Measuring Capacitor Parameters Using Vector Network Analyzers

Deniss Stepins, Gundars Asmanis, and Aivis Asmanis

***Abstract*—Vector network analyzer (VNA) is versatile measuring equipment which is primarily used for two-port device S parameters measurements. This paper addresses measurement of capacitor parameters using VNA in broad frequency range. The main attention is focused on the measurement accuracy of capacitors parameters using VNA and proper de-embedding of an experimental setup parasitics to get accurate results. Comparative measurement error analysis for different measurement techniques is presented. Suitability of each measurement technique for measurements of capacitor parameters using VNA is discussed and effect of the experimental setup parasitics on the measurement results is addressed. Moreover useful procedures for proper capacitor impedance measurement using VNA are developed.**

***Index Terms*—Capacitors, vector network analyzers, measurements, measurement accuracy.**

Original Research Paper
DOI: 10.7251/ELS1418029S

I. INTRODUCTION

CAPACITORS are used in many electronic devices, especially in radio-frequency equipment, such as transmitters, receivers, conducted electromagnetic interference filters, etc.

Capacitors capacitance is typically ranging from several pF to several thousands of µF. The main parameters of a capacitor are its capacitance C and impedance magnitude $|Z_c|$ (as a function of frequency). Real capacitors, of course, have parasitic parameters such as series resistance R_s (mainly lead wires resistance), parallel resistance R_p (due to losses in capacitor dielectric), equivalent series inductance (ESL) and self-resonance frequency f_{res}. Real capacitors can be substituted by their equivalent circuit model shown in Fig.1 (a). However in practice when designing electronic circuits with capacitors, more simple capacitor equivalent circuit model is usually used as shown in Fig.1(b). In this model ESR accounts for both R_p and R_s [1]. Usually knowing ESR is much more important than R_p and R_s separately [2]. That is why capacitor manufacturers only give ESR values in their catalogs.

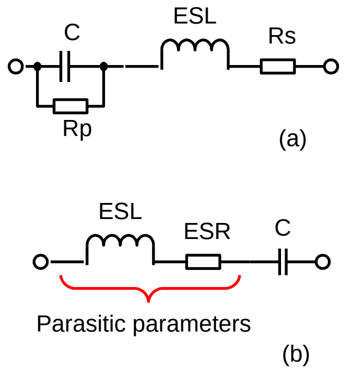


Fig. 1. Real capacitor equivalent circuit model (a) and its simplified version (b).

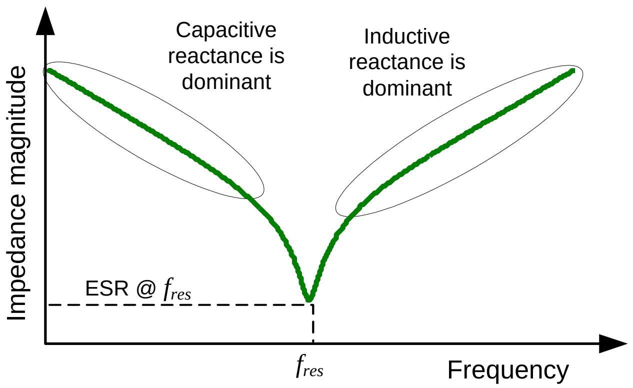


Fig. 2. Real capacitor impedance magnitude versus frequency.

At a self-resonance frequency f_{res} a capacitor has its minimum $|Z_c|$, which is equal to ESR (at f_{res}). For $f<f_{res}$, $|Z_c|$ is decreasing function of f, but for $f>f_{res}$, $|Z_c|$ increases as f increases, Fig.2.

Accurate measurement of capacitor parameters (including parasitic ones) is of major importance when designing electronic equipment. For capacitor and inductor parameters measurements in broad frequency range usually impedance analyzers are used [3] – [10]. However the impedance analyzers are expensive and the measurement frequency range is usually limited up to several hundreds of MHz [3], [6], [10]. In contrast to the impedance analyzers, vector network analyzers (VNA) are less expensive, more versatile and can be used for capacitor parameters measurements in much broader frequency range up to tens of GHz.

Manuscript received 15 April 2014. Received in revised form 7 June 2014. Accepted for publication 11 June 2014.

This work was supported by the Project "Competence Centre of Latvian Electric and Optical Equipment Production" co financed by the European Union (agreement no. L-KC-11-0006). D. Stepins, G. Asmanis and A. Asmanis are with the Latvian Electronic Equipment Testing Center, Riga, Latvia (phone: +37128327653; e-mail: stepin2@inbox.lv).

For two-terminal passive electronic components measurements using VNA, three measurement techniques can be used: reflection (based on reflection coefficient S_{11} measurement), shunt-through (based on transmission coefficient S_{21} measurements) and series-through techniques (based on S_{21} measurements) as shown in Fig.3 [3], [6]. Shunt-through technique is usually used for low-impedance passive electronic components, while series-through technique for high-impedance components [3].

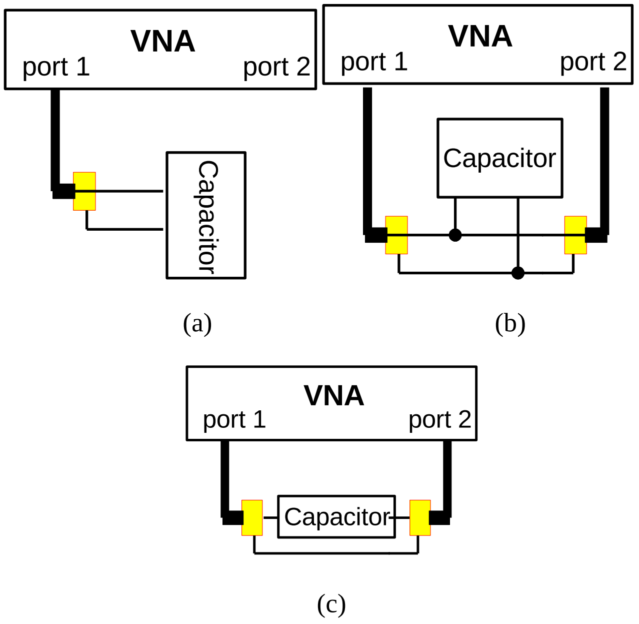


Fig. 3. Two terminal passive components measueremnt techniques using VNA: (a) reflection technique; (b) shunt-through technique; (c) series through technique.

Although different measurement techniques of two-terminal passive electronic components are investigated in [3], [6] - [10], no one of the papers consider measurement accuracy of VNA techniques. Moreover suitability of each VNA technique for capacitors parameters measurements is not addressed and proper de-embedding of experimental setup parasitic parameters is not considered in the papers. For example, in [10] the main attention is focused on auto-balancing bridge techniques for ESR measurements and VNA techniques are not investigated thoroughly, in [6] inductors and capacitors impedance measurement repeatability and temperature dependence for the radio-frequency impedance analyzers and VNA is comparatively investigated, but in [3] experimental measurements of low-impedance inductors and ferrite complex magnetic permeability using VNA are presented without addressing any measurement accuracy issues.

