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New One-Probe Method and Instruments for Instant In-Circuit Measuring Quality of Capacitors.
Infinitely Remote Point Conception - Physical Base of the Method.

Unlike well-known In-Circuit methods, based on injection the probing current through the following pass: *Meter-first probe-first terminal of capacitor-plate-dielectric-plate-second terminal of capacitor-second probe of the meter-the meter*, the new Method is based on the principally new approach.
According to it, the probing current flows through the following circuit: *Meter-the probe-envelop of capacitor- internal content-any terminal-conducting environment of the terminal.*
Physical base and appropriate equations were set forth in USA Patent 6, 198,290, March 2001.
There is no second probe. The probing current is formed due to polarization of conducting environment associated with terminal of the capacitor as well as displacement currents.

The development of physical base of the Method brought to origination of the Method of Infinitely Remote Point.

The Method and instruments were successfully tested at NASA testing facility in summer of 2001.

In electronic equipment, up to 60% of malfunctions are directly or indirectly related to capacitors.
Exploitation of the Method and its instruments made testing capacitor almost instant and drastically decreased time of repair of electronic equipment.
The Method is capable to test capacitors in powered circuits.
The paper considers physical base of the Methods in details.

1. General Conception of the Method

There are two versions of the method. They have one common feature: a probing current is being injected through the jacket of the capacitor and then passes through the stuffing of the capacitor, collecting the information about its quality [1,2].

1.1 Two-Terminal Version of the Method

The new method to test capacitors in a circuit is based on replacement of the conventional way of flowing alternating measurement current through the circuit like "meter-terminal of capacitor-plate-dielectric-another plate-terminal-meter" for a new approach: **"meter—terminal of capacitor—plate—dielectric—envelop of capacitor—**

measurement probe—meter". This allows avoiding influence of any circuit connected to capacitor in parallel and makes direct measurement in a circuit possible.
This version employs two-terminal measurement instrument.
Fig.1 illustrates this approach.
We have to note that shown in Fig.1 implies capacitors with a metal jacket. This can be both electrolytic and non-electrolytic ones. For this purposes, a tip-like probe can be employed. Metal surface of the jacket plays a role of a measurement electrode.
For capacitors with an insulating jacket, the probe has a developed conductive surface as this was shown in the Patent. Said surface initiates a displacement current, which probes the media inside the capacitor.

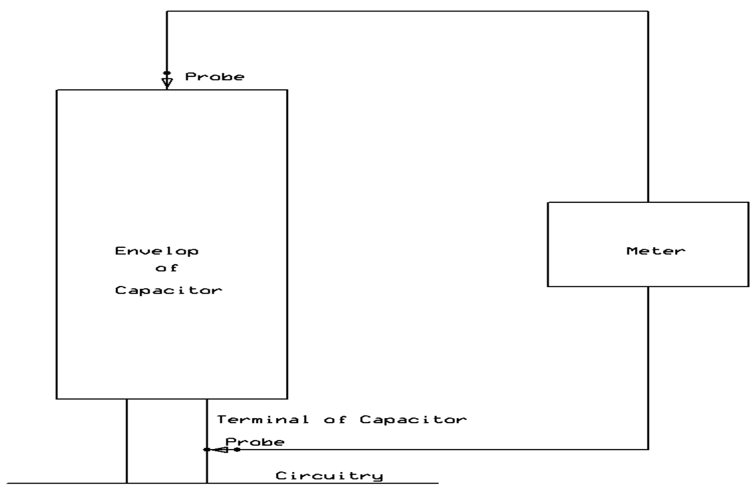

Fig.1
Employing Two-Terminal version of the Method for in-circuit testing capacitors.
Measurement current is injected through the metal jacket and then passes through the body of the capacitor.

For the insulting jacket capacitors, the upper probe has a developed conductive surface to initiate the displacement current.

1.2 One-Terminal Version of the Method

Another version of the method does not use apparent closed circuit of passing measurement current at all. Instead of that, measurement current passes the following way: **"meter—measurement electrode—envelope of capacitor—dielectric—plate—terminal of capacitor—total electric capacitance of all conductive environment, coupled to the terminal"**. This new approach enabled to create principally new, one-electrode measurement method and instruments. The nature of formation of measurement probing current is a displacement current caused by polarization processes both in the inter-plate dielectric and said total conductive environment.
This version employs one-terminal measurement instrument.
Fig.2 illustrates One-Terminal version of the Method.

