Automated Inductor Characterization System

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Abstract
This senior project aims to provide a quick and convenient way to characterize inductors by its inductance value for a range of switching frequencies. Additionally, the automated system is designed to characterize an inductor while implemented within a real world and very common application: the DC/DC converter. This will be useful when choosing a particular inductor for an optimal DC/DC converter design. The design of the automated inductor characterization system was based around computer simulations of a buck converter and its ability to generate the required switching voltage and current waveforms. LabVIEW was the software of choice to interface with the lab equipment (oscilloscope, function generator, and power supply) and automate the frequency sweep, data collection, and inductance calculations. After initial testing, results for the particular 0.47μH inductor shows a fairly stable inductance over a range of 340kHz to 3.8MHz with a maximum error of around 10% from the nominal value.
I. Introduction

The idea for this senior project arose from the observed and measured inconsistently of passive components when implemented in critical circuit subsystems. For example, in the highly competitive field of mobile consumer electronics such as phones, tablets, and media players, successful products often carry similar traits: reliable, consistent, and good performance. In an era where battery life is king, it is extremely important that the power management subsystems in these types of products are fully optimized. Additionally, over millions of units, performance must remain consistent as advertised over extended periods of time and under a vast range of operation conditions.

This poses a challenge when designing circuits for such large volumes. Individual component vendors often times cannot supply the desired quantity in the short amount of time allocated for production. As a result, large consumer electronic companies pool components from multiple vendors to meet the enormous demand. Although this is the most efficient way to produce millions of products in extremely short time periods, it is often the cause of headaches when “identical” products begin to show significant variations from one another. The underlying differences can often be narrowed down to hardware, and furthermore to individual components that make up crucial circuits.

From previous experience working with mass-produced handheld consumer electronics, the reputation of the company is on the line when it comes to the advertised vs. actual performance of the product. This level of accuracy and consistently is especially important in battery life. These mobile devices often feature complex power management systems that can feature dozens of different power rails to supply the numerous power demanding subsystems. In addition, with the increasing complexity of the products at an unimaginable pace, efficiency must be extremely high in order to provide the long battery life that consumers desire.
II. Background

DC-DC converters are the main type of power management circuits used in modern mobile electronics. Since batteries are often the main source of power, DC-DC converters are required in order to supply the various subsystems with accurate and stable voltage rails with varying input voltages (fluctuating battery voltages). Although numerous DC-DC converter topologies are used through mobile devices, this senior project will focus on unquestionably the most popular: the buck converter.

The main purpose of a buck converter is to essentially reduce or “buck” down a given input DC voltage to a lower output DC voltage. For example, if a battery supplying a system is 4.0V, numerous buck converters can be used to produce typical outputs voltages of 1.8V, 2.5V, and 3.3V. Figure 2.1 shows a simplified schematic of a standard buck converter.

![Figure 2.1: Simplified buck converter schematic](image)

In every buck converter, the main theory of operation lies with the properties of an inductor. In simplified terms (since the theory of operation of a buck converter is not the main purpose of this senior project), a rapidly switching voltage across the inductor controlled by the switch causes it to charge and discharge. Since the current through the inductor cannot change instantaneously, it creates a triangular current waveform with a DC offset (determined by load). The output voltage can be represented as a function of the switch’s duty cycle and input voltage (to be explained in more detail in section IV).

Based on the operation of a buck converter, the output voltage is independent of the switching frequency (current ripple is however). Due to this property, buck converters can be designed with certain tradeoffs. At lower switching frequencies, power losses are
minimized at the expense of a larger output current ripple. At higher switching frequencies, output current ripple is minimized at the expense of more power losses. One assumption that is taken for granted however is that the inductance value of the inductor remains constant at different frequencies.

When designing any type of circuit, it is a good idea to check all specifications of both ICs and components in order to not only ensure proper operation and prevent damage, but also to achieve optimal performance. Details about performance are often limited however for discrete and passive components. For crucial elements such as the inductor in a buck converter, the lack of detail can lead to circuits that are far from ideal. For example, Figure 2.2 shows the entire datasheet for a Taiyo Yuden 0.47μH, 0805, wire-wound chip power inductor.