The main original contribution of this paper is focused on the measurement accuracy of capacitors parameters using VNA and proper de-embedding of an experimental setup parasitics to get accurate measurement results. Comparative measurement error analysis for all the three techniques will be presented. Suitability of each measurement technique for capacitors parameters measurements using VNA will be discussed and effect of the experimental setup parasitics on capacitor measurement results will be addressed. Moreover useful procedures for proper capacitor impedance measurement using VNA will be developed.

II. MEASUREMENT OF CAPACITOR PARAMETERS

A. *Experimental setups*

In order to get capacitor impedance and other capacitor parameters, *S* parameters should be measured first. When using the reflection technique S_{11} should only be measured; for the shunt-through technique S_{21} should only be measured; when using the series-through technique S_{21} should only be measured [3],[6]. For *S* parameters measurements VNA Rohde and Schwarz ZVRE is used. Necessary capacitor parameters are then extracted from the *S* parameters measured. The measurements are done in the frequency range 100 kHz – 500 MHz, with VNA intermediate frequency filter bandwidth of 300 Hz and 1600 points per sweep. After the warm-up time of one hour, full two-port TOSM (through-open-short-matched) calibration has been performed to significantly reduce systematic errors due to imperfect VNA cables and connectors.

Experimental setups used for the capacitor parameters measurements are shown in Fig.4 – Fig.6. To perform one-port reflection measurements, a capacitor is attached to one VNA cable using type N RF connector (Fig.4(a)). To perform two-port shunt-through capacitor measurement, two VNA cables and capacitor are connected in parallel as shown in Fig.5(a). To perform two-port series-through capacitor measurement, two VNA cables and capacitor are connected in series as

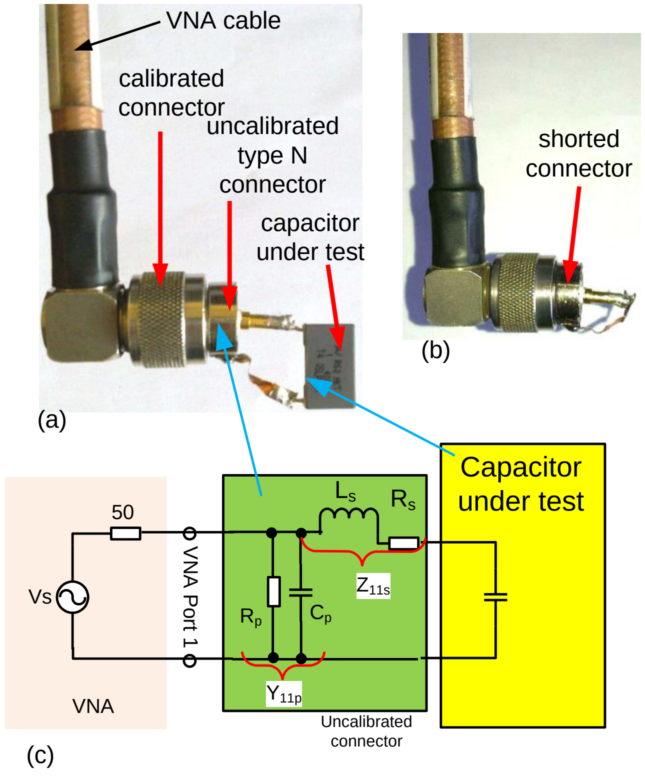


Fig. 4. (a) Experimental setup to perform the reflection technique; (b) shorted N type connector; (c) equivalent circuit model.

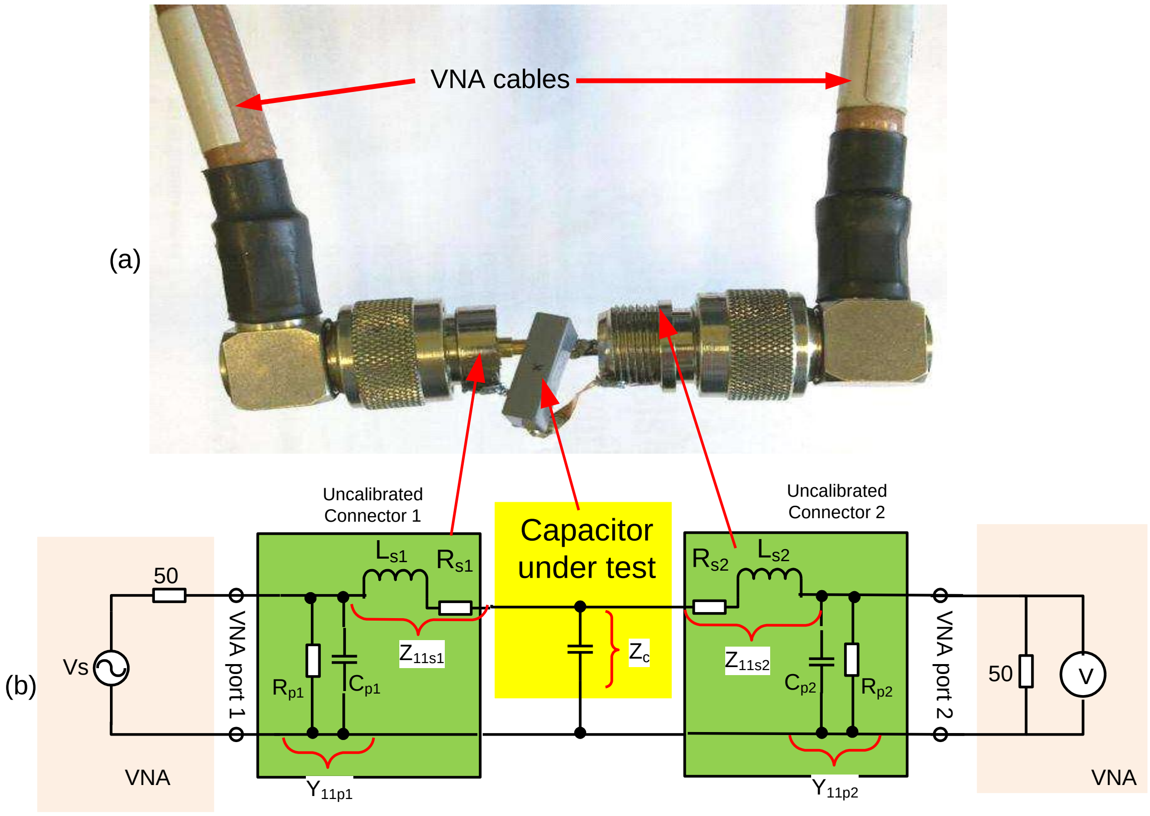


Fig. 5. Experimental setup to perform the shunt-through technique (a) and its equivalent circuit model (b).

shown in Fig.6(a).

