NDSU Electrical and Computer Engineering

SENIOR DESIGN 2024

SD405_FA24_03

Precision LCR Meter

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Project Description

The Precision LCR meter is designed to measure electronic components (Inductors, Capacitors, Resistors) and analyze their impedance through phasor analysis to as high of a degree as is possible, with a target accuracy of <1%.

Theory of Operation

The operating principle of this LCR meter is phasor analysis:

$$\omega = 2\pi f$$
$$\text{Voltage Phasor} = \tilde{V} = |V|e^{j(\omega t+\phi)} = |V|\angle\phi$$
$$\text{Measured Voltage} = V(t) = \mathrm{Re}(\tilde{V})$$

An AC sine wave of a desired frequency is generated through Direct Digital Synthesis (DDS) and then buffered through a power amplifier stage to allow for the synthesized waveform to be supplied to a Device Under Test (DUT). The resulting voltage waveform across the DUT can be represented as a phasor, which contains its amplitude and phase information. Using a series current shunt resistor of known resistance, we can measure the current through the load. By sampling voltage using a DAC, we can synthesize the representation for a phasor voltage using linear regression through matrix operations. Through Ohm's law for phasors, the impedance of the load ($\mathbf{Z}$) is determined.

$$Z = \frac{\tilde{V}}{\tilde{I}} = \frac{|V|\angle\phi}{|I|\angle\theta} = \frac{|V|e^{j(\omega t+\phi)}}{|I|e^{j(\omega t+\theta)}} = \frac{|V|}{|I|}e^{j(\phi-\theta)} = \frac{|V|}{|I|}\angle(\phi-\theta)$$

From the measured impedance, we can calculate the equivalent impedance of a capacitor or inductor that would create the measured impedance. If the reactance (complex part of the impedance, X) is negative, the DUT behaves as a capacitor. If the reactance is positive, the DUT behaves as an inductor.

$$X_C = \frac{1}{j\omega C} \qquad X_L = j\omega L$$

To minimize the resistive and inductive effects of cabling, a 4-wire Kelvin sensing technique is applied; this allows for measurement of the resulting voltage phasor directly across the load. Effects of EMI are negated with the use of shielding.

Linear Regression Through Matrix Operations

To properly synthesize a best-fit waveform for the measured data, Linear Regression should be used. This is most efficiently accomplished through matrix operations, which is how it was implemented in this project.

For a perfectly fitted curve, sampled data can be represented through a matrix equation:

$$Ax = b$$

Where:

$$A = \text{Basis matrix that defines the curve}$$
$$x = \text{Curve coefficients}$$
$$b = \text{Sampled Data}$$

With real analog data, this equation will almost never have a solution. If we want to find the coefficients that best fit the curve to the data, we can use matrix operations to isolate the coefficient matrix (x).

$$x = (A^TA)^{-1}A^Tb$$

For fitting a sine wave with a phase shift, we must separate the coefficients into linear elements. The Goal fitted curve that we need to be able to calculate impedance is:

$$y = |V|\sin(\omega t + \phi)$$

This equation does not use only linear elements. We can use a trigonometric identity to create new linear coefficients that we will solve for.