![Diagram of inductor dimensions](image)

<table>
<thead>
<tr>
<th>Products characteristics table</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaseSize (EIA/JIS)</td>
</tr>
<tr>
<td>Inductance</td>
</tr>
<tr>
<td>Inductance Measuring Frequency</td>
</tr>
<tr>
<td>Rated Current-Saturation Current</td>
</tr>
<tr>
<td>Rated Current-Temperature Rise Current</td>
</tr>
<tr>
<td>DC Resistance (max)</td>
</tr>
<tr>
<td>Avg. of DC Resistance</td>
</tr>
<tr>
<td>Temperature Range</td>
</tr>
<tr>
<td>Self-resonant Frequency (min)</td>
</tr>
<tr>
<td>RoHS Compliance</td>
</tr>
<tr>
<td>Halogen Free</td>
</tr>
<tr>
<td>Soldering Method</td>
</tr>
</tbody>
</table>

Figure 2.2: Taiyo Yuden 0.47μH inductor specifications from datasheet [1]
As you can see, not only does the inductance value of the inductor have a large tolerance (±10%), but also this value is only measured at a fixed switching frequency of 7.96MHz. Typical low voltage/high efficiency buck converters generally operate with a switching frequency ranging anywhere from 300kHz on the low end to 4MHz on the high end. With such a large operating range, the specified 1MHz switching frequency used to characterize the inductor is not a full characterization. Additionally, since DC-DC converter designs often vary in switching frequency due to performance tradeoff analysis, there is no certain standard to base the design on.

As a result of this freedom to design DC-DC converters based on need, exact inductance values for the desired operating frequencies rather than the inductance at a fixed frequency would provide more optimal simulations and thus a better, more reliable design overall. Therefore, in this senior project, the goal is to better characterize inductors by obtaining an inductance vs. frequency response plots. This would allow more accurate models of DC-DC converter designs and would leave it up to the designer to decide what exact switching frequency yields the best results. Additionally, vendor-to-vendor performance differences can be easily distinguished; some may be rated for a certain inductance, but in reality, they could vary greatly at unspecified switching frequencies.

Obtaining this type of full characterization for an inductor could be extremely tedious and difficult to achieve accurate results. Therefore, this senior project will revolve heavily around the implementation of LabVIEW with the hardware and test equipment to automatically sweep switching frequencies and collect point-to-point data. With these measurements, an inductance vs. frequency response plot can be generated for the exact inductor being tested (to be explained in greater details in section IV and VI).
III. Requirements
In order to automate the characterization of inductors, this senior project will be divided into hardware and software sections, each of which requires a desired output for proper integration and a fully automated system.

Hardware
Since buck converters are the most common application of DC/DC converters due to the simplicity, size, and efficiency of the topology, a standard, off-the-shelf buck converter (LTC3612) was chosen to provide the switching inductor voltage and current waveforms. With the inductor placed at the output, the output current (which is the same as the inductor current) was easier to observe and use to perform inductance calculations. Additionally, the use of an electronic load allowed for direct modification of the inductor current to characterize the component’s performance. In essence, not only could the inductance be characterized with respect to frequency, but also with respect to the output current (although not tested in this senior project).

The desired specifications chosen for the buck converter were arbitrarily chosen, but came from typical configurations found in low power, mobile devices. Using the battery as power supply for the buck converter, input/output voltages as well as output currents are generally low. The following list describes the desired specifications for the buck converter:

1. $V_{in} = 5V$
2. $V_{out} = 1.8V$
3. $I_{out-max} = 1A$
4. Nominal Inductor $= 0.47\mu H$
5. External clock frequency synchronization
6. Forced continuous mode of operation
7. Switching frequency range $= 300kHz - 4GHz$
8. Easily accessible inductor for quick characterization of different inductors
Software

Since calculating the inductance values revolved around obtaining the correct switching voltage and current waveforms, LabVIEW 10.1 was the software of choice (provided by the Cal Poly EE Department). LabVIEW was particularly chosen because of its simple and powerful interfacing capabilities with the standard lab equipment (oscilloscope, function generator, and power supply), given the proper drivers [6]. Once fully integrated with the equipment, LabVIEW would allow the user to customize the inductor characterization for various situations and applications.