Since it is impossible to make TOSM calibration for the N type RF connectors to which the capacitors are attached in the experiments, the parasitic parameters (parasitic equivalent series impedance Z_{11s} and parasitic equivalent conductance Y_{11p}) of the connectors should be taken into account and removed from the capacitors measurement results mathematically using de-embedding.

B. *De-embedding of the connectors parasitics*

To de-embed the connector's parasitics, simple equivalent circuit models of the experimental setups for all the three measurement techniques are developed in the paper as shown in Fig.4 – Fig.6. The equivalent circuit models can give us a possibility to derive expressions for capacitors complex impedance Z_c calculations.

- For the reflection technique it can be derived

$$Z_c = \frac{1}{1/Z_{11} - Y_{11p}} - Z_{11s} \quad , \tag{1}$$

where Z_{11} is complex impedance which can be calculated from the measured reflection coefficient S_{11} as follows [3]

$$Z_{11} = 50\frac{1+S_{11}}{1-S_{11}} = 50\frac{1-|S_{11}|^2 + j2|S_{11}|\sin\varphi}{1-2|S_{11}|\cos\varphi + |S_{11}|^2}. \tag{2}$$

If parasitics of the connectors are not high, then approximately Z_c can be calculated using (2).

- For the shunt-through technique it can be derived

$$Z_c = \frac{50Z_{11s1}Z_a + Z_{11s1}Z_{11s2} + 2500 + 50Z_{11s2}(50Y_{11p2}+1)}{\frac{100}{S_{21}} - (100 + Z_b + 50Y_{11p1}Z_{11s2} + Z_{11s2}(1+50Y_{11p2}))}, \tag{3}$$

where $Z_a = 1 + Z_{11s2}Y_{11p2}(1+50Y_{11p1}) + Y_{11p1}(50+Z_{11s2})$

$$Z_b = Z_{11s2}(1+50Y_{11p2}) + 2500(Y_{11p1}+Y_{11p2})$$

Z_{11s1} and Z_{11s2} are parasitic equivalent series impedances of the 1st and the 2nd uncalibrated connectors respectively; Y_{11p1} and Y_{11p2} are parasitic equivalent conductances of the 1st and the 2nd uncalibrated connectors respectively.

If parasitics of the connectors are not high, then approximately Z_c can be calculated as follows [3]

$$Z_c \approx 25\frac{S_{21}}{1-S_{21}} = 25\frac{|S_{21}|\cos\varphi - |S_{21}|^2 + j|S_{21}|\sin\varphi}{1-2|S_{21}|\cos\varphi + |S_{21}|^2}. \tag{4}$$

- For the series-through technique it can be derived

$$Z_c = \frac{\frac{2Z_1}{S_{21}} - 50 - Z_1 - Z_s - 50Z_1Y_{11p1}Z_s}{1+50Y_{11p1}} - Z_{11s} \quad , \tag{5}$$

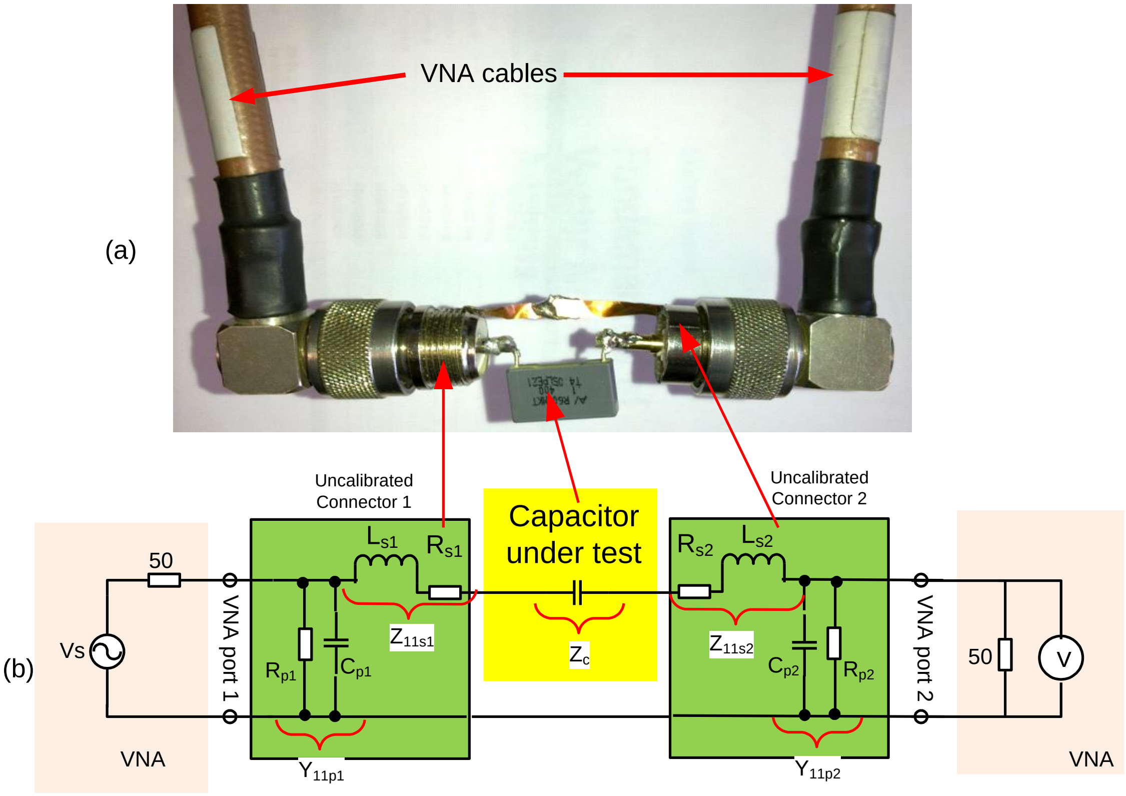


Fig. 6. Experimental setup to perform the series-through technique (a) and its equivalent circuit model (b).

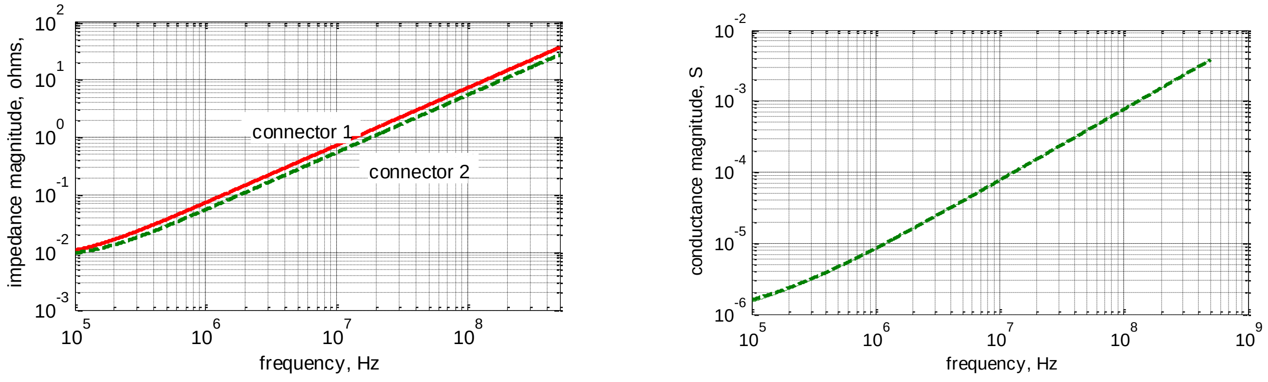
where $Z_s=Z_{11s1}+Z_{11s2}$; $Z_1=1/(1/50+Y_{11p2})$.