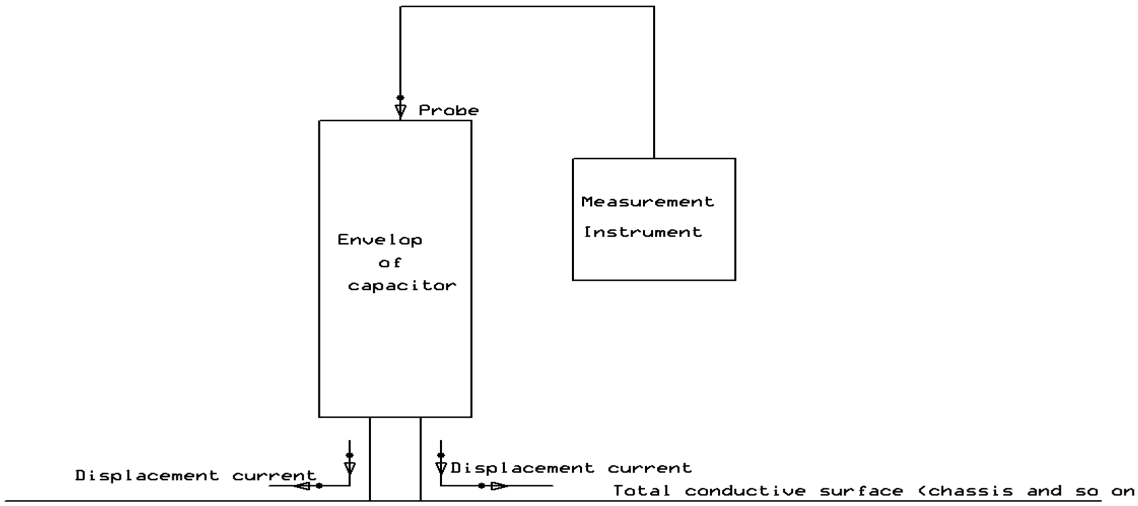

Fig.2. One-Terminal version of the Method.
Like Fig.1, this illustration implies the conductive jacket capacitors.
For the insulated jacket capacitors, the probe has a developed conductive surface.

1.3 .Adequacy of the Method

To be successful, new method has to be adequate with the commonly accepted. This is furnished by the following:
Both the losing and saving energy in capacitors depend on physical processes in a media inside the body of capacitor being tested. Consequently, disregarding the way of passage probing current through the capacitor, a lost-to-saved energy ratio (i.e. tangent of dielectric loss angle, $tg\delta=1/Q$) remains the same.

> **Attention: The following lowercase indexes will be accepted here and further for the capacitance *C* and the tangent of dielectric loss angle $tg\delta=tan\delta$:**
> ***tt*- terminal-to-terminal; *et*- envelope-to-terminal; *e*- environmental, that is an electric characteristic of the two-terminal where the probing current is formed by a polarization of the associated circuitry; *eff*- effective value, which represents the total parameter of a combined circuitry.**

The first mentioned approach is realized by means of applying AC voltage across envelop of capacitor and its either terminal. This creates a probing current, whose characteristics depend on physical processes inside the capacitor being tested.
Physical properties of matter don't depend on method and instrument with which we measure them.
Following from the stated above,

$$tg\delta_{tt} = tg\delta_{et} \qquad (1)$$

where ***tt*** means classical terminal-to-terminal method, while ***et*** means the new, envelop-to-terminal approach. Following from the equity of dielectric losses ratios, with regard to $tg\delta = \omega CR$, we have

$$C_{tt} R_{tt} = C_{et} R_{et} \qquad \text{(1a)}$$

In particular, the measurement instrument, shown in Fig.2 can measures a phase shift α between current and voltage across capacitor. In this case, taking into consideration that $\alpha + \delta = 90^o$, a scale of instrument can be calibrated either in $tg\delta$ or in its invert $Q=1/tg\delta$, which represents the quality of capacitor.

1.4 Employing the Method for Combined Testing Inductors and Capacitors.

The approach, realized in the shown measurement instrument, is also applicable to in-circuit testing inductors. Presence of short turns in inductor causes increase of tgδ.

Both in-circuit capacitors and inductors testing were embodied in LC-Mate™, the pilot instrument, which can detect both defective capacitors and inductors with no switching functions.

