Impedance-Analyzer Measurement of High-Frequency Power Passives: Techniques for High Power and Low Impedance

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Impedance-Analyzer Measurements of High-Frequency Power Passives: Techniques for High Power and Low Impedance

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Abstract— **Challenges for measurements of high-frequency passive components for power electronics applications include the difficulty in measuring the small real impedance of an efficient component, the need for high-level excitation to match operating conditions for a nonlinear component, and in some applications, the need to measure very low impedances. Commercial impedance analyzers are tested and shown to be able to meet some of these requirements. To extend their capabilities, a new test fixture with less than 100 pH stray inductance has been developed for measurements of low impedances. The use of a power booster to extend drive capability to higher powers is also presented.**

I. Introduction

CHARACTERIZING passive components for power electronics applications entails several unusual challenges. Impedance analyzers can adequately characterize resistors, capacitors, inductors, and transformers for many applications, but their limitations can become problematic for power components. Nonetheless, they are often the most convenient way to characterize a component, and high accuracy can often be achieved.

The first difficulty arises from the fact that power components are designed to minimize power loss. Thus, a good power inductor or capacitor will have a real component of impedance that is small compared to the imaginary component. Yet the smaller real component is more important to measure accurately, because it determines the power losses. This means that even very small phase errors can be critically important. High resolution and accuracy and careful calibration become essential, as discussed in Section II.

Another difficulty arises from the nonlinearity of ferroelectric and ferromagnetic materials used in ceramic capacitors and magnetic components, respectively. For nonlinear devices, small-signal sinusoidal measurements do not completely characterize the device. The impedance may change with signal level, and Fourier analysis cannot be used to predict the behavior with nonsinusoidal waveforms. Thus correct characterization requires testing with the waveforms and amplitudes that will be used in the actual application. In Section IV, we describe a power booster that enables a small-signal impedance analyzer to test components with large-signal excitation, although it is still limited to sinusoidal excitation.

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Power components span a wide range of impedance magnitudes. This makes network-analyzer measurements [1], [2], [3], [4], [5], which are referred to a 50 Ω impedance, unsuitable for many measurements. Impedance analyzers using four-terminal or four-terminal-pair (4TP) connections to the device under test (DUT) can accurately measure much lower impedances. However, for present and future microprocessor power delivery circuits (often termed voltage regulator modules, or VRMs), the impedances required are low enough that stray inductance in the test fixture becomes a severe problem. In Section III, we describe a new test fixture designed for these applications that achieves under 100 pH stray inductance.

A. Four-Terminal-Pair Configuration

Most of the work described in this paper uses impedance measurements via the four-terminal-pair (4TP) auto-balancing bridge system [6], as illustrated in Fig. 1. This system minimizes the effect of stray impedance in the interconnections. The basic operation is reviewed here; the effect of stray impedances is discussed in the appropriate sections below.

In Fig. 1, a signal is applied from the high/current terminal pair (Hc). The high/potential (Hp) terminal pair measures the voltage across the DUT with respect to a virtual ground maintained by the low/potential (Lp) terminal pair, via feedback control of a second source at the low/current terminal pair. The current flowing through the DUT is measured by monitoring the current applied through the low/current (Lc) terminal pair. From the magnitude and phase of the measured voltage and current, the analyzer can compute complex impedance.

II. Accuracy for Impedances Having Small Real Parts

For a low-loss component, the real part of impedance, or ESR (effective series resistance), R is a small fraction of the imaginary part of the impedance, X. The ratio of real and imaginary parts can be expressed as the dissipation factor $D = R/X$ or as the quality factor $Q = X/R$. For a component with a quality factor $Q = 200$, the real part of the impedance is 0.5% of the total impedance. Thus, even a 0.1% error in an impedance measurement could potentially cause a $200 \times 0.1\% = 20\%$ error in R.