Additionally, the graphical approach that LabVIEW uses (with block diagrams) made for an intuitive way to operate the equipment and manipulate the data. Since the end goal was to create a completely automated inductor characterization system, the Front Panel feature of LabVIEW could display a clean and simple user interface. The following list describes the desired specifications for the LabVIEW program:

1. Set power supply output voltage for the buck converter
2. Sweep external function generator frequency (for clock synchronization)
3. Automatically set oscilloscope parameters to capture the correct waveforms (probes, acquisition type, scales, and triggers)
4. Automatically collect voltage data points across inductor from the oscilloscope
5. Automatically collect current data points through inductor from the oscilloscope
6. Calculate inductance using voltage and current data points at each frequency
7. Generate an inductance vs. frequency response plot
8. Provide a graphical user interface (GUI) for users to customize the characterization
IV. Design & Simulation

Hardware

The first portion of this senior project involved designing a standard buck converter to be used for the inductor characterization. Additionally, the buck converter was chosen to carry similar specification to those found in mobile devices (low power and high efficiency).

The Linear Technology LTC3612 buck converter IC was selected to design the hardware test circuit around. This buck converter had specifications that matched the desired requirements as outlined in Figure 4.1.

![FEATURES]

- 3A Output Current
- 2.25V to 5.5V Input Voltage Range
- Low Output Ripple Burst Mode® Operation: \( I_Q = 70\mu A \)
- \( \pm 1\% \) Output Voltage Accuracy
- Output Voltage Down to 0.6V
- High Efficiency: Up to 95%
- Low Dropout Operation: 100% Duty Cycle
- Shutdown Current: \( \leq 1\mu A \)
- Adjustable Switching Frequency: Up to 4MHz
- Optional Active Voltage Positioning (AVP) with Internal Compensation
- Selectable Pulse-Skipping/Forced Continuous/Burst Mode Operation with Adjustable Burst Clamp
- Programmable Soft-Start
- Inputs for Start-Up Tracking or External Reference
- DDR Memory Mode, \( I_{OUT} = \pm 1.5A \)
- Available in Thermally Enhanced 20-Pin (3mm x 4mm) QFN and TSSOP Packages

Figure 4.1: LTC3612 buck converter features (snippet from datasheet) [2]

In addition to the standard input voltage and output current specification, two other features were desirable and required from the buck converter. The first was the ability to select the type of operating mode. With the advancement in control system technology, operating modes such as pulse-skipping and burst mode are often the standard to achieve higher efficiency at low output current levels. Since the design of this buck converter will be dealing with relatively low output currents, it must be able to have a forced continuous...
output regardless of the load current. Figure 4.2 demonstrates the output voltage and current waveforms seen by each of the operating modes. Since the basic relationship between inductors voltage and current can be most easily observed (and measured) with a square voltage waveform and triangular current waveform, forced continuous mode is necessary.

![Figure 4.2: Comparison between different buck converter operating modes][2]

The second essential feature required by the buck converter was the ability to sync its switching frequency with an external clock. Many off-the-shelf buck converters allow for varying switching frequencies with a timing resistor, but since the inductor characterization planned to be automated, using a function generator to provide the switching frequency clock was the preferred method of choice. The LTC3612 buck converter has a dedicated pin to allow for external clock synchronization. This would allow a simple sweep from 300kHz to 4MHz from the function generator. Figure 4.3 shows a recommended implementation for an external clock for proper synchronization.

![Figure 4.3: Recommended implementation of externally synchronized clock][3]

Since a demo board designed around the LTC3612 buck converter was available, the demo board provided the basis of the hardware implementation. The schematic shown in Figure 4.4 provides the desired configuration of the LTC3612 buck converter.
Since the LTSpice could not simulate the external clock synchronization feature of the LTC3612 buck converter, the clock-timing pin (Rt) was tied “high” to VIN to fix the switching frequency at 2.25MHz. Figure 4.5 shows the simulation of LTC3612 buck converter/demo board start-up and steady-state output voltage (1.8V).
Figure 4.6 shows the differential voltage across the LTC3612’s inductor (green) and the current flowing through the inductor (magenta). These waveforms mimic the forced continuous mode that the buck converter was designed to operate in.