1.5 Electric Equivalent of One-Probe Version of the Method. Infinitely Remote Point.

In One-Probe conception, the displacement current to probe capacitors is formed due to involvement of total conductive surface of circuitry environment. Fig.3 illustrates this.

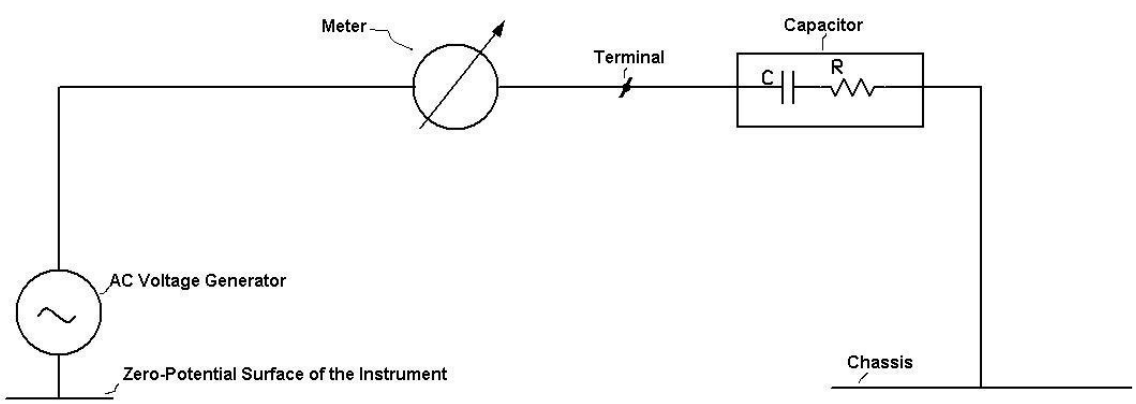

Fig.3
General Electric Equivalent of On-Probe Method for testing capacitors employing a total conductive surface for forming the displacement probing current. Said conductive surface can be formed by a chassis and/or total surface of interconnected circuitry.

Fig.3 shows a general electric presentation of the unit diagram of the Fig.3. The measurement instrument comprises AC voltage generator and a meter. The meter is a generalization of any unit, which measures either of AC characteristics.

The measurement instrument forms AC electric field inside the capacitor. Due to a developed conductive surface, coupled to the capacitor, said AC electric field forms the displacement current, which alternatively charges and then discharges the conductive surface. This current flows through the capacitor, represented by connected in series C and R, performing a probing function. The instrument analyzes characteristics of the current and converts them into an output reading. Injecting probing current inside the capacitor can be done by two ways. First of them is a touching metal envelop of the capacitor with a conductive tip connected to the measurement instrument, like it's shown in Fig.3. This way works goodly for electrolytic and some types of non-electrolytic capacitors. For capacitors with a non-conductive envelop, the probe has to have a developed conductive surface as this was shown in the patent [1]. The total conductive surface of the Fig.3 consists of two surfaces: total zero-potential surface of the measurement instrument and the total conductive surface of the tested unit.
As follows from said above, said version is an One-Probe Method.

Equations of electric circuits require a closed contour for calculations. In the seemingly open circuit of Fig.3 current nevertheless flows due to the polarization process.
It looks like the circuit joints in some fictional point, having some electric potential. Remembering a definition of electric potential at a given point as a work, needed to transfer a unit of a positive charge from the infinity to the given point, we call this point as an *Infinitely Remote Point.*

Fig.4 shows an electric equivalent of the Method, including the Infinitely Remote Point.

