AUTOMATED CHARACTERIZATION OF CERAMIC MULTILAYER CAPACITORS

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Abstract - This paper describes an automated test configuration that is used for rapid characterization of the equivalent series resistance (ESR) of ceramic multilayer capacitors. The primary components in this system are a coaxial resonant line, an HP 8753D vector network analyzer, and a personal computer. Sample measurements are provided for several 1206 style capacitors, and the trends in ESR versus the internal capacitor architecture are presented.

I. INTRODUCTION

A commonly used equivalent circuit model for a ceramic multilayer capacitor is a simple, series R-L-C combination, and this model is generally valid at RF frequencies. Typically, the C represents the nominal capacitance of the component, and the R and L are parasitic elements that account for the finite loss and propagation delay, respectively, through the internal electrode architecture (Figure 1). The resistance, or effective series resistance (ESR), is on the order of 0.1 Ohms for most capacitor styles, while the effective series inductance (ESL) is usually in the neighborhood of 1 nH. From a performance viewpoint, knowledge of the ESL is necessary in order to predict the first series resonant frequency of the capacitor. The ESR becomes critical in the design of high power circuitry and high-Q filters.

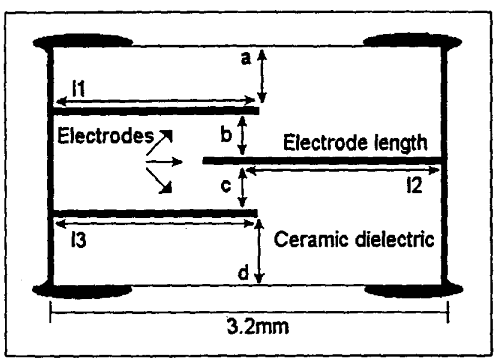


Figure 1. Cross-sectional diagram of a 1206 style ceramic multilayer capacitor.

The focus of this paper is on a rapid, accurate measurement technique for determining the ESR. The method revolves around the use of a coaxial resonant line (the Boonton Model 34A). Using the resonant line method, the ESR of a capacitor is extracted from measured differences of the cavity's Q with and without the capacitor inserted at one end of the instrument. While this is an accepted standard for the measurement of ESR (per the Electronics Industry Association), the utilization of the resonant line in its manual configuration is a very time consuming procedure even for an experienced operator. As described within, an automated test configuration has been developed by combining the Boonton line with a computer-controlled, HP 8753D vector network analyzer. While at least two orders of magnitude reduction in the measurement time is realized, it will be demonstrated that the accuracy of the approach has been preserved.

Other measurement techniques that can be applied for capacitor characterization include the reflection coefficient method and the RF-IV method. The former approach can be performed using a conventional vector network analyzer, such as the HP 8753D. Achieving accurate measurements of ESR from a reflection coefficient is limited by the fact that the reference impedance is typically 50 Ω, while the ESR can be less than 0.1 Ω. The RF-IV method can be implemented using an instrument such as the HP 4291A Impedance Analyzer. This approach is more suitable for measuring low impedance values, but the accuracy is considered to be not better than 10%.

In addition to describing the measurement setup, ESR data for several 1206 style surface mount capacitors is presented herein. In particular, the relationship between the internal electrode architecture and the resistance is shown.

II. OPERATION OF THE BOONTON LINE

The Boonton Model 34A is a high Q, resonant coaxial transmission line that is short-circuited at one end and open-circuited at the other. In practice, a stable RF signal is coupled into the cavity near the short-circuit and the standing waveform is sampled at the opposite end; in the conventional setup the sampling is done using a diode detector, while in the automated configuration a passive probe is used to sense the signal and pass it on to the vector network analyzer (constituting a two-port measurement, since the VNA is also used as the source). The manual and automated measurement configurations are shown in Figure 2 and Figure 3, respectively. At the short-circuited end of the Boonton line a movable plunger is used to form the contact between the coax center conductor and the end-wall of the cavity. When making a capacitor measurement, the plunger is backed-off to open a small gap into which the component is inserted and held in place.

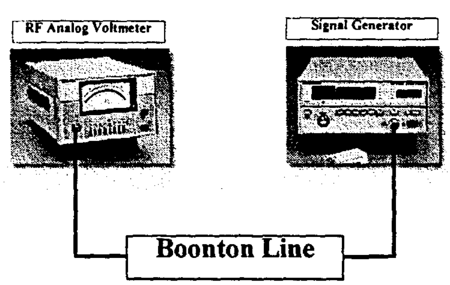


Figure 2. Configuration for manual operation of the Boonton resonant coaxial line. A diode detector connected at the output is used to supply a voltage to the RF analog voltmeter.

