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Programmable Impedance Transfer Standard to Support LCR Meters

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Summary Abstract

A programmable transfer standard for calibrating impedance (LCR) meters is described. The standard makes use of low loss chip components and an electronic impedance generator (to synthesize arbitrary complex impedances) that operate up to 1 MHz. Intercomparison data between several LCR meters, including estimated uncertainties will be provided in the final paper.

I. Introduction

Commercial digital impedance meters, often referred to as LCR meters, are used much like digital multimeters (DMMs) as diagnostic and quality control tools in engineering and manufacturing. Like the best DMMs, the accuracies of the best LCR meters are approaching those of the standards that support them. The standards are 2- to 4-terminal inductors, capacitors, and resistors that cover a very limited range of the meter's measurement capability. A typical LCR meter generates a current $I = I\angle 0$, at the desired frequency, that is applied to the impedance under test Z. The magnitude and phase of the voltage $V = V\angle\phi$ developed across Z is measured by a vector voltmeter in the LCR meter and the impedance is simply given by $Z = V/I$.

The LCR meter test current (or voltage) and frequency are generally operator-selectable, and the meter may span 15 or more decades of magnitude, e.g., capacitance from 10^{-15} to 1 F. Orthogonal components of complex impedances can also be measured. This nearly continuous measurement capability over current or voltage, frequency, and component magnitude space makes it very difficult to characterize LCR meters.

The standards for impedance are derived at the National Institute of Standards and Technology (NIST) using a calculable capacitor [1], a device that defines a 0.5 pF capacitor with an uncertainty of a few parts in 10^9. Precision transformer bridges are used to step up to a 1 nF standard capacitor at uncertainties less than a part in 10^8. The 1 nF capacitor serves as a standard for another bridge used to calibrate standard capacitors from 10 pF to 100 µF. It is also used in a quadrature bridge to calibrate a 1 kΩ ac resistor at an angular frequency of 10^4 radians (1592 Hz). A new digital impedance bridge [2], capable of intercomparing any two impedances up to 100 kHz, is used to calibrate standard inductors from 10 µH to 10 H, based on a set of ac resistors.

With all of this measurement capability, there are fewer than 30 different-value impedance standards (artifacts) available to calibrate LCR meters. What is needed is the impedance equivalent of a multifunction calibrator for DMMs. This paper describes several techniques that have been investigated to develop such a calibrator for LCR meters.

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II. Programmable Impedance Standards

Miniature impedances

Conventional impedance standards like air-core inductors, gas-dielectric capacitors, and wire-wound resistors have served the standards community for decades. They were designed for stability and a number of other qualities, but not compactness. They are typically mounted in cases that are 10 to 20 cm on a side with large connectors, and are not easily incorporated into a programmable impedance standard. To overcome this problem, chip components were evaluated as possible impedance standards and it was discovered that some of these chips are approaching the quality of the older laboratory standards. For example, 1 nF ceramic chip capacitors are available with temperature coefficients of 30 ppm/°C compared to 5 ppm/°C for gas capacitors. While gas dielectric standard capacitors have lower dissipation factors (10^{-6} compared to 10^{-4} - 10^{-5}), they are also about a thousand times more expensive and occupy about a million times the volume. Chip resistors and inductors are available with temperature coefficients of 100 ppm/°C. However, 1 ppm/°C metal film resistors are available in packages that are only about 10 times larger than the chip components.

These miniature components are easily configured as 4-terminal programmable impedances, which when calibrated, have adequate stability in the dc to 1 MHz range to be used as transfer standards to support the calibration of the best commercial LCR meters. They can also be combined to form complex impedances to test the ability of the LCR meter to differentiate between resistive and reactive elements. One of the limitations of the chip inductors and capacitors is that the most stable components are available only in limited values (<100 µH and <10 nF).

Synthetic impedances

To calibrate an LCR meter as a two-terminal device, where the current and voltage (sense) terminals are tied together, requires an actual artifact. For four-terminal measurements, it becomes possible to use a synthesized impedance to cover a much wider range than would be practical using actual inductors, capacitors, and resistors. Two techniques were investigated to synthesize arbitrary impedances.

In the first, shown in simplified form in Fig. 1, the LCR meter current I is converted to a voltage V using a known resistor R. This voltage is sampled by a Waveform Digitizer, modified in a Digital Signal Processor, and reconstructed in a Waveform Generator. The resultant synthesized voltage V_S is a scaled version of V, modified in magnitude and phase to simulate the voltage that would be developed across the desired arbitrary impedance carrying the test current I.