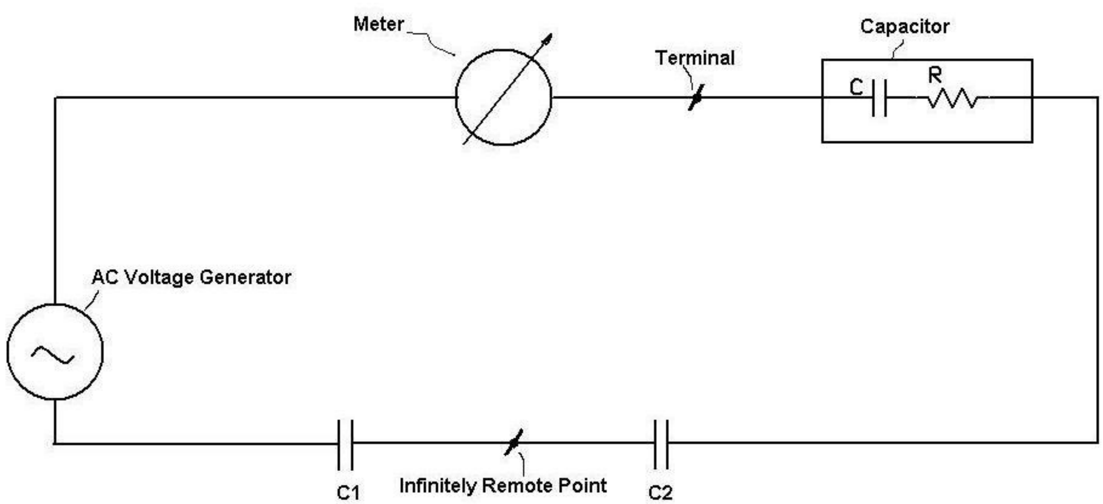

Fig.4. Electric Equivalent of the One-Probe, Infinitely Remote Point Method of measuring quality of capacitors. Capacitors C1 and C2 represent conductive surfaces of Fig.3, connected at the Infinitely Remote Point

The circuit consists of AC voltage generator, which is coupled to RC circuit of a measurement instrument and a metal surface, a terminal and a capacitor being tested, which is coupled to a chassis with its other terminal. As applied to One-Terminal Method, the capacitor consists of internal resistor **Ret,** marked as R in Fig.4, connected in series with capacitance **Cet** (C in Fig.4). In terms of electrical equivalency, both metal surfaces can be shown as two capacitors C_1 and C_2 connected in series at an the infinitely remote point **P**. As was said, the validity of this definition outcomes from definition of electric potential of a given point: this is a work done by a system to bring unit of a positive charge from infinity to the given point of field. In the Method, energy of the generator moves electric charges back and forth through the capacitor from the probe to infinity, because there are no a second pole like it takes place in conventional circuits. This is why we also call the Method as an Infinitely Remote Point Method.

Our purpose is to establish a correlation between set of parameters of traditional methods and that of the new approach.

Dielectric losses ratio of combined series circuit, comprising an internal resistor R_{et} and a total capacitance of conductive environment C_e and that internal C_{et}, can be shown as,

$$tg\delta_e = \omega R_{et} C_e \quad (2)$$

because $C_e << C_{et}$.

From here, taking into consideration (1a), one can show that

$$tg\delta_{tt} \cong tg\delta_e C_{et} / C_e \qquad (3),$$

where $tg\delta_e$ is a tangent of a dielectric loss angle at one-terminal measurement, and ***Ce*** is a total capacitance of all conductive environment to which the capacitor is coupled. Equation (3) is a very important to the Method because it bridges between traditional approach and the new one.

Studying this method has shown that for majority of capacitors *Cet*~0.3-2.0 uF, Table 1, while capacitance of metal chassis represented by **Ce** vary within tens of pF. This allows us to use C_{et} / C_e as a known coefficient, which simplifies the problem.

Because of what a measurement instrument really reads is $tg\delta_e$, its value will be always lower than $tg\delta_{tt}$ so, a scale has to be calibrated with regard to a ratio (3). Because Ce<<Cet, the major components which define the value of $tg\delta_e$ are R_{et} and $C_e, tg\delta_e = \omega C_e R_{et}$

While C_e remains invariable within a tested unit, R_{et} depends on C_{et} which, in turn, is defined by a size of capacitor at invariable $tg\delta$. Table 1 shows C_{et} vs. total surface of capacitor S dependence. As seen from the table, for the majority of capacitors, variation of C_{et} remains within the limited range of quantities. Only for high capacitance it differs as much as 2-4 times, that can be compensated technically.

Because Ce is defined by a total capacitance of the conductive environment of the capacitor and capacitance of the measurement instrument, there is always a chance to adjust the last one to compensate Ce.

Ctt	Size, r*h (radius by height, mm)	*Cet*,uF	Company	Total S, mm^2	*Cet*/S
1uf250V	6.5*12	0.407	Elite	623	6.54
100uF35V	6.5*12	0.668	Elna	623	10.73
47uF35V	6.5*11.5	0.417	GE	602	6.93
2.2uF250V	8*12	0.286	Elna	804	3.56
10uF50V	10.5*5	0.435	Elna	408	10.66
2.2uF350V	12*10	0.465	JH	1068	4.36
220uF100V	12.5*25	0.398	Elna	2453	1.62
100uF200V	16*26.5	0.75	Elna	3467	2.16
2200uF50V	18*36	1.833	Elna	5087	3.6

Table1. Conventional capacitance *Ctt* of various capacitors and their capacitances between the envelope and the terminal *Cet,* as well as other comparative characteristics.