If parasitics of the connectors are not high, then approximately Z_c can be calculated as follows

$$Z_c \approx 100\frac{1\text{-}S_{21}}{S_{21}} = 100\left[\frac{\cos\varphi}{|S_{21}|} - 1 - j\frac{\sin\varphi}{|S_{21}|}\right] \qquad (6)$$

C. Determination of the connectors parasitics

Typical RF N type connector parasitic capacitance is about 1 pF and inductance of shorted connector is about 10nH. This means that parasitic resonant frequency of the connectors is well above 1 GHz. Since all the measurements are done in the frequency range up to 500 MHz, then parasitic series impedances Z_{11s1} and Z_{11s2} can be determined by measuring impedance of shorted connectors, but parasitic parallel conductances Y_{11p1} and Y_{11p2} can be determined by measuring conductance of open connectors. The measurement results for the two connectors used in the experiments are shown in Fig.7. As it can be seen the shorted connector impedance magnitude increases almost linearly as frequency increases, because inductive reactance (due to L_s) is dominant, and conductance magnitude of the open connectors also increases almost linearly because capacitive conductance (due to C_p) dominates.



(a) (b)

Fig. 7. Measured impedance magnitude of short connectors (a) and conductance magnitude of open connectors (b).

D. Procedures for capacitor impedance measurement

In this section the procedures developed for capacitor impedance measurements using all the three measurement techniques are presented.

Procedure for the capacitor impedance measurement using the reflection technique

- make full two-port TOSM calibration;
- connect the type N RF connector with soldered capacitor (Fig.4(a)) to VNA cable;
- measure complex S_{11};
- desolder the capacitor from the connector and connect shorted connector without capacitor (Fig.4(b)) to the VNA cable and measure complex Z_{11s};
- connect open connector without capacitor to the VNA cable and measure complex Y_{11s};
- calculate complex impedance Z_{11} using (2);
- de-embed the connector parasitics using (1) to calculate the capacitor complex impedance Z_c;
- end.

Procedure for the capacitor impedance measurement using the shunt-through technique

- make full two-port TOSM calibration;
- connect both N type RF connectors in parallel and solder a capacitor under test to them (Fig.5(a));
- measure complex S_{21} using VNA;
- measure both connectors parasitcs Z_{11s1}, Z_{11s2}, Y_{11p1} and Y_{11p2};
- calculate the capacitor complex impedance Z_c using (3);
- end.

Procedure for the capacitor impedance measurement using the series-through technique

- make full two-port TOSM calibration;
- solder a capacitor under test to both connectors in series as shown in Fig.6(a);
- connect them to VNA cables;
- measure complex S_{21} (with the capacitor under test);
- measure both connectors parasitics Z_{11s1}, Z_{11s2}, Y_{11p1} and Y_{11p2};
- calculate the capacitor complex impedance Z_c using (5);
- end.

E. Extraction of capacitor parameters from complex impedance Z_c

- capacitance C can be calculated at the lowest frequency f_1 (at which parasitic inductive reactance is negligible):

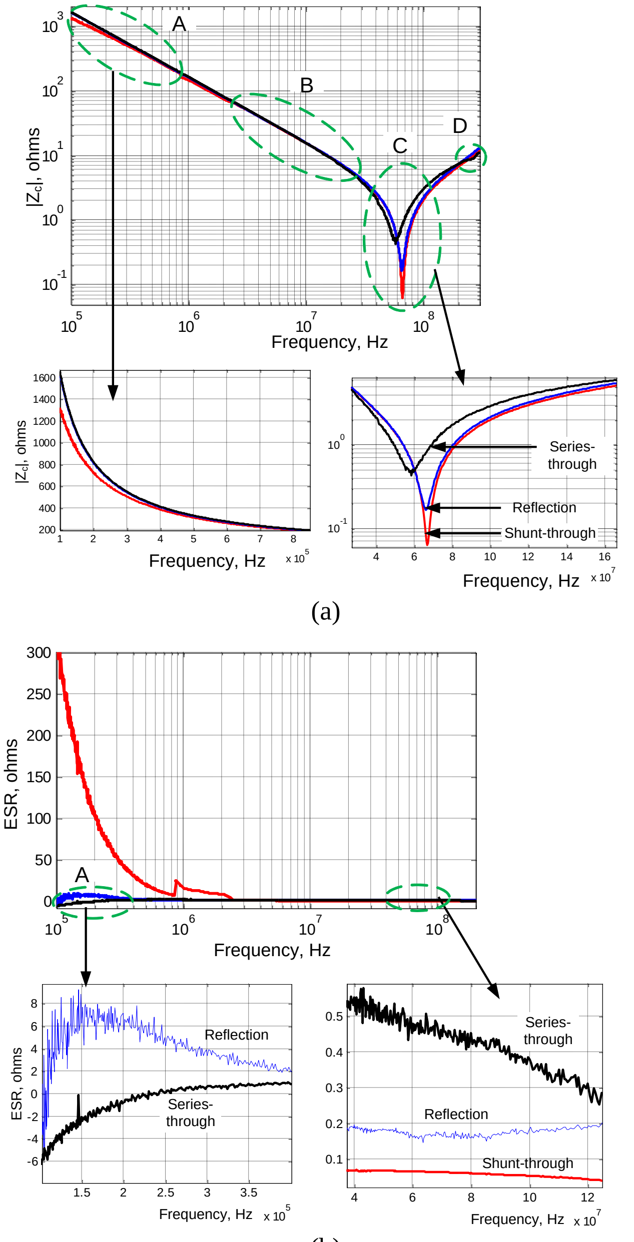
$$C = \frac{1}{2\pi f_1 \,|imag\{Z_c\}|} \tag{7}$$