$$|V|\sin(\omega t+\phi) = V_1\sin(\omega t) + V_2\cos(\omega t)$$

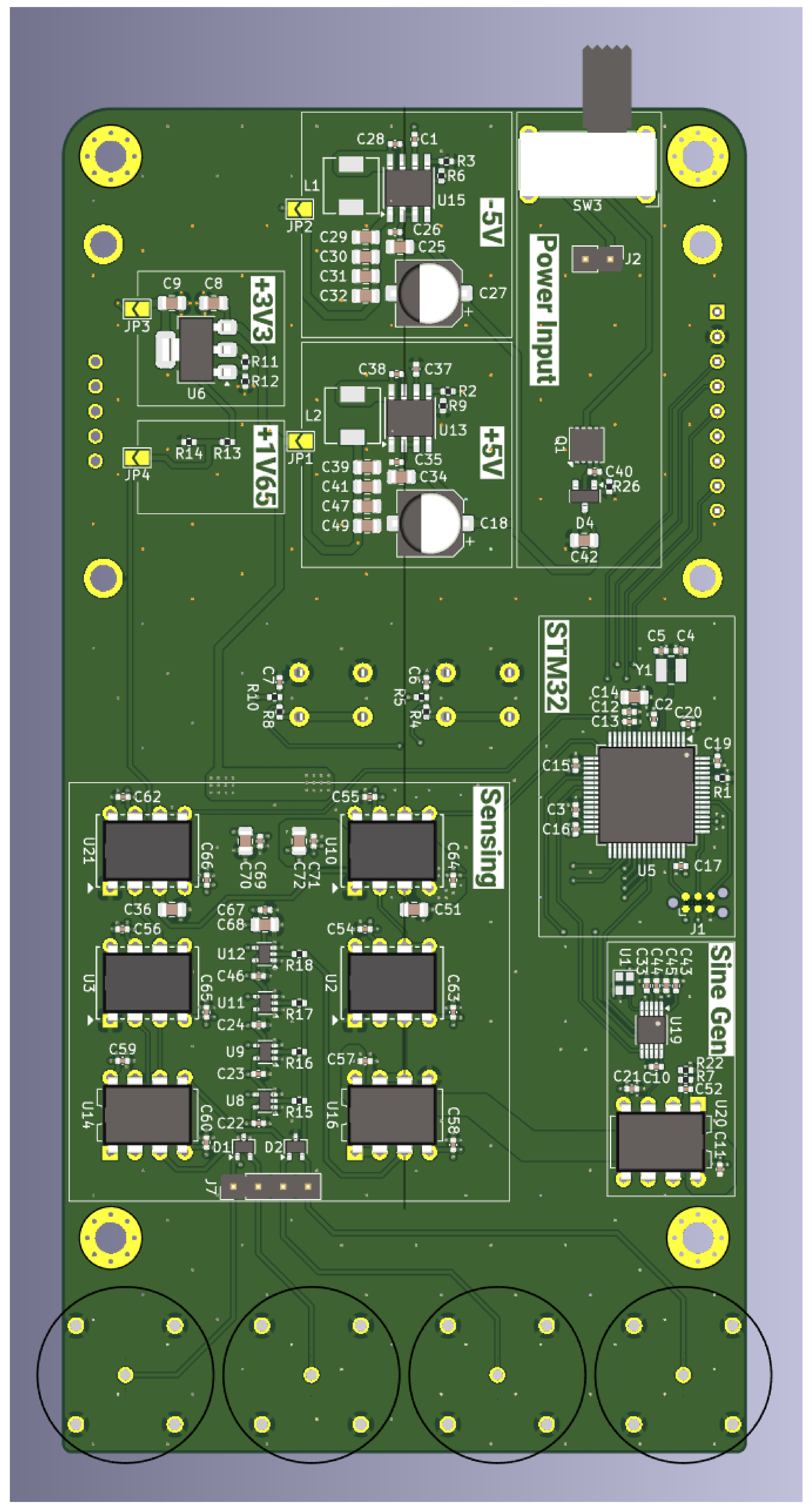
Where:

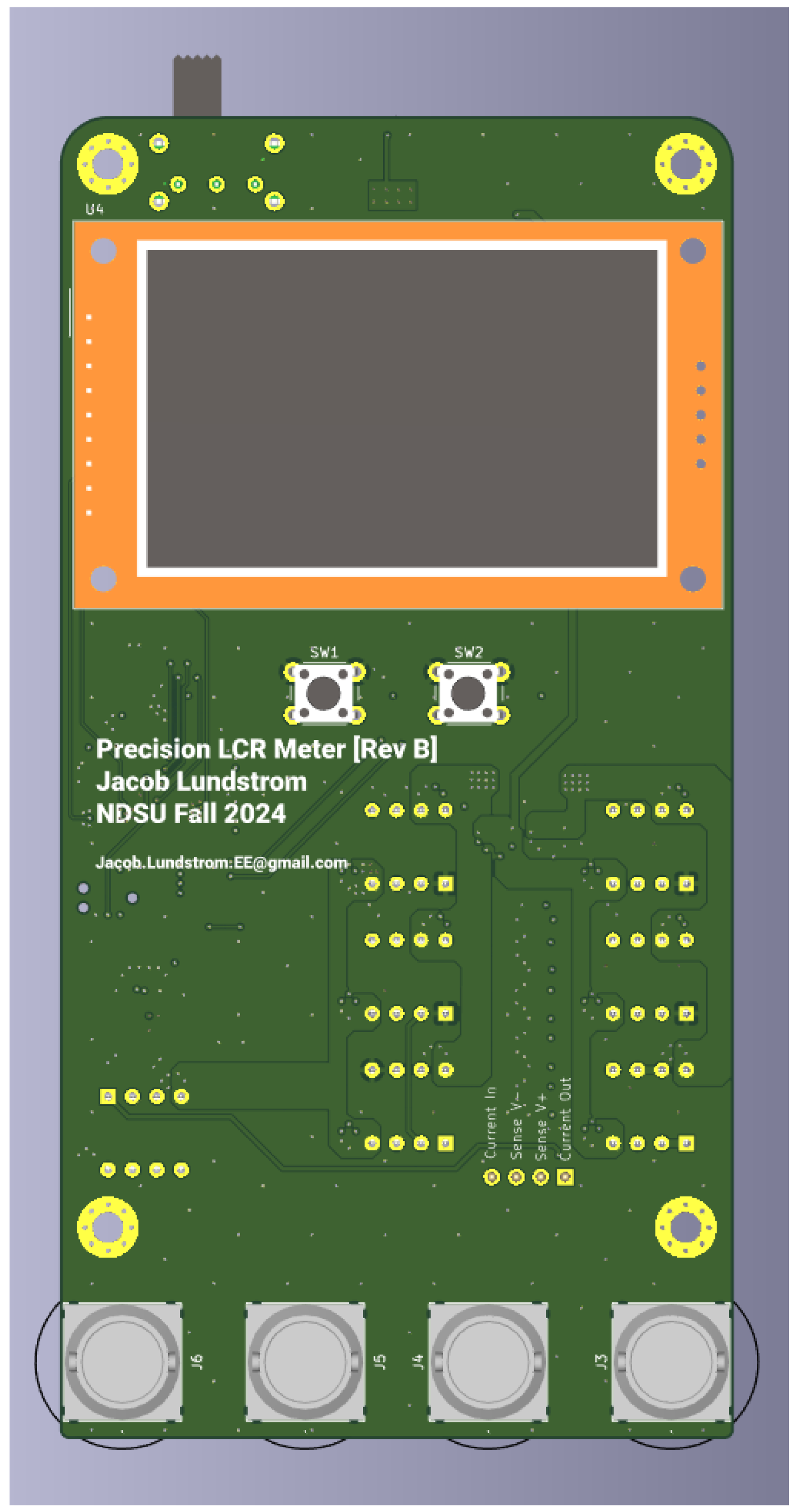
$$|V| = \sqrt{V_1^2 + V_2^2} \qquad \phi = \mathrm{atan2}(V_2, V_1)$$

Using this information, we then compose the matrices needed for the least squares regression formula:

$$x = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \qquad A = \begin{bmatrix} \sin(\omega t_1) & \cos(\omega t_1) \\ \sin(\omega t_2) & \cos(\omega t_2) \\ \vdots & \vdots \end{bmatrix} \qquad d = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \end{bmatrix}$$

Where t_n is the time at which data d_n was sampled. With the solution for x, we can synthesize the desired phase (ϕ) and amplitude ($|V|$) information.