1.6. Combined Series-Parallel RC-Circuit Formed by Residual and External Elements at Invariable Frequency

The instruments, working with free oscillations can use external capacitance as an element of RCL –circuit.

For practical purposes, we need to calculate equivalent (effective) parameters of the combined circuit: effective resistance R_{eff}, capacitance C_{eff} and tangent of dielectric loss angle $tg\delta_{eff}$.
In this Method, connection to the external circuitry increases the total complex capacitance of the system. So, we have to consider a parallel circuitry, analyzing its behavior.

Lets consider the circuit formed by residual capacitance C_1 and its series resistance R_1 when external C_2R_2 circuit is connected, Fig. 5.

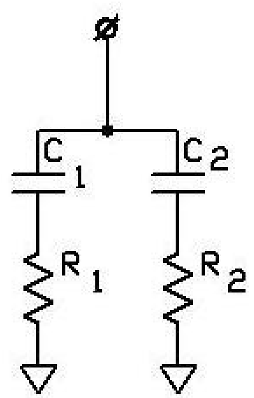

Fig.5. Parallel circuitry in realizing the Method. C_1R_1 represents the instrument, while C_2R_2- the measured capacitor.

Taking into consideration that $R = tg\delta / \omega C$, a residual admittance of the left portion of the circuits is

$$Y_1 = \frac{(tg\delta_1 + j)\omega C_1}{tg^2\delta_1 + 1} \qquad (4)$$

Connecting external circuit C_2R_2 brings a parallel branch with the admittance

$$Y_2 = \frac{(tg\delta_2 + j)\omega C_2}{tg^2\delta_2 + 1} \qquad (5)$$

In free oscillations version of the measuring instrument only, one has to take into consideration that frequency of free oscillations gets lower when connecting C_2R_2. Generally, $\omega_o \geq \omega_e$. As follows from that, $tg\delta_0$ not equals $tg\delta_e$. However, for the relaxation type of polarization, widely existing in capacitors, and its scattered dielectric loss band, $tg\delta$ remains almost unchangeable in vicinity of ω_0.

Now, the total admittance is

$$Y = Y_1 + Y_2 \qquad (6)$$

$$Y = \frac{(tg^2\delta_2 + 1)(tg\delta_1 + j)\omega C_1 + (tg^2\delta_1 + 1)(tg\delta_2 + j)\omega C_2}{(tg^2\delta_1 + 1)(tg^2\delta_2 + 1)} \qquad (7)$$

Here, for convenience, $tg^2\delta_1 + 1 = A$ and $tg^2\delta_2 + 1 = B$

Taking into consideration that $Z = 1/Y = R - j/\omega C$ one gets an effective resistance of the combined circuit

$$R_{eff} = \frac{AB(Btg\delta_1C_1 + Atg\delta_2C_2)}{\omega\left[(Btg\delta_1C_1 + Atg\delta_2C_2)^2 + (BC_1 + AC_2)^2\right]} \qquad (8)$$

Its effective capacitance

$$C_{eff} = \frac{(Btg\delta_1C_1 + Atg\delta_2C_2)^2 + (BC_1 + AC_2)^2}{AB(BC_1 + AC_2)} \qquad (9)$$

And effective $tg\delta$:

$$tg\delta_{eff} = \omega C_{eff} R_{eff} = \frac{Btg\delta_1 C_1 + Atg\delta_2 C_2}{BC_1 + AC_2} \qquad (10)$$

1.7. Special Case of Low Dielectric Loss of External Circuitry.

For the method, the case of $tg\delta_2 << 1$ has a special interest because, as it was said above, in the One-Electrode Method $tg\delta_e$ is drastically less than that of $tg\delta_{tt}$. Here, $tg\delta_2$ is $tg\delta_e$. Beside that, $tg\delta_1 << 1$ for a good measurement system.