Figure 4.6: LTSpice simulation of the LTC3612 demo board differential inductor switching voltage and current

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Differential Inductor Voltage (V)</th>
<th>Current through Inductor (A)</th>
<th>Current Slope (di/dt)</th>
<th>Instantaneous Inductance (H)</th>
<th>Average Inductance (H)</th>
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</thead>
<tbody>
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<td>-3.9596E-06</td>
<td>4.695001075E-07</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.7: Snippet of tabular data points obtained from the LTSpice simulation to calculate inductance

From Figure 4.7, point-by-point data was obtained from the simulation and used to calculate the “experimental” inductance. By averaging 2000 points, the inductance was
calculated to be $4.711 \mu H$ at 2.25MHz. This type of measurement was the basis for the software implementation.

**Software**

The goal of this senior project was to provide full automation of the inductor characterization process while giving the user flexibility in the speed and precision of the measurements. Since taking proper voltage and current measurements required the use of various lab equipment such as power supplies, function generators, and oscilloscopes, LabVIEW was the software of choice to interface with the lab equipment and the hardware. Figure 4.8 shows a block diagram of the LabVIEW algorithm used to complete the automated inductor characterization.

![Figure 4.8: Block diagram of LabVIEW automation](image)

Figures 4.9 – 4.11 show the three pieces of test equipment automated with LabView.

![Figure 4.9: Agilent E3640A DC power supply](image)

The Agilent E3640A DC power supply used for powering the LTC3612 buck converter was programmed to automatically set the output voltage to 5.0V and current limit to 2.0A. Additionally, the power supply output was turned on after initialization and turned off after all the computations were complete.
The Agilent 33220A function generator provided the switching frequency for the LTC3612 buck converter’s external clock synchronization and was automated to provide the proper output waveform and levels (square wave 1.5Vpp with a 750mV DC offset). The LabVIEW GUI also allowed users to specify the frequency sweep range and frequency step.

The Agilent 54622D oscilloscope was automated to collect point-by-point data of the waveforms being displayed for both channels. This involved proper initial setup (probe settings and acquisition type) so that both the inductor voltage and current waveforms would be correctly scaled (both horizontally and vertically) and triggered. Additionally, to maintain consistent resolution of the waveforms, the horizontal time scale dynamically changed with the switching frequency so that the data points were always captured at similar locations, but at corresponding time intervals.
Using point-by-point data obtained from the oscilloscope, inductance was calculated with the fundamental formula relating an inductor's voltage and current:

\[ V_L = L \frac{di_L}{dt} \rightarrow L = \frac{V_L}{\frac{di_L}{dt}} \]

The inductor voltage \( V_L \) was obtained directly from the point-by-point data collected by the oscilloscope. The \( \frac{di_L}{dt} \) term, or the slope of the triangular current waveform, was obtained by subtracting the level of two adjacent data points and dividing by the time increment between the two points. Since LabVIEW was able to automatically obtain the data and perform the computations for the inductance, it was possible to generate an accurate representation of the inductance by averaging hundreds of inductances for instantaneous inductor voltages and current slopes. This could be accomplished in a relatively short amount of time for a sweep of frequencies.
V. Test Plans
The hardware and software portions of this project were tested separately until a solid design was accomplished for both. Since the buck converter design was based off an LTC3612 demo board, it was expected to follow the same behavior as the LTSpice simulations. The main hardware testing involved verifying the following cases:
a. Correct output voltage
b. Correct switching voltage waveform (measured at the switching node)
c. Correct triangular current waveform through the inductor
d. 1:1 frequency synchronization with the function generator for switching frequencies of 300kHz to 4MHz.

Since a major portion of the project dealt with the design of the LabVIEW software, different test cases were used to verify the automation functionality of the lab equipment. The following test cases were automated and used arbitrary function generator waveforms for easy analysis and debug:
a. Set power supply output voltage and current limit
b. Configure function generator frequency sweep for a user specified range and step size
c. Acquire oscilloscope waveform data for both channels (one for voltage data and the other for current data)
d. Use waveform data manipulation and computation to calculate inductance
e. Combine data acquisition/calculations automation through a frequency sweep
f. Generate a graphical representation for inductance vs. switching frequency
g. Allow users to define equipment parameters for customized inductor characterization

Once the above test cases were all satisfied, both the hardware and software portions were integrated and tweaked with the correct equipment parameters. The final test for this project was to obtain an accurate representation of the inductor for a range of frequencies not available with the current equipment provided at Cal Poly (impedance bridge only rated for a switching frequency of 1kHz and the vector network analyzer rated for a switching frequency of >10MHz). The inductors were expected to maintain values somewhat close to the nominal rating with some drift depending on frequency.
VI. Development and Construction

Hardware

The LTC3612 buck converter demo board layout is shown in Figure 6.1. As highlighted, the inductor was placed near the output pin of the IC facing towards the output peg (VOUT).