ESR measurements are performed at discrete frequencies which represent the resonances of the line+capacitor system. For this description, assume that the n^{th} resonant frequency of this system is $f_{o,n}$. Corresponding to each $f_{o,n}$, there will be a resonant frequency for the cavity when not disturbed by the additional capacitance (i.e., when the plunger is making a direct short-circuit connection) which is $f_{c,n}$. In order to calibrate the system, the Q of the cavity is determined at $f_{c,n}$ by measuring the half-voltage points, and this Q is translated to $f_{o,n}$ by assuming a $(f_c/f_o)^x$ frequency dependence. (The exponent 'x' is the slope of the Q, determined from measurements made at consecutive resonant frequencies of the line.) After measuring the system Q at $f_{o,n}$ with the capacitor in place, the capacitor quality factor can be extracted. By repeating this measurement process at a second pair of resonant frequencies, the nominal capacitance of the component can be determined. A similar set of measurements using a brass plug (or "dummy" capacitor) is used to determine the effective inductance of the capacitor. Once the Q, capacitance and inductance are known, the ESR is calculated by applying the series RLC equivalent circuit model for the capacitor.

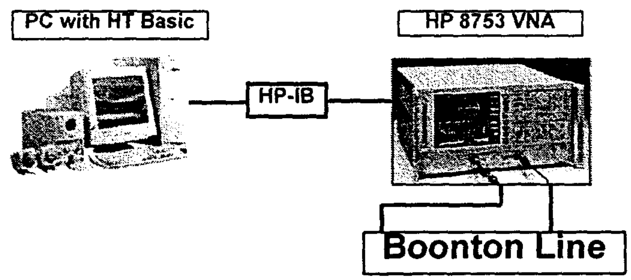


Figure 3. Configuration used for the automated Boonton line setup.

III. AUTOMATED CAPACITOR MEASUREMENT

The software program created to take automated measurements of the capacitor parasitic characteristics using the Boonton line is outlined in Figure 4. As described in Section II, the automated setup includes an HP 8753D Vector Network Analyzer to apply a signal to the input of the line and to detect the power level near the open-circuited end of the line. The software is written in HT Basic, and communications are done via the HP-IB bus.

The program runs in the following fashion:

(1) The user is instructed to short circuit the input end of the Boonton line and then to press <ENTER> on the keyboard when completed. The software then completes the short circuit calibration.

(2) The user is then instructed to open circuit the input end of the Boonton line and again press <ENTER> when completed. The open circuit calibration is then completed at this time.

(3) The user is then given the option to complete a discontinuity inductance calibration using a "dummy capacitor" of the same dimensions as the capacitor under test (CUT). If the user chooses to complete the calibration, the user is then instructed to place the "dummy cap" in series with the Boonton line and press <ENTER> when completed. The software then completes the discontinuity inductance calibration to take discontinuity effects between the CUT and the center conductor of the line into account. If the user chooses against calibration, an optional approximation based on capacitor volume is applied.

(4) The user is finally instructed to place the CUT in series with the line and to press <ENTER> when completed. The first to nth quarter wavelength resonant frequencies are then determined for the CUT, along with their corresponding 6 dB bandwidths.
(5) The ESR, ESL, effective capacitance, and Q-factors for each resonant frequency are then calculated and printed to the computer screen.
(6) Immediately following this is an option for the user to measure another capacitor. If the user chooses to complete another measurement, an option to complete another discontinuity inductance calibration is given to the user. If the response is positive, the program starts over at step 3 above where the user must place a "dummy cap" in series with the line. If the response was negative, the user is given the option to use either the previous calibration or the volume-based approximation and the program returns to step 4 above.