Taking this into consideration,

$$tg\delta_{eff} \cong \frac{tg\delta_1 C_1 + tg\delta_2 C_2}{C_1 + C_2} \qquad (11)$$

$$R_{eff} \cong \frac{tg\delta_1 + tg\delta_2}{\omega(C_1 + C_2)} \qquad (12)$$

And $$C_{eff} = C_1 + C_2 \qquad (13)$$

For developing One-Terminal Method, behavior of R_{eff} has a special value. Within this method, C_2 is defined mostly by capacitance of conductive environment, which is invariable at least for testing in one unit, while C_1 is a residual capacitance of the measurement instrument. Consequently, R_{eff} is the only (at the invariable frequency), which is responsible for reading $tg\delta$

1.7. Critical (Inverse) Point

As seen from (11) and (12), in some cases of low $tg\delta_2$ resulting $tg\delta_{eff}$ and R_{eff} can be even lower than $tg\delta_1$ and $tg\delta / \omega C_1$ respectively. It's easily explainable because contribution of capacitance is a saving energy while $tg\delta$ characterizes its loss. So, if the system gains its capacitance while the losses remain low, it saves more energy, i.e. $tg\delta$ decreases. There is come critical value of external $tg\delta_{cr}$ at which dissipation of energy does not change.

This can be used to make a differential scale when there is a critical point of $tg\delta_{cr}$ in vicinity of which a needle of a measurement instrument changes a direction of deflection. If the tangent of dielectric loss angle of an external circuit with the capacitor being tested equals $tg\delta_{cr}$, the loss of energy caused by imperfectives of the circuit equals the

additional energy gained by connecting the capacitor. A needle of the measurement instrument stays at the rest when the instrument reads the circuit with $tg\delta_{cr}$.
Taking into account (11), the following takes place at a critical (inverse) point:

$$tg\delta_1 \approx \frac{tg\delta_1 C_1 + tg\delta_2 C_2}{C_1 + C_2} \qquad (14)$$

As it follows from (14), this takes place at $tg\delta_2 = tg\delta_{2cr} \approx tg\delta_1$

Let's go to instrument-related notations, where C_1 is a residual capacitance C_r of a measurement instrument, $tg\delta_1$ is its residual $tg\delta_r$ while C_2 is defined by the capacitance C_e of the conductive environment of the external circuit with the tested capacitor.
The quested - $tg_{tt} = tg\delta_e C_{et} / C_e$. Taking into consideration that the ratio of these capacitances is a constant *k* at least within one tested unit, $tg\delta_{tt} = ktg\delta_e$. From here

$$tg\delta_r \approx \frac{tg\delta_{ttcr}}{k} \qquad (15)$$

$$R_{rcr} = \frac{tg_{ttcr}}{k\omega C_r} \qquad (16)$$

For instance, if the critical $tg\delta$ of the tested capacitor is chosen 10 (which is real in electrolytic capacitors) at $k = 10^3$ (that is, the total capacitance of a chassis is Ce=200pF, while the cross-capacitance of the tested capacitor Cet=0.2uF, then $tg\delta_{rcr} = 10^{-2}$.
That is, in this particular case, any tested capacitor with tgδ less than 10 causes the instrument to show a decrease of total dielectric loss, while external tgδ more than 10 will result in increase of the loss reading for the instrument with a residual $tg\delta_{rcr} = 10^{-2}$.

2. Employing RLC Circuits in Measuring Instruments Supporting the Method

2.1. Basic Conceptions of Instrumental Approach to Implementation of the Method.

Fig.6. shows a simplified application of One-Probe Method, realized on a base of pulse drive of LC-circuit. Here, Cx is a capacitance between envelop and the conducting chassis. The pulses drive shock-excited damping oscillations, which depends on a process of loss of energy in the tested capacitor.