Figure 6.1: Linear Technology LTC3612 demo board layout

In order to measure and obtain the current waveform through the inductor, it was rotated 90° towards the bottom of the demo board and a current loop was soldered between the open end of the inductor and its original solder pad. This allowed the use of a current probe and a current probe amplifier to display the waveform on the oscilloscope. Figure 6.2 on the following page shows an annotated image of the actual demo board. Note that both the power supply and function generator were applied through the breakout pegs provided from the demo board. The switching node waveform was captured with an oscilloscope voltage probe with the green wire and the inductor’s current waveform was captured with the red wire current loop and the current probe.
Since LTSpice did not have the capabilities of simulating the LTC3612 buck converter’s external clock synchronization feature, this was verified manually with a function generator. The demo board was set to EXT SYNC mode and a 0 – 1.5V square wave was applied to the SYNC peg at various frequencies. Figures 6.3 and 6.4 on the following page show the function generator output (top waveform) and the LTC3612’s switching node (bottom waveform) for switching frequencies of 400kHz and 2.5MHz.
Figure 6.3: Oscilloscope capture of function generator external clock (top) and LTC3612 switching node (bottom) at $f = 400$ kHz

Figure 6.4: Oscilloscope capture of function generator external clock (top) and LTC3612 switching node (bottom) at $f = 2.5$ MHz

Note that the switching waveform was relatively clean with a desired response. Due to the limitation of the oscilloscope (only 2 channels), the voltage across the inductor was obtained by subtracting the buck converter’s output DC voltage (1.8V) from the switching node voltages. Any strange transients in the function generator’s clock waveform did not affect the switching node voltage and was therefore ignored.
The inductor’s current waveform was verified with the use of the oscilloscope, current probe, and current probe amplifier. In order to correctly display the triangular current waveform on the oscilloscope, degaussing, calibrating, and adjusting the correct scaling of the current probe/current probe amplifier combination was required. With no load connected to the DC-DC converter, the triangular current waveform was centered at 0V as shown in Figure 6.5.

Figure 6. 5: Linear Technology LTC3612 demo board switching node and inductor current waveforms; note that since inductor voltage will be used in calculations rather than the switching node voltage, the DC output voltage (1.8V) must be subtracted from the switching node voltages
Software
The LabVIEW automation was a major focus for the senior project and required interfacing with the lab equipment. The first portion designed involved the Agilent 3640A DC power supply. Since the allowed operating voltage for the LTC3612 buck converter ranged from 2.25V to 5.5V, 5.0V was selected. Since mobile devices emphasis low power consumption, the current limit was set to 2.0A (mainly to operate the LTC3612 rather than drive a load). Power supply voltage and current VIs were placed inside the frequency sweep WHILE loop to monitor the power consumption for each frequency. Figure 6.6 shows a screenshot of the LabVIEW block diagram for the DC power supply implemented within the entire automation system.

![LabVIEW Block Diagram](image)

*Figure 6.6: LabVIEW block diagram of the Agilent DC power supply automation; note that chain is divided into two images*

