 4.00 micro-seconds per major division along the X-axis. The voltage measured across the load resistor with a multi-meter is 2.0 volts DC.

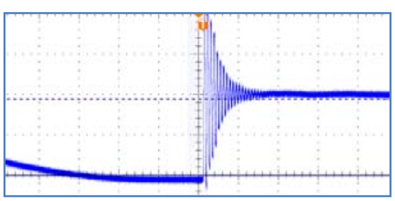

Figure 9: Close-up of Buck SMPS ringing waveform indicative of EMI. This is a close-up of the waveform shown in Figure 8. The Y-axis is set at 1.00 micro-second per major division.

In both SMPS laboratories cleaning of the waveform is accomplished by using successive steps in which the student modifies the value of the inductor and those of the various resistors and capacitors. The student switches the diode from an inexpensive general diode to one that is more expensive with fast-recovery characteristics, and inserts new components such as filters. Throughout the laboratory the student manually changes the input switching cycle rise and fall times to maintain constant output voltage and to observe how each component affects circuit power consumption. At each step the student observes the effect each change has on cleaning the waveform. As an example, Figure 10 shows the affect on ringing that increasing the duty cycle fall time has on reducing the buck SMPS output waveform.

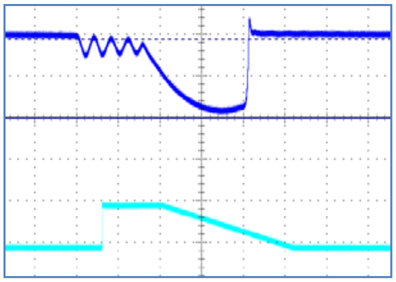

Figure 10: Buck SMPS waveform displaying reduced ringing (top) after the switching signal duty cycle fall time has been increased (bottom). The switching duty cycle is set at 30.0%. The oscilloscope data scales represent 10.00 volts per major division along the Y-axis and 4.00 micro-seconds per major division along the X-axis. The switching signal rise time is set at 18 nano-seconds with the fall time set at 10 micro-seconds. The voltage measured across the load resistor with a multi-meter is 2.0 volts DC.

After just eighteen steps for the flyback laboratory and fifteen steps for the buck lab, as shown in Figure 11 and Figure 12, the student will achieve a relatively clean output waveform. Note the sharp, ring-free, spike on the back side of the output waveforms. This is caused by the “snap” of the fast-recovery diode. This spike is not an ideal situation and is indicative of a noise, expected to yield higher frequency spectra in the current than will be observed when using soft-recovery diodes[11]. This diode was deliberately chosen so that the student can recognize that more expensive and faster acting components are not always the best solution to a power supply problem.

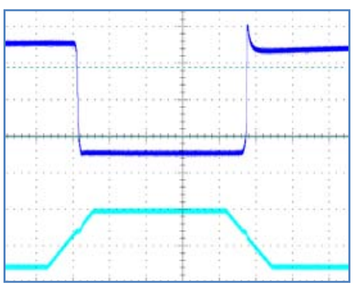

Figure 11: Flyback SMPS waveform (top) with switching signal (bottom) at the completion of the laboratory exercise. The switching duty cycle is set at 29.3%. The oscilloscope data scales represent 10.00 volts per major division along the Y-axis and 2.00 micro-seconds per major division along the X-axis. The switching signal rise and fall times are each set at 2 micro-seconds. The voltage measured across the load resistor with a multi-meter is 7.0 volts DC.

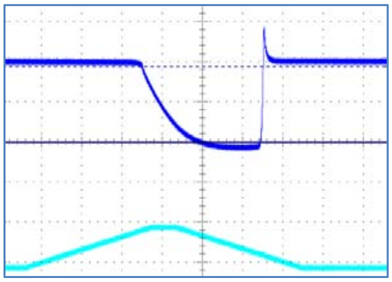

Figure 12: Buck SMPS waveform (top) with switching signal (bottom) at the completion of the laboratory exercise. The switching duty cycle is set at 37.3%. The oscilloscope data scales represent 10.00 volts per major division along the Y-axis and 4.00 micro-seconds per major division along the X-axis. The switching signal rise and fall times are each set at 10 micro-seconds. The voltage measured across the load resistor with a multi-meter is 2.0 volts DC.

Conclusion

With the traditional teaching method the study of electromagnetic interference is advanced throughout the semester by individually discussing the susceptibility to EMI of various individual components. In this regard the newer teaching method presented here is not much changed from the traditional. Theory is still presented to help the student understand the concepts and causes of EMI.

After having reviewed the requisite theory in the classroom, the student creates in the laboratory three power supplies, a linear power supply, a flyback SMPS, and a buck SMPS. These simple power supplies are initially built with less than optimal component configurations. While modifying components and input settings, the student takes the output waveform from one exhibiting high EMI to one that conforms closer to the ideal. In so doing, each concept becomes the building block for understanding the next.

This method is unique as the student is able to understand the effect individual components have on power supply design while concurrently comparing the benefits and disadvantages of the three various power supply configurations. The difference between this method and the traditional, then, is that the focus of the laboratory exercises is placed more on application than on theory. By the end of the exercises it is expected that the student, if paying even a moderate level of attention, will easily see how theory is applied in practice.

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