Not all types of errors are as severe as the above simple example would indicate. For example, a scaling error of 0.1% in

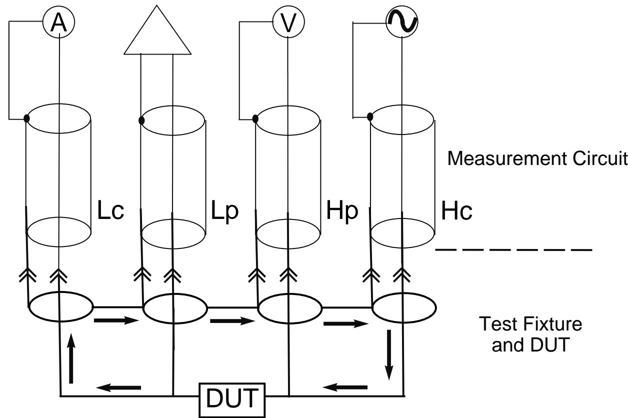

Fig. 1. Schematic of the Auto Balancing Bridge Measurement [6]

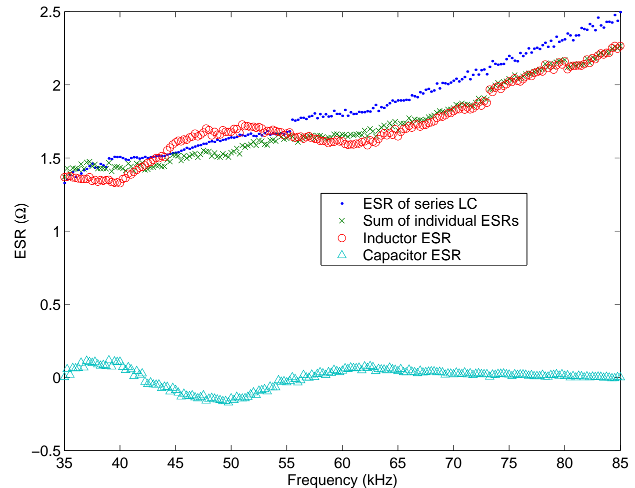

Fig. 2. ESR measurements of a high-Q capacitor, a high-Q inductor, and a series combination of the two.

the impedance measurement would lead to just a 0.1% error in the real part. However, phase errors can have detrimental effects. A Q of 200 corresponds to a phase angle of complex impedance of just $0.3°$. For 5% accuracy in ESR in a measurement of such a component, the precision of the phase measurement must be $0.014°$.

Most impedance analyzers do not have this degree of phase resolution or accuracy. Thus, the loss of high-Q components was traditionally measured using a resonant circuit, in a "Q meter." However, a new impedance analyzer (Agilent 4294A) has been advertised as having sufficient phase accuracy that it make the Q meter obsolete [6]. We examined the performance of the instrument in measuring very high Q components.

A. *Experiments*

To study the measurement capability at high frequencies, we constructed a very high Q inductor and a very high Q capacitor. The capability of the meter at extracting the real part of impedance was assessed by measuring the ESR of the individual inductor and capacitor, and then measuring the ESR of the series combination in and near resonance.

The inductor is similar to the one described in [7], but with the errors in the original design, as described in [7], corrected such that a Q of 600 to 1000 is achieved. In order to achieve this high value of Q, we had to be careful of dielectric loss in the insulation as well as minimizing the winding and core loss. For low dielectric loss, we used thick polypropylene tape as insulation between winding layers.

The capacitor is a simple air capacitor made with two 20 cm $\times$ 30 cm aluminum plates, approximately 3 mm thick. The plates are spaced apart by small pieces of polypropylene, placed only in the corners (in order to minimize any dielectric loss). After observing the effect that nearby materials (such as a person's hand) could have on the loss in the capacitor, we supported the plates by a large glass beaker in order to keep them away from any other materials that might have large dielectric loss. Measuring the Q of this capacitor was in fact beyond the capability of the analyzer, but it appears to be on the order of 8000 or better.

The individual ESR measurements of the capacitor and the inductor, the sum of these, and the ESR measured in the series combination are shown in Fig. 2. The measurement of the series combination shows impressive performance, and is shown again in Fig. 3. In this test, the analyzer must measure the roughly-constant real part of the impedance as the imaginary part ranges from under negative 1 kΩ, through zero, to over positive 1 kΩ—a range between a small fraction of the real impedance to three orders of magnitude higher than the real impedance. The fact that the real part measured shows no significant disturbance as the test network passes through resonance shows that the meter (Agilent 4294A) is very good at extracting the real part independent of the imaginary part.