The second portion of the LabView automation dealt with the Agilent 33220A function generator. This particular section was important since it would provide the basis of the generating the inductance vs. frequency response plot. To execute the frequency sweep, a WHILE loop was implemented in LabVIEW with a user specified start frequency (GHz), stop frequency (GHz), and step size parameters (kHz), all of which were manipulated and sent to the SET WAVEFORM VI. Figure 6.7 on the following page shows the initialization/closure of the function generator as well as the user input controls. Note that a time delay was implemented in order to assure that the power supply to power the buck converter was executed first.
Relying on the fundamental inductor formula $V_L = L \frac{di}{dt}$, the square voltage waveform and triangular current waveform had to be properly displayed on the oscilloscope to maintain high accuracy of the point-by-point data collection. Due to this requirement, the LabVIEW automation software left the scope settings and parameters as defined by the user to allow for the proper waveforms with any hardware setup. Note that the READ WAVEFORM VIs for both channels were placed inside the frequency sweep for loop. Each of these blocks acquired the point-by-point data for the specified channel. Additionally, the ACQUISITION RECORD VI was set to 500 data points to provide accurate and consistent measurements to be used in later calculations. In order to further increase the consistency of the data collection, the horizontal timescale of the oscilloscope dynamically changed depending on the switching frequency. By using a constant divisor of 300kHz, the LabVIEW program would display three full periods of the switching waveforms regardless of the switching frequency. Figure 6.8 on the follow page shows the initialization block diagrams for the oscilloscope control and data acquisition.
Since the automated LabVIEW system dealt with collecting hundreds of data points and performing computations on both the square wave voltage waveform and triangle wave current waveform, large arrays were generated to keep track of all the data. These arrays were then manipulated in various ways to properly scale and shift the point-by-point data as shown in Figure 6.9 on the following page and explained below:

i. X-increment (time between data points) multiplied by the number of data points collected to from time scale

ii. 1.8V subtracted from each value of the voltage data obtained by the oscilloscope

iii. Current waveform data scaled by the user specified settings used on the current probe amplifier

iv. Scaled current waveform data shifted down by 1 index to allow for row-by-row subtraction of data (to calculate slope)

With the help of these arrays, the voltage and current waveform data could be then used in calculations to ultimately solve for inductance. Each modified array was sent to a BUILD ARRAY VI where a two-dimensional array was created to observe all the data at once.
As a result of the limited resolution on the oscilloscope, when the triangular current waveform decreased with increasing frequency, the ability to capture accurate slope measurements would also decrease. For slopes that were calculated to be 0, the inductance would equate to $\infty$H. Therefore, an array cleaning function was created to remove all 0 and INF array values and resize the array. Figure 6.10 shows the LabVIEW block diagram of the function that takes in the array of instantaneous inductance values and filters out the error inductance values (negative and INF values).
The main LabVIEW section that performed the computations for the inductance is shown in Figure 6.11. Since the inductance formula calls for the raw inductor voltage, this value was used directly. However, in order to calculate the slope of the current waveform, the point-by-point difference was taken between the normal current waveform data and the current waveform data shifted by 1 index. This difference was then divided by the time between the two data points (x-increment) as determined by switching frequency. The instantaneous inductance was then calculated by dividing the instantaneous inductor voltages by the instantaneous slopes of the inductor current. The array of inductances was then filtered using the function shown in Figure 6.10 and averaged by the total number of valid inductance values. After computing the inductance value for a single frequency, the rest of the frequency sweep (WHILE loop) was executed to generate an array of inductance values and their corresponding frequency. These values were lastly plotted to graphically represent the characteristics of the inductor.

Figure 6.11: LabVIEW block diagram of the portion that calculates instantaneous inductance values, filters out the error values, averages the array of inductances, and graphs the averaged inductance vs. frequency
VII. Integration and Test Results

Figure 7.1 shows the test bench setup used for running the automated inductor characterization system. The equipment required to use the system were a buck converter with an available inductor current loop, current probe, current probe amplifier, DC power supply, function generator, oscilloscope, and a computer with LabVIEW 10.1 software.

![Test bench with all the equipment setup to execute the automated inductor characterization](image-url)
Figure 7.2 shows the LabVIEW front panel that allows users to input the desired settings for a customized inductor characterization. Users can change the frequency sweep range and resolution by adjusting the start/stop frequency as well as the frequency step. Additionally, after determining the optimal scaling on the current probe amplifier that returns a desired inductor current waveform, matching that value in the Current Amp Scale field will automatically scale the oscilloscope data (since it’s set on a 10mV scale for the current probe). Different Acquisition types can also be selected. Averaging was used in these test cases for increased accuracy. Lastly, probe settings and vertical scaling must be adjusted to center and maximize waveforms on the oscilloscope for increased accuracy.
Once the User Inputted Settings are correctly determined, the waveforms as seen in Figure 7.3 should be displayed. Notice that both the voltage and current waveforms are stretched out to cover most of the oscilloscope screen. This provides the most accuracy when obtaining the point-by-point data. Also, the dynamically changing horizontal time scale automatically adjusts to show and capture three periods of data.