While conceptually quite simple, this *digitally synthesized impedance generator* is difficult to realize using commercial waveform samplers and generators. To simplify the digital processing, the clock frequency (that controls the sampling and synthesis rate) must be synchronized with the test frequency generated by the LCR meter. This requires accurate phase locking

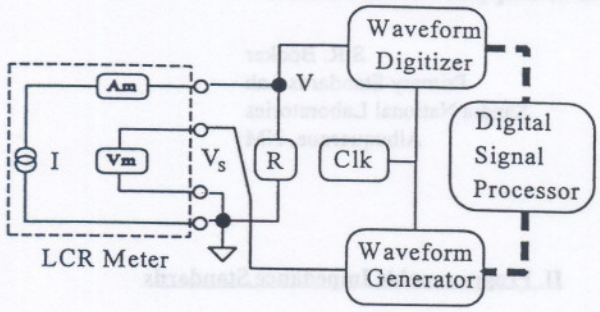

Fig.1. Digitally synthesized impedance generator that samples the LCR meter test current, modifies it digitally, and reconstructs a voltage waveform using a waveform generator. Heavy dashed lines represent a data bus.

circuitry that operates over the LCR meter's frequency range (10 Hz to 1 MHz for certain meters). An alternative is to sample asynchronously over enough periods to minimize truncation errors, and then extract the magnitude and phase of V with more complex signal processing.

In the second approach, shown in Fig. 2, the voltage V is modified using analog techniques. The phase locking problem is overcome by scaling V using multiplying digital-to-analog converters ($MDAC_I$ and $MDAC_Q$) to produce programmable in-phase and quadrature components V_I and V_Q. These are combined to form V_S, which when applied to the voltage terminals of the LCR meter, simulates the desired arbitrary impedance.

The output of $MDAC_I$ is an inverted (shifted 180°) version of V, adjusted in amplitude by the digital setting of $MDAC_I$. If this signal were applied to the voltage terminals of the LCR meter, the meter would register a negative resistance. Its inverse (shifted 180° in inverter INV_I) is in phase with V and will cause the LCR meter to display a positive resistance.

The quadrature component is produced by integrating V to produce a sine wave phase shifted 90° with respect to V. Its amplitude is determined by the digital setting of $MDAC_Q$. To the LCR meter this signal looks like the signal that would appear across an inductor. Inverted, through INV_Q, it looks like the signal across a capacitor. The sum of V_I and V_Q (V_S) simulates the signal that would appear across any arbitrary impedance ranging from a pure resistance to a pure reactance.

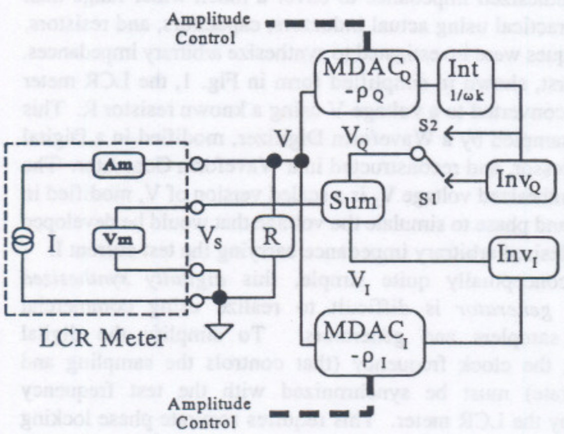

Fig. 2. Analog impedance generator that uses MDACs and an integrator to generate in-phase and quadrature components.

LCR meters separate and display components that are orthogonal (e.g., resistance in series with capacitance). In a similar manner, the voltage V_S can be expressed in terms of components of inductance C_L, capacitance C_C, and resistance C_R. These terms are related to the $MDAC_I$ transfer function $-\rho_I$ (between 0 and 1), the $MDAC_Q$ transfer function $-\rho_Q$, the test frequency ω, the integrator transfer function $1/\omega k$, and the input resistor R by:

$$C_L = R\rho_Q/\omega^2 k \tag{1}$$

$$C_C = k/R\rho_Q \tag{2}$$

$$C_R = R\rho_I \tag{3}$$

For example, if $R = 1\,k\Omega$, $\rho_I = .5$, $\rho_Q = 0.02$, $k = 10^{-6}$, $\omega = 10^4$, and the switch is in position S1, then equations 2 and 3 apply and the LCR meter will interpret V_S as a 50 nF capacitor in series with 500 Ω. In switch position S2, equations 1 and 3 apply. V_Q will have the same magnitude as in S1, but be shifted in phase by 180°. This will cause the LCR meter to indicate 200 mH in series with 500 Ω.

The circuit was designed to cover the range of inductors and capacitors that are not available as miniature components. In the mid audio-frequency range, inductors between 10 μH and 10 H, and capacitors between 100 pF and 100 μF can be synthesized using this *analog impedance generator* technique.

III. Conclusions

Designs for a programmable impedance transfer standard have been proposed. A study of relay-switched miniature components, configured as 4-terminal impedances, has shown that they are stable enough to support the best LCR meters. This will be substantiated in the final paper. Several techniques to electronically synthesize impedances have also been investigated. A circuit evaluation of the *analog impedance generator* is presently underway. Its performance as an impedance transfer standard as well as benefits and disadvantages of this method will also be reported in the final paper.

References:

1. J.Q. Shields, R.F. Dziuba, and H.P. Layer, "New realization of the ohm and farad using the NBS calculable capacitor," IEEE Trans. Instrum. Meas., IM-38, pp. 249-251, April 1989.

2. N.M. Oldham, O. Petersons, B.C. Waltrip, "Automatic impedance bridge for calibrating standard inductors," CPEM'92 Digest, 1992.