However, the individual measurements (Fig. 2) show some signs of error. The capacitor ESR measurement contains the most obvious errors, since the ESR is measured as a physically-impossible negative value in the vicinity of 50 kHz. Interestingly, the inductor ESR has a hump in exactly the same frequency range that the capacitor ESR has a dip. This is symptomatic of a phase error in this region, of about 6.5 millidegrees (m°). Although this sounds small, it is enough to be significant for high Q components, causing 2% error at a Q of 200, or 10% error at a Q of 1000. There is also about a 0.2 Ω discrepancy between the individual measurements and the sum. This could be at least partly due to contact resistance in the connection between the components, or it could be indicative of other measurement errors.

In order to investigate the hypothesis that the complementary bumps in the inductor and capacitor ESR plots are due to a phase error in the instrument, we measured a simple resistor to check for phase deviations from zero. For this measurement, any stray capacitance or stray inductance would of

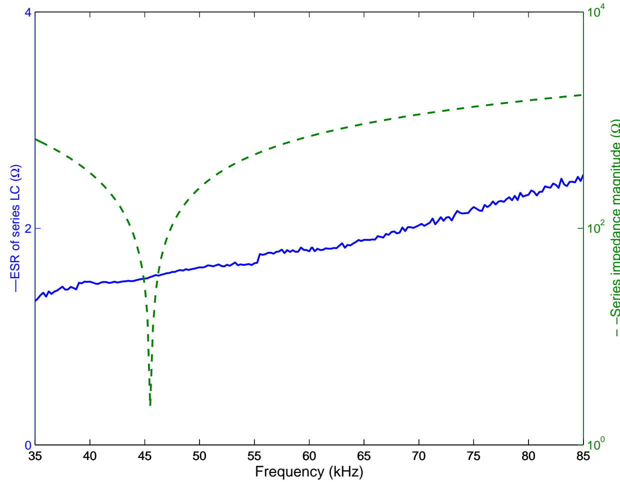

Fig. 3. Impedance measurement of the series combination of a high-Q capacitor and a high-Q inductor. Impedance magnitude is on the right-hand scale, and the real part of impedance is on the left-hand scale. This illustrates the capability of the impedance analyzer (Agilent 4294A) to measure small impedances real parts of impedance consistently with or without large imaginary impedances present.

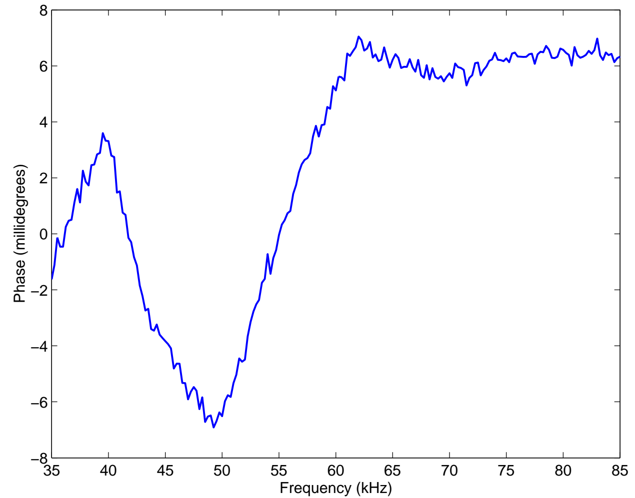

Fig. 4. Phase measurement with a 100 Ω resistor.

course affect the accuracy. For this and the other measurements discussed in this section, we used a simple test fixture with approximately 10 cm of solid, teflon-insulated wire on going from each center-pin of the four terminal pairs (Fig. 1) to Kelvin clips, and a copper bus bar directly shorting together the ground connections of the terminal pairs. The Hc and Lc wires are twisted together, as are the Hp and Lp wires, to minimize mutual inductance. This simple fixture has a stray inductance of about 33 nH and a stray capacitance of about 8 pF. Although both of these can be reduced in more sophisticated test fixtures, they are good for a test fixture that offers the convenience of clip-lead connections to the DUT. Although the stray values vary some as the wire positions are changed, the solid wire allows minimizing changes, so that short-circuit and open-circuit calibrations are effective.

For the resistor test, we wished to stay midway between the high-impedance range where stray capacitance causes large errors and the low-impedance range where stray inductance causes large errors. To do this, we choose a 100 Ω axial lead 1/4 W metal film resistor, near in the value to the 65 Ω characteristic impedance of the fixture strays. We also performed short-circuit and open-circuit fixture calibrations prior to the measurement.