Results

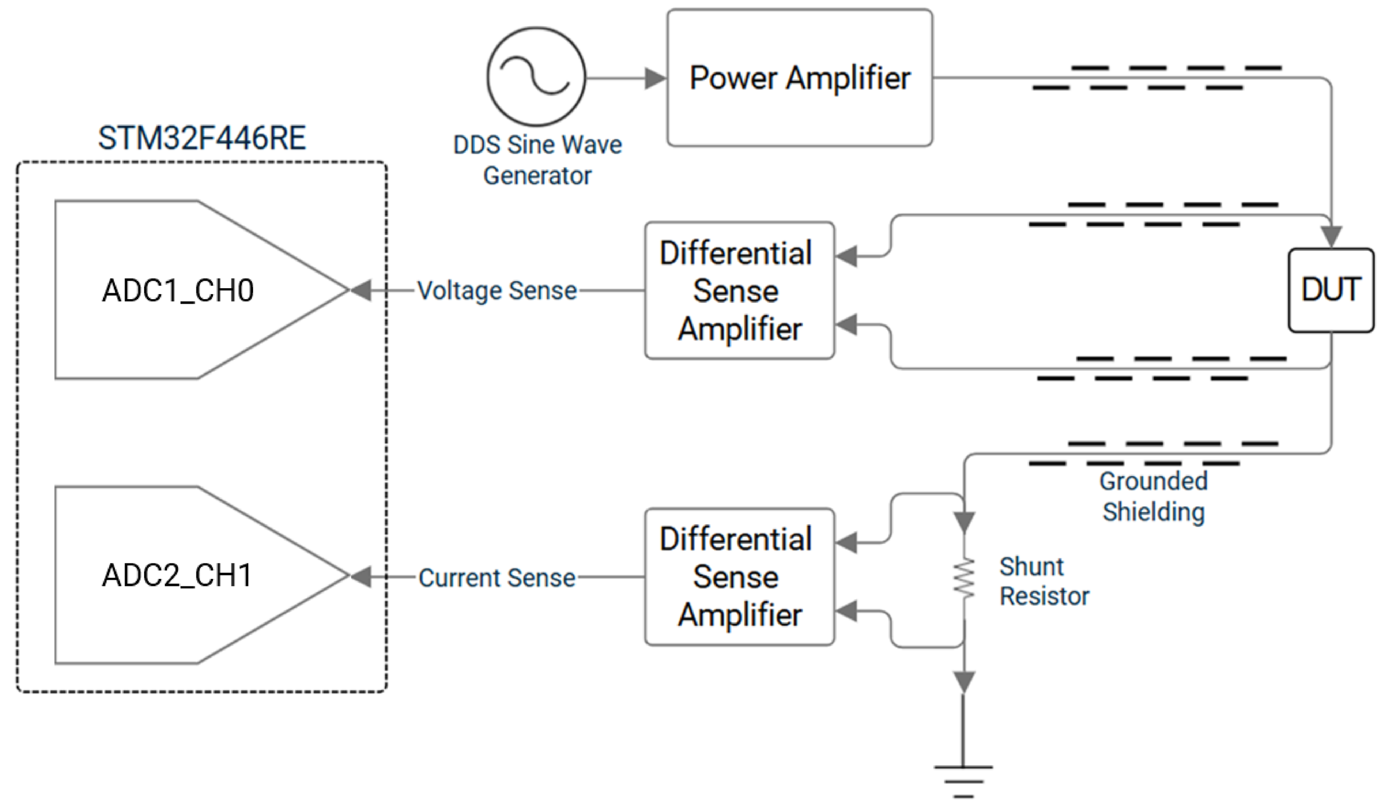
Capable Sine wave generation: **0 Hz to 100 kHz**
Generated Sine wave amplitude: **0.6 Vpp + 0.3 VDC**
Smallest resolution of measurable Capacitance: **1 pF**
Smallest resolution of measurable Inductance: **10 µH**

Component measurements:

Component Value (@ 1 kHz)	External measurement by DE-5000 (Used as "truth")	This LCR meter's measurement	Calculated Error
20 nF Capacitor (Calibration standard)	19.998 nF	19.994 nF	0.020%
2 H Inductor	1.9627 H	1.9453 H	0.887%
2200 nF Capacitor	2198 nF	2196 nF	0.091%
400 µH Inductor	374.5 µH	376.2 µH	0.454%
100 pF Capacitor	133.0 pF	134 pF	0.752%

This device is also capable of measuring **Parasitic Capacitance:**
Calibration standard isolated: 19.994 nF
Calibration standard with hand in contact: 20.385 nF
Hand parasitic capacitance is ~389 pF! Stronger contact yields higher capacitance.

System Block Diagram



Bill of Materials

The components listed here are the most important ones; for a more detailed BOM with passives and other excluded components, visit the GitHub page!

Reference Designator	Qty	Component MFG P/N	Function
U1	1	KC2016Z20.0000C15XXK	Reference Oscillator for Sine wave Generator
U10, U2, U21, U3	4	AMP03GPZ	Precision differential amplifier for sensing
U11, U12, U8, U9	4	TMUX1101DCKR	Muxes used for switching current shunt resistors
U13, U15	2	LMR33640DDDAR	Buck converters
U14, U16, U20	3	LM833N/NOPB	Sensing buffer amplifiers, sine wave power amplifier
U19	1	AD9833BRMZ	Sine wave DDS generator
U5	1	STM32F446RET6TR	Main MCU
U6	1	LM1117MP-ADJ/NOPB	Adjustable linear regulator
Y1	1	CG04874-8M	MCU oscillator

Want to know more? This project is open source!
Software: https://github.com/Jacob-Lundstrom/lcr-meter-software
Hardware: https://github.com/Jacob-Lundstrom/lcr-meter-hardware