The current ripple varied directly with the switching frequency. At lower switching frequencies, the current ripple was much larger than at higher switching frequencies. Due to this behavior, sweeping a large frequency range would yield less accurate results at the upper end of the sweep. Once the current ripple started to decrease at higher frequencies, the limited resolution of the oscilloscope could not obtain as many instantaneous slope values, thus the amount of averaging is significantly less.

![Figure 7.3: Switching node voltage (square waveform) and inductor current (triangular waveform) shown on the oscilloscope after being automatically set by the LabVIEW automation program; switching frequency = 500kHz](image-url)
Figure 7.4 shows a portion of the LabVIEW front panel that contains both the array of calculated inductance values at the respective frequency and the associated inductance frequency response plot generated from the array. Additionally, the power supply measurements are displayed for monitoring the power consumption of the buck converter at measured frequencies obtained from the oscilloscope. There are also indicators to present the sweep count and the number of instantaneous inductance calculations being averaged for each frequency.

The example shown in Figure 7.4 measured the inductance for a frequency sweep of 2MHz - 2.5MHz. For this particular range, the inductance showed a decreasing trend as frequency increased from about 0.485μH at 2MHz down to 0.465μH at 2.5MHz. This was extremely close to the inductors nominal value of 0.47μH with a maximum of only 3.2% error. However, it was difficult to determine whether or not the decreasing inductance was “real” or a limitation of the automation program itself. The following sections will explain the consequences of using large frequency sweeps.
Figure 7.5 shows an example frequency sweep from 340kHz to 700kHz. At the lower end of the frequency sweep (340kHz – 450kHz), the inductance was measured to range around 0.51μH to 5.25μH, which is about a 9.6% error from the nominal value. As the frequency increased, the value of the inductor decreased to the rated value of 0.47μH at 700kHz. In this frequency range, the significant decrease inductance could have been the direct result of a rapidly decreasing current ripple. Since resolution was lost at smaller current ripple values, the inductance measurements became less accurate.

Because the LTC3612 buck converter was rated up to a 4MHz switching frequency, a higher range was tested. From Figure 7.6 on the following page, the inductance vs. frequency plot shows a similar frequency sweep range, but starting at 3.4MHz. At this switching frequency, the current ripple was significantly smaller than switching frequencies in the 100’s of kHz range, therefore the current probe amplifier and the User Inputted Settings had to be adjusted accordingly. Additionally, at this switching frequency, the current ripple did not change as significantly through the 3.5MHz – 3.8MHz range as it did in the 340kHz – 700kHz range. As a result, the inductance response was much more stable and did not drift down. The average inductance through the higher frequency sweep was around 0.49μH.
Although still a 4.3% error, the measurement seemed more accurate as it did not vary as much with the inductor current ripple.

Figure 7.6: LabVIEW front panel plot of inductance vs. frequency for a 0.47μH inductor from 3.4MHz – 3.8MHz
VIII. Conclusion

Since the Electrical Engineering Department at Cal Poly is limited to two pieces of equipment that could measure inductance accurately (the impedance bridge that has fixed frequencies of 100Hz/1kHz for large inductors and the VNA that has a minimum frequency of 10MHz for RF applications), this project aimed to obtain an accurate characterization of an inductor for one of its most prominent applications, the DC-DC converter. In DC-DC converter applications, switching frequencies ranging from hundreds of kHz to low MHz are common, and thus there was no available equipment that could provide this type of measurement on campus. Additionally, the automated system developed in this project allowed for inductor characterization while implemented within a DC-DC converter, meaning measurements could be taken in real-world scenarios that involve high power consumption.

With the proper oscilloscope setup, the automated inductor characterization system performed as expected and returned accurate inductance values through a sweep of switching frequencies. This was accomplished through acquiring hundreds of data points from the oscilloscope, performing necessary calculations, and averaging hundreds of inductance values. Using an inductor with a nominal inductance of 0.47μH, the generated inductance frequency response waveform showed values that were close to nominal at lower frequencies and drifted down as the switching frequency increased as shown in Figure 7.4.