The measured phase of the 100 Ω resistor is shown in Fig. 4. The shape of this curves shows a strong correspondence to the shape of the capacitor ESR curve in Fig. 2, confirming that phase error explains the hump in the capacitor ESR curve. If the resistor is assumed to be perfect, and this is interpreted as being purely the result of phase errors in the instrument, we can use these values to correct the phase of the measurements shown in Fig. 2. A standard load compensation calculation as described in [8] should correct the phase, but on the Agilent 4294A it appears to only compensate the magnitude without compensating the phase. We performed the phase compensation in a simple MATLAB program. The results for capacitor ESR with and without compensation are shown in Fig. 5. The error has been reduced substantially, and the corrected curve is much smoother with the hump almost entirely eliminated. However, significant error is still apparent as the corrected curve is still largely below zero. The maximum error, taken as the most negative value, is about half of the maximum error before correction. The remaining error is likely due largely to fixture strays affecting the resistor measurement. For example, a 15 nH fixture compensation error in the measurement of the 100 Ω resistor as a zero-phase standard would almost completely explain the deviation from zero in the phase-compensated capacitor ESR in Fig. 5.

The first conclusion we can draw from this phase compensation experiment is that the instrument's inherent phase error is an important part of the measurement error in loss measurements of very low loss components. The second conclusion is that the instrument's high phase resolution makes phase compensation effective. The third conclusion, however, is that if phase compensation is used, it is essential to use fixtures with extremely low strays. We hope to construct a phase calibration fixture using precision thin-film resistors in combination with the low-stray-inductance test fixture described in Section III and use this to achieve much lower phase errors. Another possibility would be to use a capacitor with known low losses, such as the one we measured, as the standard for load compensation.

It is important to be alert to other possible problems when making sensitive measurements. For example, a persistent glitch at about 64 kHz in one measurement was traced to third-harmonic noise from an electronic ballast in the overhead flu-

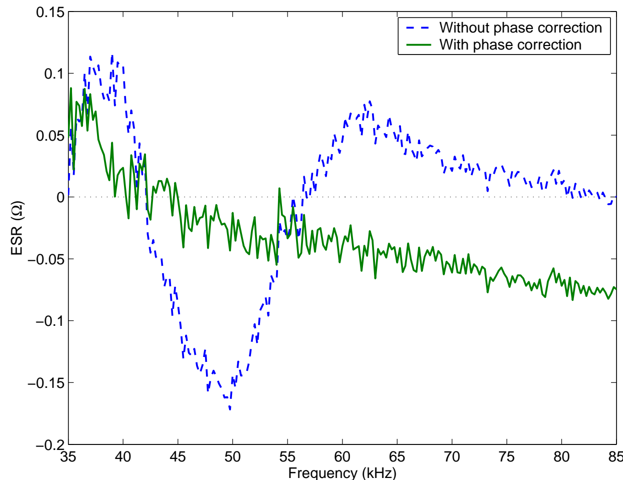

Fig. 5. ESR measurements of a high-Q capacitor, a high-Q inductor, and a series combination of the two.

orescent lights.

Without phase compensation, one could estimate the measurement error as either the largest negative capacitor ESR observed, -0.15 Ω, or as the maximum discrepancy between the sum of individual ESR measurements and the ESR measurement of the series combination. We conservatively choose the latter (the larger number) as our estimate of ESR error even though it may be due merely to contact resistance. This 0.2 Ω error corresponds to an error in D of 1.2×10^{-4}, or a phase error of $0.007°$. If this is correct, it would mean that a Q of 1000 could be measured with 12% accuracy, and a Q of 100 with 1.2% accuracy. This is well within the specified typical Q accuracy of the 4294A of $\pm 3\%$ for $Q = 100$ [9]. Compared to the specified accuracy of an industry standard Q meter, the HP4342A (no longer in production), our results are slightly better at high Q values ($\pm 12\%$ vs. $\pm 15\%$ at $Q = 1000$), and considerably better at lower Q values ($\pm 1.2\%$ vs. $\pm 7\%$ at $Q = 100$). Also, note that Q meters typically have a limited maximum Q value that can be measured (1000 for the HP 4232A), whereas the HP4294A is essentially unlimited in the maximum value it will display—although the readings of up to at least 10^6 that it can display with noisy data and low loss are more misleading than helpful. It appears that phase compensation could be used to achieve a significant further reduction in error, but preventing stray reactances from distorting the resistor measurement used for calibration is critical.