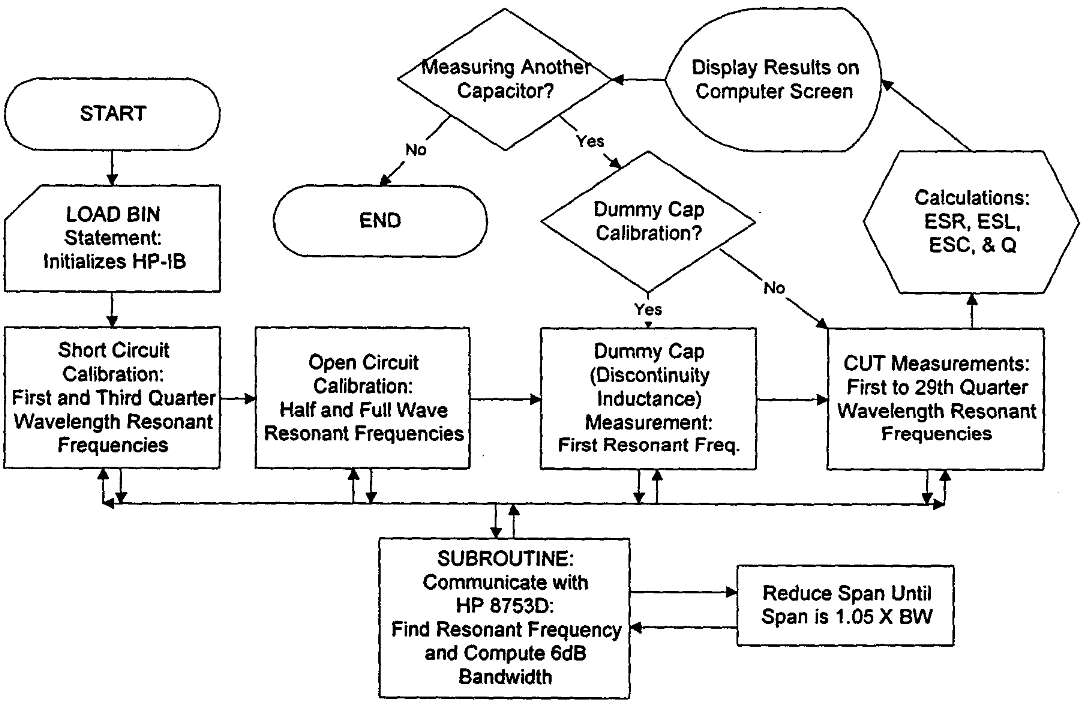
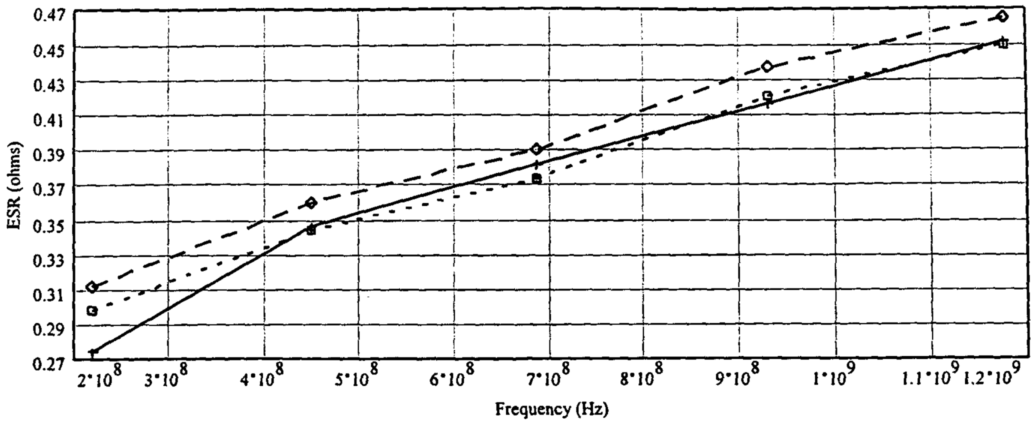


Figure 4. Flow graph illustrating the automated capacitor measurement process.

IV. EXPERIMENTAL RESULTS

The measured ESR for a 4.7 pF, 1206 style ceramic multilayer capacitor is shown in Figure 5. The data points shown correspond to the discrete resonant frequencies, $f_{o,n}$, described above. Included in the figure are the results which were obtained using the manual (conventional) measurement method and those from the automated setup. Also shown in the figure are the results obtained using the automated setup when an empirical correction for the effective inductance has been used (corrected*), instead of extracting this value from calibration measurements on the brass "dummy" capacitor (corrected). The empirical correction is that mentioned in Section III, which relates the inductance to the volume of the capacitor.



Corrected manual results
Corrected* automated results
Corrected automated results

Figure 5. Measured ESR for a 1206 style, 4.7 pF ceramic multi-layer capacitor. With reference to Figure 1, the capacitor dimensions are (in mm): l1=l3=1.73, l2=1.78, a=0.254, b=c=0.048, d=0.18.

By characterizing several capacitor values from the same 1206 family, a strong correlation between the ESR and the internal electrode architecture was ascertained. Shown in Figure 6 are the ESR values versus capacitor size; in this figure each curve represents the data for the nth resonant frequency observed during the measurements. The significant change that occurs between the 9.1 and 12 pF values results from the corresponding decrease in the non-overlapping length of the internal electrodes, which is illustrated in Figure 7.