Please note that although the inductance values generated by the program were assumed to be accurate, there was no valid way to fully verify the results for the specific DC-DC converter switching frequency range. Likewise, no other available equipment could measure inductance with high amounts of current going through the inductor, thus the results will be left up to the user to decide whether they are accurate or not. That being said, the following sections will explain difficulties and improvements that could be made in order to further improve the automation system.

In order to obtain the accurate inductance values, the hardware used in this project had to generate the correct inductor waveforms (square voltage waveform and triangular current
waveform). For this project, a standard demo board for the LTC3612 buck converter was chosen. Although this particular buck converter circuit did a good job of producing cleaning waveforms, the board had excessive pin breakouts and long traces to allow for user flexibility when designing with the LTC3612 buck converter. Since the project only required one specific test case (as outlined in section III), the board layout and component selection could have been optimized.

Likewise, a different type of circuit could have been implemented to drive the inductor. For example, a properly designed H-bridge or square wave inverter could potentially accomplish the same job and provide the correct inductor waveforms. Optimizing a hardware design for a wider range of inductor and current values would provide a good foundation for the designed LabVIEW automation program to capture waveform data and compute inductance.

Improvements could have also been made to the LabVIEW automation program and its interfacing algorithms with the equipment. One feature that made the automation program robust was the dynamic horizontal time scaling of the oscilloscope with the changing switching frequency. This was programmed to display a consistent 3-period waveform on the oscilloscope regardless of frequency. Due to the lack of LabVIEW automation with the current probe and current probe amplifier however, the same dynamic scaling of the current levels could not be accomplished. From the standard buck converter topology, as the switching frequency increased, the current ripple decreased. As a result, resolution in the point-by-point data acquisition also decreased. If a current probe that could interface directly with the oscilloscope was available, dynamic vertical scaling could be accomplished and the inductor measurements would be extremely accurate across a large frequency sweep range.
Figure 8.1: Recommended current probes that allow direct interfacing with the oscilloscope (no current probe amplifier required); Tektronix TCP0030 Current Probe (left) and Agilent 1147B Current Probe (right)

Given the amount of time allotted for this project, the automated inductor characterization system successfully accomplished the desired task with relative accuracy. The user required setup was kept as minimal as possible and once properly configured (hardware and LabVIEW equipment settings), obtaining inductance response plots did not require any manual measurements or calculations. The system has only scratched the surface of how beneficial the tool could be in terms of usability, speed, and accuracy, and should provide a good foundation for future improvements.
References


[2] Linear Technology “LTC 3612: 3A, 4MHz Monolithic Synchronous Step-Down DC/DC Converter” Datasheet


[4] Linear Technology LTC3612EFE DC1574A Schematic

http://www.vishay.com/docs/34253/lp20bz01.pdf

Appendix A

Linear Technology DC1574A Demo Board Schematic and Board Layout

Figure A. 1: Linear Technology DC1574A schematic [4]

Figure A. 2: Linear Technology DC1574A board layout [3]
Appendix B
Vishay IHLP-2020BZ-01 Low Profile, High Current IHLP Inductor

![IHLP-2020BZ-01 power inductor datasheet](image)

**FEATURES**
- Shielded construction
- Lowest DCR/µH in this package size
- Handles high transient current spikes without saturation
- Ultra low buzz noise, due to composite construction
- Excellent DC/DC energy storage up to 5 MHz. Filter inductor applications up to SFR (see “Standard Electrical Specifications” table)
- Material categorization: For definitions of compliance please see [www.vishay.com/doc?39912](http://www.vishay.com/doc?39912)

**APPLICATIONS**
- PDA/notebook/desktop/server applications
- High current POL converters
- Low profile, high current power supplies
- Battery powered devices
- DC/DC converters in distributed power systems
- DC/DC converter for Field Programmable Gate Array (FPGA)

**STANDARD ELECTRICAL SPECIFICATIONS**

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**Figure B.1: Vishay IHLP-2020BZ-01 power inductor datasheet**
Appendix C

Bill of Materials

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