For comparison, a common older impedance analyzer (HP 4192A) was also used to measure the same components. Similarly, it appeared to be limited by phase error, but, unlike the 4294A, it was also limited by phase resolution. The best phase resolution could be obtained by displaying D, which is displayed with resolution of 1×10^{-4}, corresponding to a phase resolution of $10^{-4} 180/\pi$ degrees $= 6$ m°. Its phase error exceeded its resolution, but not by much. The dissipation factor of the same air capacitor was measured as -2×10^{-4}, indicating a error of at least 12 m°. This is good given the lower resolution of the instrument, but not as good as the 4294A. In addition, implementing improved compensation would not be worthwhile, because the limited resolution would not allow substantial improvements.

III. Test Fixture

A test fixture is necessary to connect the device under test (DUT) to an impedance analyzer, which typically uses the four terminal pair (4TP) configuration with the auto balancing bridge technique, as shown in Fig. 1. Unfortunately, commercially available test fixtures are not adequate for measuring very low impedances at frequencies extending into the MHz range, as is becoming critical for developing high-performance high-current power systems for microprocessor power delivery.

The four-terminal-pair (4TP) configuration (Fig. 1) is effective at preventing stray impedances of the cables, including series inductance and resistance and shunt capacitance, from appearing in the measurement [6]. However, the stray impedances in the immediate vicinity of the DUT remain. For example, the resistance of the ground path adjacent to the DUT appears as part of the measurement. This resistance is often negligible, even for low-impedance devices, but more important is the inductance of the current loop comprising the DUT and the adjacent ground path. The inclusion of this loop inductance might be considered a defect in the design of the 4TP system. However, inductive impedance is not defined other than for a loop [10]. Thus, it is a fundamental requirement for any impedance measurement to include the inductance of a current loop through the DUT and returning through some ground path. It is essential for test fixture users and designers to be aware of what that current loop is, in order to ensure that the measurement is appropriate for the application.

In modern high-performance circuit applications with surface-mount devices, the return path is ordinarily a ground plane immediately beneath the device. Other return paths introduce additional inductance that is better considered as inductance of the board rather than inductance of the device. The vertical distance to the ground plane also contributes to the loop inductance. Thus, it makes most sense to consider the inductive impedance of a surface-mount component as the inductance of the loop comprising the current path through the device and a return path in a plane immediately beneath the device.

Presently available commercial test fixtures for surface-mount devices typically have the return path spaced 5 to 10 mm way from the device. This configuration results in two problems. Firstly, the inductance of the loop with the fixture shorted is in the range of 100 nH. Impedance analyzers have the capability to compensate for test-fixture strays based on open-circuit and short-circuit measurements. However, attempting to compensate for stray impedance much larger than

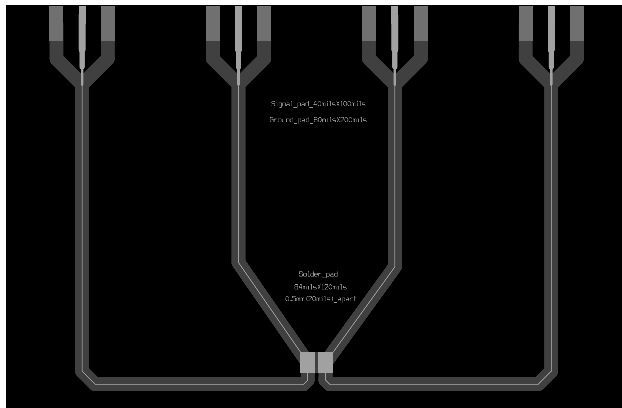

Fig. 6. Layout of the test fixture designed for low stray impedance.

the impedance of the DUT can lead to poor resolution and accuracy. Secondly, the current distribution in the DUT is affected by the proximity of the ground return path, which establishes the boundary conditions that determine the electromagnetic phenomena that occur in the DUT. Since in an actual application, the return path would be close to the DUT to minimize stray inductance, it is necessary to replicate this configuration in the test. This is important both to reduce errors that arise from fixture loop impedance that is comparable to the DUT impedance, or often much larger, and to make the behavior of the DUT itself match the in-circuit behavior by establishing proper boundary conditions.

Recently-introduced coaxial test fixtures reduce the stray inductance of the current loop, but, for most applications, the boundary conditions they establish for the DUT are very different from the boundary conditions in the application. Coaxial fixtures provide repeatable results, but not results that are relevant for a typical application.