- capacitor ESR(f)=real{$Z_c(f)$};
- capacitor resonant frequency f_{res} is frequency at which capacitor complex impedance magnitude $|Z_c|$ is minimum;
- capacitor equivalent series inductance can be calculated as follows:

$$ESL = \frac{1}{4\pi^2 f_{res}^2 C} \, . \tag{8}$$

F. Comparison of the measurement results

Using the procedures developed capacitors with different

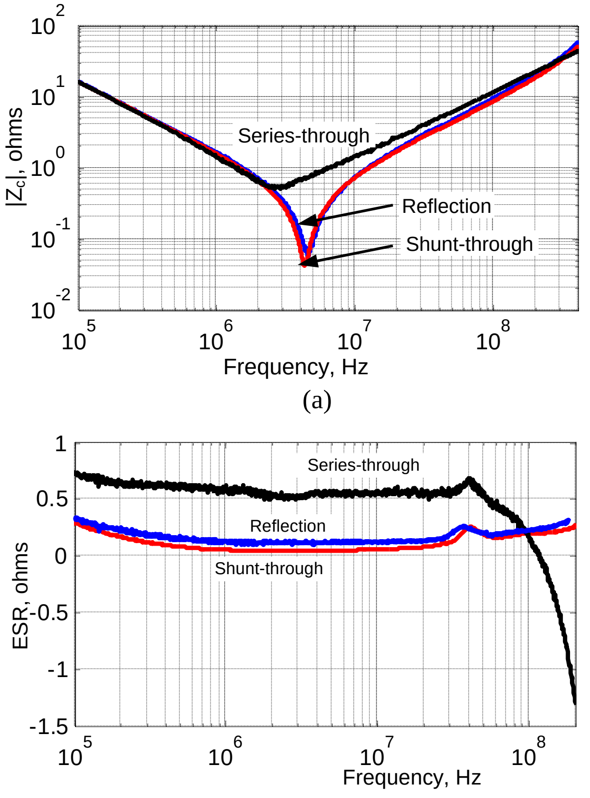


(a)

(b)

Fig. 8. Measured 1nF capacitor impedance magnitude (a) and ESR (b) versus frequency.

nominal capacitance values (1nF, 10nF, 100nF and 1000nF) have been measured using the reflection, shunt-through and series-through techniques. The capacitors with nominal capacitances of 1nF, 100nF and 1000nF are metalized polypropylene film capacitors with capacitance tolerance of ±5%, but the capacitor with nominal capacitance of 10nF is polyester film capacitor with tolerance of ±20%.



(a)

(b)

Fig. 9. Measured 100nF capacitor impedance magnitude (a) and ESR (b) versus frequency.

Measured $|Z_c|$ and ESR versus frequency for several capacitors are comparatively depicted in Fig.8 and Fig.9. But in Table 1 measured capacitor C and ESR (at f=100kHz) using VNA and high-precision LCR meter Instek LCR 819 are tabulated. Analysis of the measurement results and measurement errors will be presented in section IV.

TABLE 1
COMPARISON OF MEASURED CAPACITANCE AND ESR (AT 100KHZ) USING HIGH-PRECISION LCR METER AND VNA FOR DIFFERENT CAPACITORS

Nominal capacitance, nF			**1**	**10**	**100**	**1000**
LCR meter		**C, nF**	1	8.48	100.2	998.7
		ESR, Ω	2.5	3.6	0.29	0.04
VNA	**refle-ction**	**C, nF**	0.96	8.22	98.5	984.8
		ESR, Ω	*-2.61*	2.86	0.19	0.041
	shunt-through	**C, nF**	1.25	8.74	99.3	991
		ESR, Ω	288	7.8	0.28	0.04
	series-through	**C, nF**	0.98	8.29	99	1200
		ESR, Ω	*-5.9*	2.86	0.59	0.39

G. *Effect of connectors parasitics on capacitor parameters measurements*

It is interesting to observe how uncalibrated connectors parasitics affect measurement results. Measured $|Z_c|$ and ESR versus frequency before (using (2), (4) and (6)) and after (using (1), (3) and (5)) de-embedding is depicted in Fig.10. As it can be seen the reflection and the series-through techniques are very sensitive to the connectors parasitics in MHz range for both ESR and $|Z_c|$ (Fig.10(a,b,e,f)). If the connector parasitics are not removed from the measurement results using (1) and (5), then measured f_{res} is noticeably lower, but $|Z_c|$ is noticeably higher (for f above f_{res}) than it is. This is mainly due to parasitic inductance of the connectors used.

$|Z_c|$ and f_{res} measured using the shunt-through technique is much less affected due to the connector parasitics. For f up to several hundreds of MHz effect of the connector's parasitics is negligible (Fig.10(c)). However ESR measured using the shunt-through technique is affected much higher due to connectors parasitics for f higher than several tens of MHz (Fig.10(d)).

III. CALCULATION OF THE CAPACITOR PARAMETERS MEASUREMENT ERRORS

Since capacitor Z_c, ESR and other parameters are indirect measurement results then for measurement error calculation partial differentiation method [12] can be used. When partial errors are known, indirect measurement absolute error (ΔY) can be calculated

$$\Delta Y = \sqrt{\sum_{i=1}^{K}\left(\frac{\partial Y}{\partial x_i}\Delta x_i\right)^2}\,, \tag{9}$$

and relative error

$$\varepsilon = 100\frac{\Delta Y}{Y},\ \ \%\,, \tag{10}$$

where $\partial Y / \partial x_i$ is partial derivative with respect to argument x_i; Δx_i is x_i argument absolute error.

- For the reflection technique capacitor impedance is the function of 6 arguments (according to (1) and (2)): $x_1=|S_{11}|$, $x_2=\varphi$; $x_3=|Z_{11s}|$, $x_4=\varphi_s$, $x_5=|Y_{11p}|$, $x_4=\varphi_p$,

where $S_{11}= |S_{11}|e^{j\varphi}$, $Z_{11s}=|Z_{11s}|e^{j\varphi_s}$, $Y_{11p}==|Y_{11p}|e^{j\varphi_p}$.

- For the shunt-through technique capacitor impedance is the function of 10 arguments (according to (3)): $x_1=|S_{21}|$, $x_2=\varphi$; $x_3=|Z_{11s1}|$, $x_4=\varphi_{s1}$, $x_5=|Y_{11p1}|$, $x_6=\varphi_{p1}$, $x_7=|Z_{11s2}|$, $x_8=\varphi_{s2}$, $x_9=|Y_{11p2}|$, $x_{10}=\varphi_{p2}$.
- For the series-through technique capacitor impedance is the function of 10 arguments (according to (5)): $x_1=|S_{21}|$, $x_2=\varphi$; $x_3=|Z_{11s1}|$, $x_4=\varphi_{s1}$, $x_5=|Y_{11p1}|$, $x_6=\varphi_{p1}$, $x_7=|Z_{11s2}|$, $x_8=\varphi_{s2}$, $x_9=|Y_{11p2}|$, $x_{10}=\varphi_{p2}$.