One very useful application of automated ESR measurements is as an aid in microwave equivalent circuit model development. A typical "family" of capacitors may contain 50 or more part numbers, each corresponding to a different capacitance value. In order to realize each value of capacitance, the manufacturer will make changes to the internal electrode overlap and spacing; generally, the details of the inner architecture are not known to the model developer but they do have a direct impact on the equivalent circuit parameters used for a model. The correlation between electrode overlap and ESR was shown above in Figures 6 and 7. Although the data is not presented here, the ESL versus capacitance trends are essentially the same as that for ESR. The way in which the ESR information can be used is to identify groups of capacitors within the family that have similar architectures. Then, equivalent circuit models can be extracted for selected capacitors within each group, and models for the remaining capacitors in the group can be derived through interpolation. In this way, a library of models for an entire family can be generated by a thorough model extraction for a few, well-chosen capacitor sizes.

A final demonstration of the use of ESR screening can be described with the aid of Figure 8. In this figure, the same ESR data shown previously is plotted for the different capacitor values versus frequency. (Here, a curve fit of the form $ESR = a + b\sqrt{f}$ has been generated from the measured data points to extrapolate out to 3 GHz.) It can be observed that the ESR for the 12 pF capacitor shows a rather anomalous trend, particularly at the low end of the band. From 2-port S-parameter measurements, it was found that this size of capacitor also exhibited considerably different parallel resonance phenomena in comparison to other sizes that fall within the lower grouping in Figure 8. This more detailed level of ESR information, therefore, can indicate which capacitor sizes within a particular grouping should be selected for equivalent circuit model extraction.

V. SUMMARY

This paper has presented an automated configuration that is used for the rapid characterization of the equivalent series resistance of ceramic multilayer capacitors. The data which is shown indicates the manner in which the ESR can be correlated with the internal electrode configuration of the capacitor, and discusses how ESR screening can be applied in capacitor model development.

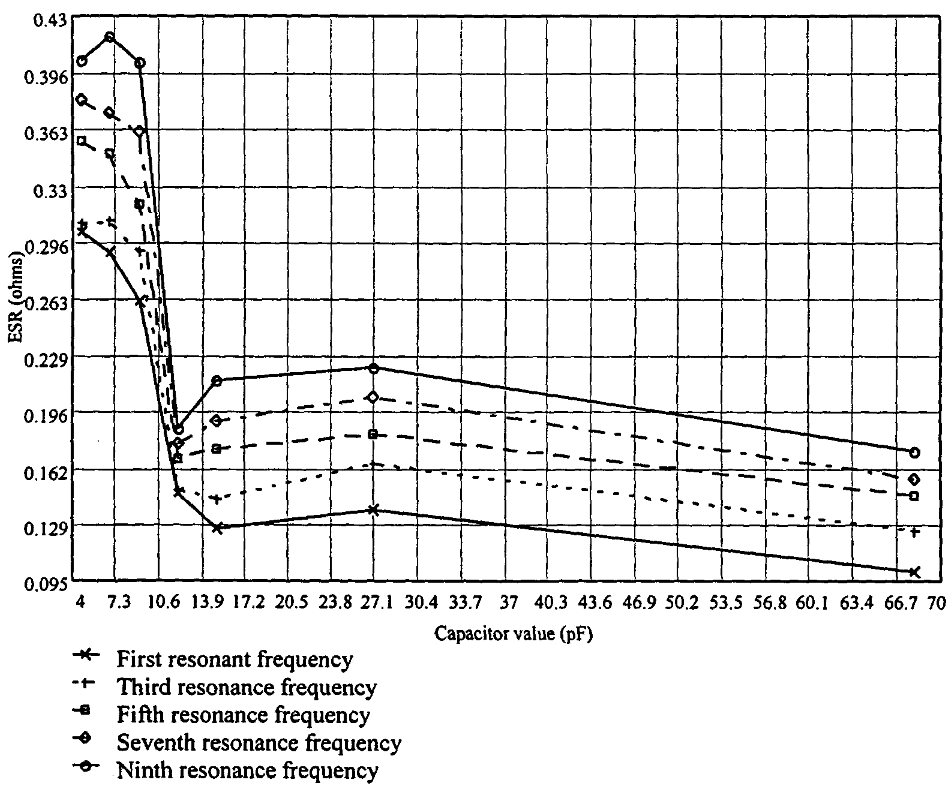


Figure 6. ESR versus capacitor value, with each curve corresponding to a different resonant frequency of the line+capacitor system.