Some high-frequency test fixtures do place the component directly on top of a ground plane. Thus, they can achieve low stray inductance and realistic boundary conditions. However, to our knowledge, all such fixtures that are commercially available use dry two-point contacts to the DUT, and thereby introduce series resistance that can be large compared to the resistance of the DUT. Furthermore, the resistance is highly variable each time a DUT is placed in the fixture, such that compensation based on a short-circuit measurement does not solve the problem. The commercial four-point contact fixtures we are aware of use large return-path spacing, and so have the disadvantage of high stray inductance and unrealistic boundary conditions.

To make a test fixture with much lower stray inductance, and with a ground-plane return path in close proximity to the DUT, we designed a test fixture using high-resolution printed-circuit board technology on a thin polyimide substrate (Fig. 6). In this figure, dark gray is the conductor on the bottom side, and light gray is the conductor on the top. The polyimide is 76μm (3 mils) thick, such that a trace with a ground return path beneath it has an inductance of less than 100 pH per square. Careful layout can keep the effective number of squares below one, making it possible to achieve very low stray inductance. The thin substrate could potentially lead to high stray capacitance, but minimizing stray capacitance was not our primary objective, since we are interested primarily in very low impedance devices.

We chose to use two-point solder connections to the DUT. Although the solder-joint resistance then appears in the measurement and reduces precision compared to a four-point connection, the solder connection has lower resistance and better repeatability compared to a two-point dry contact, and it is a realistic model of how the component will be used.

To minimize the portion of stray impedance appearing in the measurement, the 4TP interface of the analyzer is maintained until the traces reach the solder pads for the DUT. Thus, only the stray impedance of those pads, and not that of the traces, appears in the measurement. The traces are designed as 50 Ω strip lines, with 1.27 mm lines above much wider ground lines. This matches the lines to the 50 Ω 4TP interface that the Agilent 4294A analyzer uses above 15 MHz [6]. The traces connecting to the corners of the pad needed to be tapered to avoid breakage due to thermal stresses arising in processing.

The geometry of the pads and the connections to them were designed to minimize sensitivity to solder location. Manual soldering of the DUT leads to variations in its position. If the stray impedance is sensitive to the position of the solder connection to the DUT, calibrating using a short and then replacing the short with the DUT would lead to errors because the short and the DUT are not soldered in exactly the same position. A set of finite-element simulations was used to evaluate the effect of different pad geometries on both the magnitude of stray impedance and on the sensitivity of stray impedance to the location of solder connections. This led to the choice of pad geometry as shown in Fig. 6.

We have also fabricated some pieces with the pads shorted in the board. That allows testing and calibrating based on the short-circuit impedance without any solder joints included in the measurement, such that the measurement of the DUT will include the resistance of its solder joints. With these pre-shorted test fixtures, we measure stray inductance and resistance to be 43 pH and 1.1 mΩ, respectively, at 10 MHz. This is close to what we expected to achieve. Although low stray capacitance was not one of our goals, we measured 15 fF stray capacitance with an open-circuited test fixture. The low stray capacitance can be attributed to the fact that the 4TP configuration ignores capacitance to ground. The pads are effectively shielded from each other by their close proximity to the ground path. Thus, this configuration is excellent for low-capacitance measurements as well as inductance mea-

surements.

With copper-foil shorts soldered in place, we have measured stray inductance ranging from 87 to 115 pH and series resistance between 1.3 and 1.8 mΩ. With zero thickness of the solder, the 17 μm thickness of the traces spaces the solder short above the board, adding an additional 25 pH per square. However, the solder adds additional thickness, and, in our initial tests, we had trouble keeping the copper foil flat, which results in additional stray inductance. The range of values obtained indicates the importance of good solder technique and of using a flat, rigid copper piece for a short. The effect of stray inductance and resistance on the measurement can be removed by calibrating the analyzer with a short in place (or by simply subtracting the short-circuit values from the measurement), but the variability leads directly to error in the final measurement. We hope to achieve better repeatability, but even with 30 pH error in the inductance, this represents many order of magnitude better precision than is achievable with commercially available test fixtures. The sensitivity to solder technique also underscores the importance of good solder technique in an application where small stray impedance is needed.