Absolute measurement errors of the main capacitor parameters can be calculated using the following expressions:

$$\Delta ESR = \Delta\,\mathrm{Re}\{Z_c\} = \sqrt{\sum_{i=1}^{K}\left(\frac{\partial\,\mathrm{Re}\{Z_c\}}{\partial x_i}\Delta x_i\right)^2} \tag{11}$$

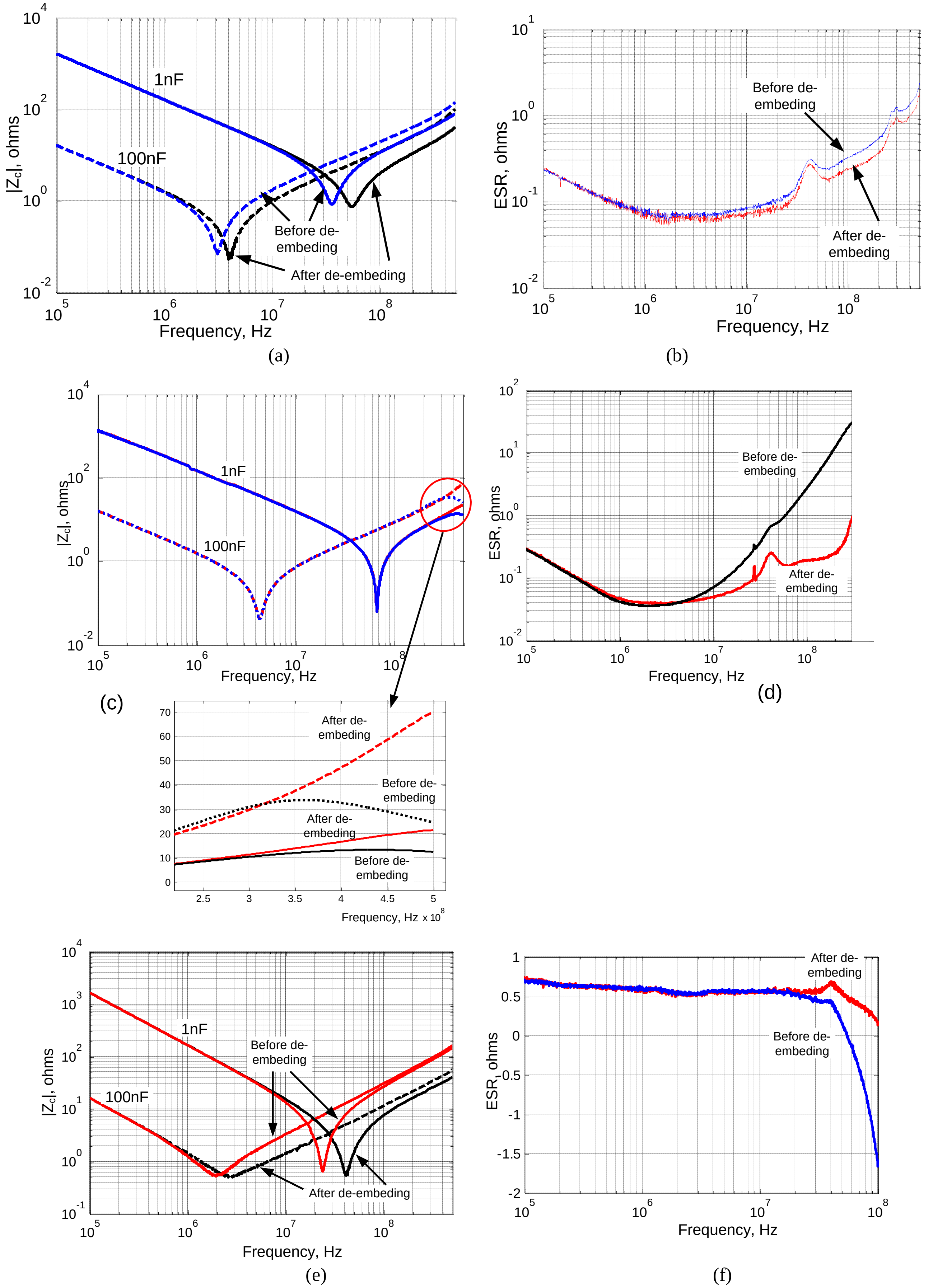


Fig. 10. Measured $|Z_c|$ and ESR versus frequency before and after de-embedding: (a), (b) for the reflection technique; (c), (d) for the shunt-through technique; (e), (f) for the series-through technique. Note: ESR versus frequency before and after de-embedding (b,d,f) is shown only for 100nF capacitor.

$$\Delta \mathrm{Im}\{Z_c\} = \sqrt{\sum_{i=1}^{K}\left(\frac{\partial \mathrm{Im}\{Z_c\}}{\partial x_i}\Delta x_i\right)^2} \tag{12}$$

$$\Delta |Z_c| = \sqrt{\left(\frac{\mathrm{Re}\{Z_c\}}{|Z_c|}\Delta \mathrm{Re}\{Z_c\}\right)^2 + \left(\frac{\mathrm{Im}\{Z_c\}}{|Z_c|}\Delta \mathrm{Im}\{Z_c\}\right)^2} \tag{13}$$

$$\Delta C = \frac{\Delta \mathrm{Im}\{Z_c\}}{2\pi f_1 (\mathrm{Im}\{Z_c\})^2} \quad . \tag{14}$$

If capacitor impedance is calculated using approximate expressions (2), (4) and (6), then more simple expressions for measurement error can be used. For the reflection technique the approximate expressions are

$$\Delta ESR = \Delta \mathrm{Re}\{Z_c\} \approx \sqrt{\left(\frac{\partial \mathrm{Re}\{Z_c\}}{\partial |S_{11}|}\Delta |S_{11}|\right)^2 + \left(\frac{\partial \mathrm{Re}\{Z_c\}}{\partial |\varphi|}\Delta \varphi\right)^2} \tag{15}$$

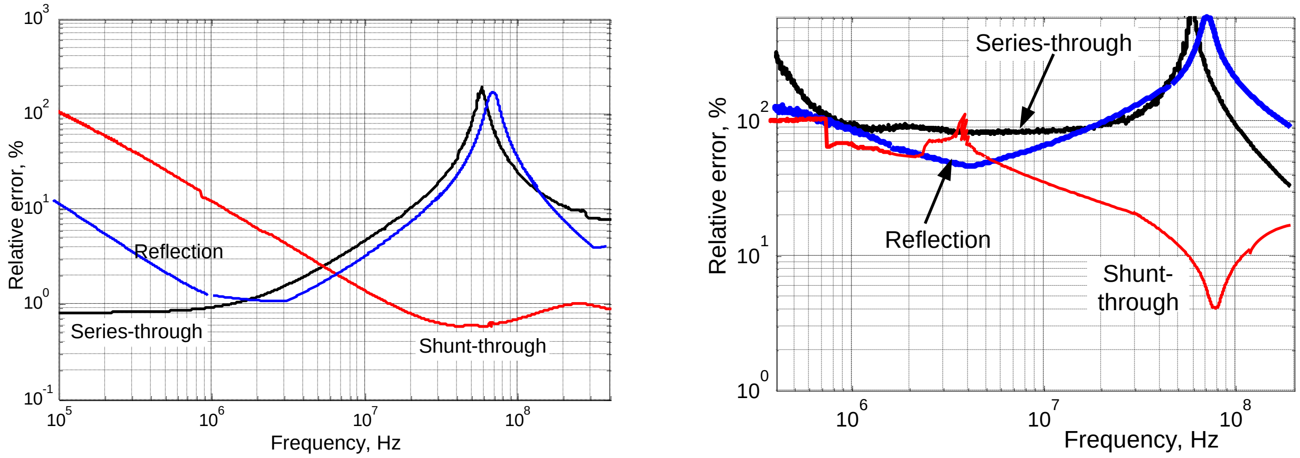
$$\Delta \mathrm{Im}\{Z_c\} \approx \sqrt{\left(\frac{\partial \mathrm{Im}\{Z_c\}}{\partial |S_{11}|}\Delta |S_{11}|\right)^2 + \left(\frac{\partial \mathrm{Im}\{Z_c\}}{\partial |\varphi|}\Delta \varphi\right)^2} \tag{16}$$