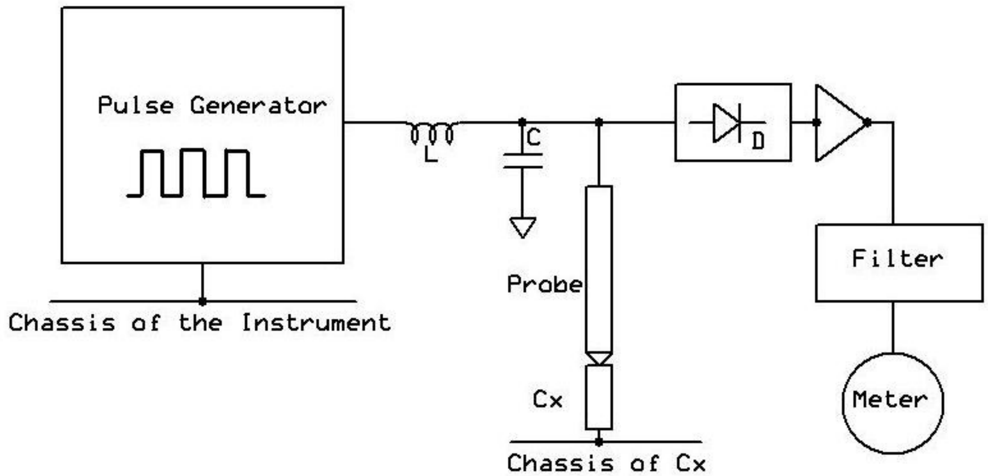

Fig.6. The simplified application of One-Probe Method, realized on a base of the shock-excited damping oscillations. Here, Cx is a capacitance between envelop and the conducting chassis. The pulsed drive damping oscillations, which depends on a process of loss of energy in the tested capacitor

Fig.7 shows a practical application of the On-Probe Method of testing capacitors in-circuit with *C-Miracle* measurement instrument.

Fig.7. Measuring quality of capacitors with C-Miracle instrument. The instrument measures a quality Q=1/tgδ

Attention! When applying the shock-excited damping oscillations for realization of the Method, higher harmonics of a pulse train have not match a resonant frequency of LC testing circuit in vicinity of its band-pass. Or, the amplitude of the higher harmonics has to be small enough to not compete with the free oscillations. This can be achieved by means of maximal spectral distance of major frequency of the pulse

train and the free oscillations. At least, couple hundred time ratio of the frequencies is required.

2.2. Displacement Current Stimulators, DCS, as a Mean to Bypass High Resistance Coupling Problems

The One-Probe Method is based on formation of displacement current through the capacitor due to polarization processes of associated conducting surface.

In majority of cases, one of terminals is directly coupled to developed surface of metal chassis or integrated surface of PCB. But in a less number of cases, both of the terminals of the capacitor have no direct connection with the developed conducting surface. These terminals are connected to high-impedance points of circuitry. By this reason, employing the Method will result in a false reading, caused by resistors connected in series.

To bypass this problem, the following solutions are offered [2].

Either terminal of the capacitor can be touched with an insulated metal surface like a tube, having an elastic contact. The insulated tube, called a Displacement Current Stimulator, DCS, are hold by an operator, that provides a sufficient total capacitance to develop the probing currents.

Another DCS realization is a soft conductive surface laid under an opposite side of PCB with soldered terminals.

Attention! Never use DCS in powered equipment!

2.3. Advantages of the Method.

The Method has the following advantages when compared to existing In-Circuit methods.

1. No need to connect probes of the instruments to terminals of the capacitor, frequently located inconveniently;
2. No need to know capacitance of the capacitor because the existing in-circuit methods and instruments measure Equivalent Series Resistance, ESR, rather than an ultimate characteristic – dielectric loss. The ESR is not the ultimate characteristic, and can be used only together with known capacitance;
3. Instance results –one touching a cap of the capacitor for 1s is enough to get the result.
4. Possibility to measure the quality or tangent dielectric loss angle in powered equipment.

Attention! Although C-Miracle and other special instruments for realizing the Method can operate in powered equipment, we don’t recommend doing that. In any case, a high-voltage decoupling capacitor has to be placed between the LC circuit and the probe.

The Method and Instruments were successfully exploited since 1996 in the computer maintenance company, New York. Application of the Methods and Instrument resulted in considerable increase of troubleshooting rate in the company [3].

Conclusion.

The principally new measurement method and instruments to test capacitors in-circuit have been developed.

Unlike existing methods of injecting a probing current through two terminals of the capacitor, due to applied voltage, the new one forms the probing current by means of applying the voltage to the envelop of capacitor and further developing the probing current due to polarization processes on a conductive surface, associated with the terminal of the capacitor.

New approach results in numerous advantages including instant testing quality of capacitors and possibility to do this in powered equipment.

Literature and Links

1. M. Krinker. *Method to Detect Defective Capacitors in Circuit and Meters for That,* US Patent No. 6198290. March 2001.
2. M. Krinker. *In-Circuit Testing Capacitors. New Approaches and Instruments. Infinitely Remote Point Method of Measurement.* http://www.scribd.com/doc/79607702/First-One-Terminal-In-Circuit-Method-to-Measure-Quality-of-Capacitors
3. Reference Letter from *Key Systems*, company exploiting the Method and Instruments since May 1996, New York.