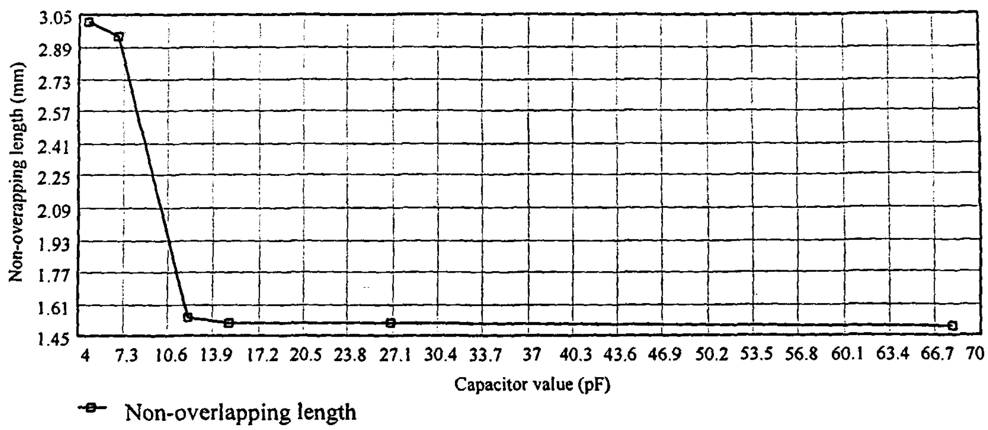


Figure 7. Non-overlapping electrode length versus capacitor value. Referring to Figure 1, the non-overlapping length is given by (l1+l2)-3.2 mm.

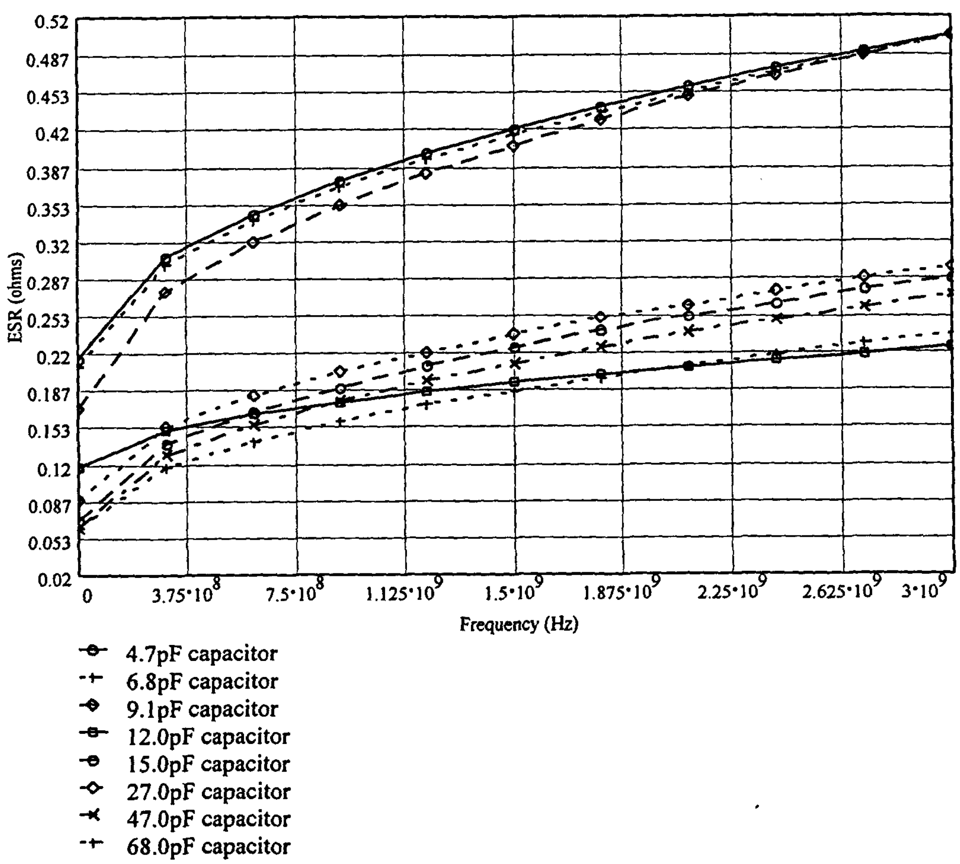


Figure 8. ESR versus frequency for different capacitor sizes, extrapolated out to 3 GHz.