The necessity of soldering on components is the main disadvantage of this test fixture. Soldering takes much more time than popping a DUT into a spring-loaded fixture. This means that the fixture's application is limited to design and research; it is not a production tool. As discussed above, soldering imposes limits on repeatability; although we designed the fixture to be insensitive to the exact placement of the solder joints, both the resistance and the inductance are sensitive to the thickness of the solder joints, and the 30 pH variation we saw as a result is the largest error in our inductance measurement. An additional disadvantage of the solder connection is that the life of a single test fixture is limited. Fortunately, they can be mass produced inexpensively.

The fixture allows measuring low-impedance components with accuracy of 30 pH or better, and provides correct boundary conditions such that the electromagnetic behavior of the DUT matches its behavior in a high-performance circuit with a ground plane. The fixture has been applied to measuring low-impedance capacitors in [11], and is being applied to measuring the microfabricated inductors discussed in [12].

IV. Impedance Measurements at High Drive Level

This section describes a method for measurement of loss in passive components at higher power levels using a 4TP impedance analyzer. The idea is to use a boosting network, introduced between the impedance analyzer and the test fixture, to deliver an amplified signal from the analyzer to the DUT and perform loss measurements at the same power levels at which it was designed to operate. The high-power impedance measurement system includes three modules: an impedance analyzer, a high power module, and a test fixture, as shown in Fig. 7. Both the analyzer and the test fixture may be any standard 4TP units, as the high-power module interfaces with both through standard 4TP connections. Thus, the high-power module is the only special equipment, and it may be used with a wide variety of test fixtures and analyzers for different applications.

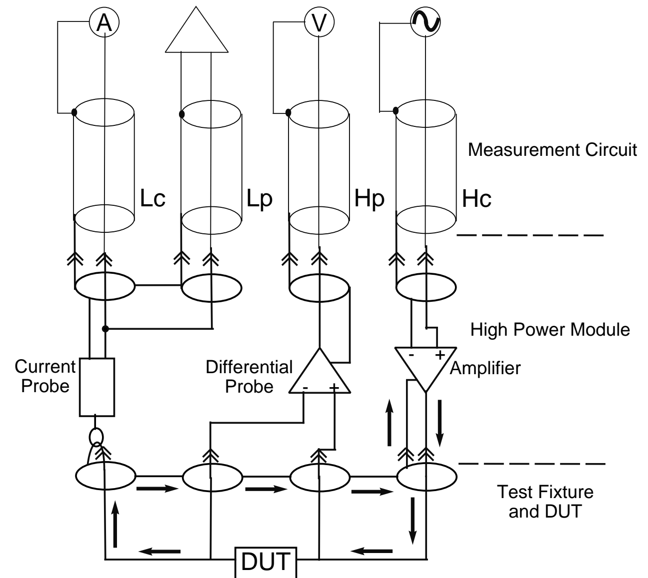

Fig. 7. Schematic of the loss measurement method at high power

The high power module consists of an amplifier, a differential voltage probe and a current probe. The amplifier boosts the signal from the Hp terminal pair of the analyzer and delivers the larger signal to the test fixture Hp terminal pair. A differential probe with attenuators is used to step down the high voltage applied across the DUT to a level compatible for measurement at the Hp terminal pair of the analyzer. A current transformer is used to step down the high current through the DUT to a level compatible for measurement at Lc terminal pair. Since feedback from the Lp terminal pair is used to ensure that the Lc terminal pair drives the correct current to maintain a virtual ground, Lc and Lp are tied together and connected to the current transformer output. The current and voltage sensed by the analyzer are thereby scaled versions of the current and voltage in the DUT, and with knowledge of these scale factors, we can calculate the DUT impedance from the measured impedance.

Note that by using a single differential probe instead of fully utilizing the separate Hp and Lp terminal pairs we are not using a full-blown 4TP system at the DUT. This introduces a slight error because the low end of the DUT is no longer held at virtual ground. The signal we apply to Hp still accurately represents the voltage across the device, because we use the differential probe, but there will be minor errors in current because the capacitive current in the Lp cable in the test fixture is no longer zero, without the low end of the DUT held at zero potential. Thus, we rely on the series impedance (inductance and resistance) of the Lc wiring in the test fixture being

small compared to the shunt impedance (capacitance) of the Lp wiring. For small test fixtures, this is not a problem.