For shunt-through and series-through technique the approximate expressions are

$$\Delta ESR = \Delta \mathrm{Re}\{Z_c\} \approx \sqrt{\left(\frac{\partial \mathrm{Re}\{Z_c\}}{\partial |S_{21}|}\Delta |S_{21}|\right)^2 + \left(\frac{\partial \mathrm{Re}\{Z_c\}}{\partial |\varphi|}\Delta \varphi\right)^2} \tag{17}$$

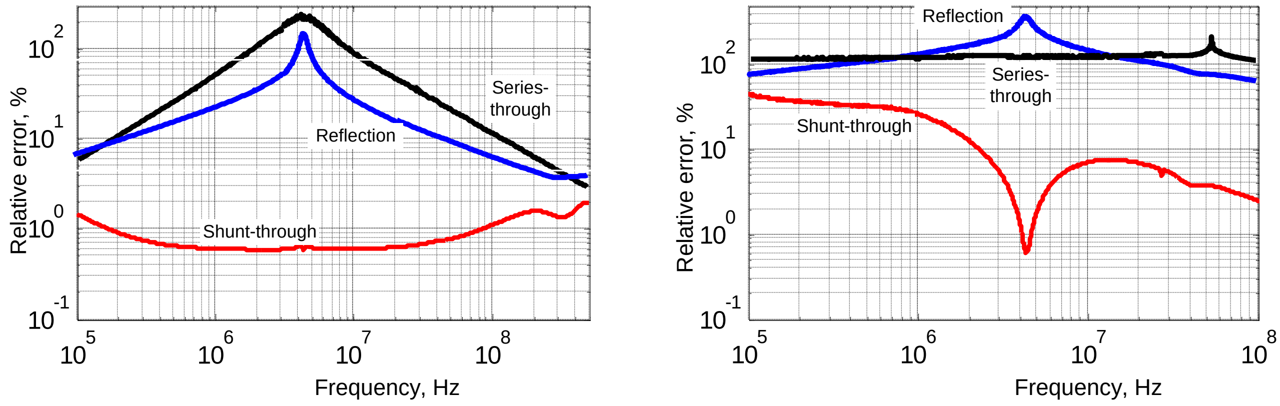
$$\Delta \mathrm{Im}\{Z_c\} \approx \sqrt{\left(\frac{\partial \mathrm{Im}\{Z_c\}}{\partial |S_{21}|}\Delta |S_{21}|\right)^2 + \left(\frac{\partial \mathrm{Im}\{Z_c\}}{\partial |\varphi|}\Delta \varphi\right)^2} \quad . \tag{18}$$

It should be noted that in VNA technical data-sheet manufacturer shows transmission and reflection coefficients magnitude errors (in *dB*) and phase errors (in degrees) [11]. But in the expressions described above, Δ|S$_{11}$| and Δ|S$_{21}$| are not in *dB*, and φ is in radians. For example, if it is needed to calculate absolute error Δ|S$_{11}$|, then the following expression



(a) (b)

Fig. 11. Calculated relative measurement errors of 1nF capacitor |Zc| (a) and ESR (b) versus frequency for all the three measurement techniques.



(a) (b)

Fig. 12. Calculated relative measurement errors of 100nF capacitor |Zc| (a) and ESR (b) versus frequency for all the three measurement techniques.

should be used

$$\Delta|S_{11}| = |S_{11}|\left(10^{(\Delta|S_{11}|_{dB})/20} - 1\right), \qquad (19)$$

where $\Delta|S_{11}|_{dB}$ is reflection coefficient measurement uncertainty in *dB* from VNA data-sheet. In its turn, phase absolute error (in radians) from VNA data-sheet can be calculated as follows

$$\Delta\varphi = \pi\frac{\varphi_{\mathbf{deg}}}{180}, \qquad (20)$$

From VNA ZVRE data-sheet [11] it can be deduced that in frequency range 20kHz – 4GHz: $\Delta|S_{11}|_{dB}$<0.4dB and $\Delta\varphi_{deg}<3^o$ (when $|S_{11}|$ is in range -15dB – +3dB); $\Delta|S_{11}|_{dB}$<1dB and $\Delta\varphi_{deg}<6^o$ (when $|S_{11}|$ is in range -25dB – -15dB). Accuracy of transmission measurements: in the frequency range 20kHz – 300kHz: $\Delta|S_{21}|_{dB}$<0.2dB and $\Delta\varphi_{deg}<2^o$ (when $|S_{21}|$ is in range -20dB – +3dB); $\Delta|S_{21}|_{dB}$<0.5dB and $\Delta\varphi_{deg}<4^o$ (when $|S_{21}|$ is in range -20dB – -30dB); in the frequency range 300 kHz to 1 MHz: $\Delta|S_{21}|_{dB}$<0.1 dB or $\Delta\varphi_{deg}<1°$; in the frequency range 1MHz to 4 GHz: $\Delta|S_{21}|_{dB}$<0.05 dB or $\Delta\varphi_{deg}<0.4°$. This data will be used for capacitors measurement error calculation. Calculated relative measurement errors of ESR and $|Z_c|$ versus frequency for all the three measurement techniques are shown in Fig.11 and Fig.12. In the next section the measurement error analysis will be presented.

IV. ANALYSIS OF THE MEASUREMENT RESULTS AND MEASUREMENT ERRORS

Capacitors impedance magnitude $|Z_c|$ measurement analysis

Results presented in Fig.11 and Fig.12 clearly show that measurement error of capacitors $|Z_c|$ depends not only on capacitor impedance magnitude (and frequency) but also on the measurement technique used.

For the shunt-through technique, the lower $|Z_c|$ is, the lower measurement error is. The best measurement accuracy (below 1%) can be achieved at f_{res} and in the vicinity of it using the shunt-through technique. When using the technique for $|Z_c|$>30Ω, the measurement error exceeds several %. In kΩ range the shunt-through technique exhibits very poor accuracy (region A in Fig, 8(a)), because $|S_{21}|$ is very close to 0dB.

As opposed to the shunt-through technique, series-through technique exhibits lower measurement error for higher $|Z_c|$. Measurement accuracy at f_{res} and in the vicinity of it using the series-through technique is very poor, because $|S_{21}|$ is very close to 0dB. However when $|Z_c|$>30Ω, the measurement error is lower than several %, and in kΩ range the series-through technique exhibits very good accuracy.

The reflection technique should not be used for capacitor parameters measurements because it can give accurate results only when capacitor $|Z_c|$ slightly differs from 50Ω (Fig.11(a)).

Capacitors resonant frequency f_{res} measurement analysis

The best suited technique for capacitor f_{res} measurement is the shunt-through technique, because measurement accuracy of capacitor impedance at f_{res} and in the vicinity of it is very good (Fig.11(a) and Fig.12(a)) and this technique is less sensitive to the connectors parasitics.

Capacitors capacitance C measurement analysis

C measurement accuracy highly depends on the measurement technique used. Since *C* is calculated using (7) and capacitor $|\mathrm{Im}\{Z_c\}|$ at f_1 can vary from hundreds of mΩ to kΩ (depends on capacitor *C*), then for *C* measurements it is better to use the shunt-through technique when *C*>50nF. However, when *C*<50nF, then the series-through technique is the best choice for *C* measurements. This can also be deduced from the Table 1. For capacitors with nominal capacitance values of 100nF and 1000nF, the lowest difference between *C* values measured using VNA and high-precision LCR meter is achieved using the shunt-through technique (the difference below 1%). However, for capacitors with nominal capacitance of 1nF and 10nF, the lowest difference between *C* values measured using VNA and high-precision LCR meter is achieved using the series-through technique (the difference below 3%). The reflection technique should not be used for capacitance measurements.

Capacitors ESR measurement analysis

According to the results presented in Table 1 and Fig.8(b) - Fig.12(b) the most problematic parameter to measure accurately with VNA is capacitor ESR. Only the shunt-through technique should be used for accurate ESR measurements. However there are some limitations. ESR can accurately be measured only at f_{res} and in vicinity of it (ESR measurement error below 3% can be achieved). For frequencies which are much higher or lower than f_{res} the measurement accuracy can be very poor, even using the shunt-through technique, because when capacitor reactance is much higher than its ESR, then the measurement error can increase enormously. Moreover accurate measurements of ESR of capacitors with *C* lower than several tens of nF are impossible: series-through and reflection techniques for capacitors with *C* below 1nF, can give even negative ESR which is completely unrealistic (Table 1). Even the shunt-through technique gives very erroneous ESR measurement results for small-capacitance capacitors. So ESR measurements of small-capacitance capacitors (below 10nF) using VNA is completely useless, because of very poor measurement accuracy.

V. CONCLUSION

Vector network analyzers can be very useful for accurate capacitor impedance, resonant frequency, capacitance and ESL measurements in broad frequency range if proper measurement technique and de-embedding is used. Measurement accuracy of several % and even lower can be achieved using proper measurement technique. Measurement error of capacitors impedance and ESR depends not only on capacitor impedance magnitude (and frequency) but also on the measurement technique used.

The best suited technique for capacitor f_{res} measurement is the shunt-through technique, because measurement accuracy of capacitor impedance at f_{res} and in the vicinity of it is very good (even below 1%) and this technique is less sensitive to the experimental setup parasitics. For capacitor impedance measurements in broad frequency range (when capacitor $|Z_c|$ can change from mΩ to kΩ) it is better to use combination of the shunt-through and series-through techniques: when $|Z_c|$ is below several tens of ohms, then it is better to use shunt-through technique; when $|Z_c|$ is above several tens of ohms, then it is better to use series-through technique. The reflection technique should not be used for capacitor parameters measurements because, firstly, it can give accurate results only when capacitor $|Z_c|$ slightly differs from 50Ω and secondly, it is very sensitive to uncalibrated connectors parasitics.

The most problematic parameter to measure accurately with VNA is capacitor ESR. Only shunt-through technique should be used for accurate ESR measurements. However there are some limitations. ESR can accurately be measured only at f_{res} and in vicinity of it (ESR measurement error below 3% can be achieved). For frequencies which are much higher or lower than f_{res} the measurement accuracy can be very poor, even using shunt-through technique, because when capacitor reactance is much higher than its ESR, then the measurement error can increase enormously. Accurate measurements of ESR of capacitors with C lower than several tens of nF are impossible. ESR measurements of small-capacitance capacitors using VNA is completely useless.

Overall it can be concluded that VNA can substitute more-expensive impedance analyzers for accurate capacitor parameters measurements in broad frequency range with some limitations in terms of ESR measurements.

REFERENCES

[1] Kazunari Okada, Toshimasa Sekino. Impedance Measurement Handbook. Agilent Technologies, 2006.

[2] A.M.R. Amarel, A.J.M. Cordoso, “An economic offline technique for estimating equivalent circuit of aluminum electrolytic capacitors,” *IEEE Transactions on Instrumentation and Measurement*, vol.57, No.12, pp. 2697 – 2710, Dec. 2008.

[3] R. Dosoudil, „Determination of permeability from impedance measurement using vector network analyzer,” *Journal of electrical engineering*, vol. 63, No.7, pp. 97-101, Oct. 2012.

[4] Satish Prabhakaran, Charles Sullivan, "Impedance-analyzer measurements of high-frequency power passives: Techniques for high power and low impedance," *In proc. IEEE Industry Applications Conference*, Pittsburgh, PA, USA, 2002, pp. 1360 – 1367.

[5] William B. Kuhn, Adam P. Boutz, "Measuring and reporting high quality factors of inductors using vector network analyzers," *IEEE Transactions on Microwave Theory and Techniques*, vol.58, No.4, pp. 1046-1055, Apr. 2010.

[6] Advanced Impedance Measurement Capability of the RF I-V Method Compared to the Network Analysis Method. Agilent Application Note No. 1369-2.

[7] Ultra Low Impedance Measurements Using 2-Port Measurements. Agilent Application Note, 2004.

[8] L.D. Smith, D. Hockanson, “Distributed SPICE circuit model for ceramic capacitors,” *In. proc. Electronic Components and Technology Conference*, 2001, pp. 523-528.

[9] Rosa M. García Salvador, José A. Gázquez Parra, Nuria Novas Castellano, “Characterization and Modeling of High-Value Inductors in ELF Band Using a Vector Network Analyzer,” *IEEE Transactions on Instrumentation and Measurement*, vol.62, No.4, pp. 415-423, Feb. 2013.

[10] Gregory L. Amorese, "Reducing ESR measurement errors," *Microwaves & RF*, vol. 42, No.4, 2003.

[11] Vector Network Analyzer Family ZVR datasheet. Rohde and Schwarz.

[12] John R. Taylor, *An Introduction To Error Analysis: The Study Of Uncertainties In Physical Measurements*. Sausalito, University Science Books, 1996.