In our implementation of this system, we used a Hafler P4000 audio amplifier, capable of driving up to 8.3 A rms at 33 V rms, with a full-power low-distortion bandwidth of 200 kHz, and reduced power capability at up to higher frequencies. For a current transformer, we used a Tektronix ac current probe, P6021, with 60 MHz bandwidth and 125:1 turns ratio. The output of the transformer is fed directly into the terminals of the impedance analyzer without the use of the resistive terminator normally used with these probes to convert the current into a voltage for display on an oscilloscope. The differential probe is an Agilent 1141A. Although this probe, with a 100X attenuator, has a voltage range of only 30 V peak, other types of differential probes with higher common mode voltage capability can be used to extend this technique to higher voltages. Substituting other amplifiers and current probes is also possible for different bandwidth, voltage, and current requirements.

To verify the accuracy of measurement with the power module in place, we compared the impedance of an air-core inductor as measured with and without the power module. First, the air-core inductor was directly connected to the analyzer through the same Kelvin-clip test fixture described in Section II-A. Since the air-core inductor should be linear (assuming its temperature does not rise), its impedance should be the same at any drive level–with or without the power module. Without the power module, an inductance of 0.698 mH and a resistive component of 3.22 Ω were measured at 155 kHz. With the power module set up as in Fig. 7, the changes in the reading included a phase difference of less than 0.15° and an overall impedance magnitude error of less than 0.4%. The phase error was most significant, leading to a variation of $\pm 2\Omega$ in the real component of impedance.

To demonstrate the importance of being able to use a realistic high drive level for measuring components with nonlinear loss mechanisms, an inductor with a ferrite core was measured at a range of different drive levels at 10 kHz. The results (Fig. 8) show a factor-of-two variation in the real component of impedance (ESR) with drive level, as a result of the nonlinearity of the core loss.

For primarily reactive components, it is possible to add a second reactive element to resonate with the DUT at the test frequency in order to reduce the drive capability needed from the amplifier. Transformers or matching networks can be useful as well to match drive requirements to the output capability of the amplifier.

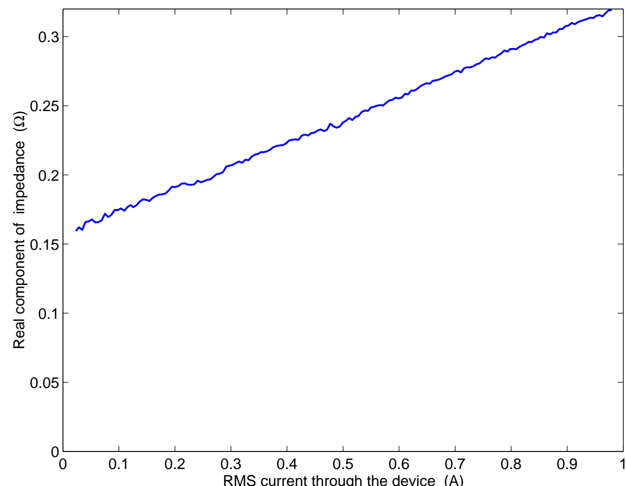

Fig. 8. Variation in real component of impedance of an inductor with a ferrite core with increasing drive levels at 10 kHz, as measured using the system diagrammed in Fig. 7

V. Conclusion

A broad range of issues have been discussed related to the use of impedance analyzers for characterizing passive components for power-electronics applications.

Although measuring the small component of real impedance in a low-loss component is fundamentally difficult to do, the high phase resolution and accuracy of at least one modern analyzer is found to be sufficient to result in less than half of its specified typical error in of $\pm 3\%$ at $Q = 100$. Calibration of phase can reduce this error, but a precise standard in a jig with low stray impedance is essential if phase calibration is used.

Standard test jigs have large stray impedances that are unacceptable in characterizing the low-impedance components needed in many applications including power electronics and power bypass capacitors for high-current digital systems. We have developed a new test fixture that provides under 100 pH stray inductance. It has proved useful in characterizing low-impedance inductors and capacitors. Its primary limitation is the solder connections to the DUT which must be made carefully and consistently to achieve accurate measurements. However, the largest error we have seen introduced by solder connections, about 30 pH, is still very small compared to errors in other types of fixtures.

For measurements of nonlinear components at the drive level used in the application, we have demonstrated a power module that can be inserted between a 4TP impedance analyzer and a 4TP test fixture. It is possible to achieve virtually any drive level by choosing amplifiers, current transformers, and voltage probes appropriately.

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