FACTA UNIVERSITATIS
Series: **Electronics and Energetics** Vol. 36, Nº 4, December 2023, pp. 499 - 507
https://doi.org/10.2298/FUEE2304499B

Original scientific paper

RECENTLY DEVELOPED INDUSTRIAL DIELECTRIC ENABLES RF CAPACITORS FOR HIGH-KVAR RESONANT TANK USE

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Abstract *This article describes designer's experience with radiofrequency (RF) high reactive power capacitors problems, which in many cases may be a critical element for various devices - like ICP plasma torches; SMPS converters; induction heaters; radio transmitters etc. New materials at the markets allow to solve the problem that at small capacitance - high voltage - high amperage combination, capacitors have to withstand circulating reactive power load from kVAR to MVAR range, hence the value of loss factor tan(δ) of the selected insulator material has a critical role, to minimize overheating. Few designer strategies are disputed, and convincing experimental data on selected new industrial materials are presented.*

Key words: *capacitor heat-up, RF reactive power, design choices, new industrial dielectrics, power capacitor loss*

1. INTRODUCTION

For radiofrequency (RF) power electronics creating may be observed market lack of cheap capacitors able to stand the high reactive power. RF reactive power circulating in the LC tank may make a massive loss, thus overheating the device up to the explosion. Such an effect is absent at DC or rather small at low-frequency AC.

To evaluate the heating, electrotechnical applications use the PF (power factor) where PF = $\cos\varphi$; φ is the phase angle and $\varphi = 90^\circ - \delta$, (formula 1)

but for small angle values of $\delta \ll 10^\circ$, what is the case of any capacitor, may be written an approximation $\tan\delta = \sin\delta = \cos\varphi$, (formula 2)

creating the thumb-rule: DF = PF. (formula 3)

The lossy capacitor model uses the term dissipation factor (DF), where DF = ESR/Xc = $\tan(\delta)$; (formula 4)

Received February 24, 2023; revised March 04, 2023 and June 02, 2023; accepted November 10, 2023
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where δ is the loss angle, and the thermal output flux

P(therm) = ESR*i^2 (formula 5)

or for the capacitor P(th) = P(circ)*DF (formula 6).

Sometimes it is handy to write it in terms of equivalent serial resistance

ESR = DF*Xc = DF/(2*π*f*C) (formula 7)

or in terms of quality factor Q = 1/DF (formula 8)

So, high-kVAR persistent RF capacitors are in demand in devices and technologies applied for many spheres, including inductively coupled plasma (ICP) spectroscopy, quadrupole mass spectroscopy (QMS), induction heating, radio-communication transmitters, switched-mode power supplies. In the context of this article, we thought about 50pF–50nF capacitance in the range of current 5–50A at voltage 2–50kV. In particular, such capacitors are crucial to femtosecond lasers aiming to generate coherent extreme ultraviolet radiation or for laser-induced plasma formation to generate high-order harmonics [1].

For currents remarkably below 5 Amperes, there are many cheap alternatives like mica capacitors, Johansson or air dielectric trimmers, ceramic capacitors, etc. In the case of larger currents, the cost of the electronic device under design strongly depends on the price of the used power capacitor. Available in the market 10–1000 kVAR range capacitors well suited for heavy-duty conditions (air-cooled or water-cooled) are ultimately costly, even if their resonant frequency is troublemaking low. Such capacitors are offered by Vishay [2], Murata, Celem, Jennings, and other companies [3]. Science articles on that topic are exclusively thin and mostly about new composites [4] or patents [5], except some publications on dielectrics advances like [6], [7], [8]. Certainly, Facta Universitatis journals issued proper input in this field also, like [9] and [10] being specially rich with further references over newest GHz range capacitor designs and providing the most recent stage in the development of a passives for RF. The newest technologies, ideas, and features actually is the definition for State of the Art.

2. Realized Experiments

First experiment/case study: design a 30 kW, 3 MHz generator by stacking 20 capacitors of 1000 pF or 200 pieces of 100 pF in a resonant tank array. If Vishay products are selected, such as R16HQ ceramics (ε = 17, tgδ = 0.00015 gives a resonant quality factor Q = 6666) or at R7 and R42 materials (ε = 7 and 40 accordingly, and tgδ = 0.0005 for both that gives Q = 2000). Such capacitor fabrication costs >1 k$ per piece, thus >20 k$ whole apparatus. If all other components in the apparatus take, guess, takes 10-100 $, the designer and clientele are not happy.

A good loss factor has a vacuumed quartz glass capacitor with copper plate electrodes. Unfortunately, they are too big for miniature designs and also not cheap. In the case of an array, the mount geometry is problematic due to attenuation and inductance in the wires. Even one of the best-ever known mount geometries with two near-standing sandwich plates (making depressed inductance transmission line) on which capacitor bodies are wired star-shaped, gives unpleasantly large parasitic inductance and resistance. We applied the multiple Teflon-base two-sided metalized PCB plates instead of the capacitor and got about 10x fewer expenses for the unit, keeping the Q-factor about 700.

Second experiment/case study: designing a generator for ICP supply must have the tank capacitor for (27–100) MHz in (3–10) A, where at least 30 kVAR of reactive power circulates in the tank at (3–10) kV. For this task, various high-voltage doorknob capacitors were examined. Power loss was low only for those genuine for RF. It is typically made for only a few kVAR, thus we need to stack an array, again resulting in project-stopper costs and limited array size. Therefore, there was examined a larger array of cheap, non-specialized ceramic capacitors. Typically pipe-form and disc-form capacitors are not well suited for arrays and can take 10–30 VAR per piece. Even, if the dielectric losses may be minimized, the Foucault losses in wiring and wire inductance become limiting factors. For example, the skin-effect depth in copper at 100 MHz is as small as 6.5 microns. Years long we thought the best design choice here is to set the high-voltage 1206-size SMD capacitors in the array; the best found (10 pF, 2 kV) for about few cents per piece was tiny enough to avoid the inductance effects and physical form factor permitted to solder them like bricks in the wall, side to side. Capacitors were GHz range products, which means extra tiny DF. To create demanded 100 pF array, we stacked two such capacitors in series and 20 parallel and in later devices - 3 in series and 33 parallel. The thermal (mid-infrared) FLIR-T62-101 camera tells surface temperature in the range of 50-90ºC, which was on the edge of the specified allowance. Unfortunately, the PCB pad of FR4 material used for holding the assembly read about 150ºC. Initially, we mal-classified this effect as being the result of bad cooling, which means glass-textolite stops the airflow, thus trying to identify the optimal geometry for cooling air gaps. That was not a case of help. We realized it obvious at 100–200 W consumption when the SMD stack many cases violently exploded. Then we expected that probably piezoelectric effect is provocative for the damage and thus designed a more elastic soldering cradle – but harvested no big effect at all. SMD stack is small by size, aesthetically attractive, cheap, and therefore an acceptable solution. Some firms are soldering it (SMD) together at the factory and sell it as one complete capacitor. So, we condemned FR4 textolite for solder that capacitors and began machining a Teflon sheet as a mechanic keep-together element due to lower DF for Teflon. Copper bars were fixed in holes so the SMD capacitors were soldered in between these bars with the intent that the air gap would now be wide enough to provide sufficient air circulation from all sides and cradle is well springy. The outcome was far off what we expected. The Q-factor grew indeed, but the operational time of the serial tank was a few minutes before the explosion, producing a deep carbonized hole into the Teflon. Easy to guess the resonator's Q-factor raises the series tank voltage high over allowance (serial tank voltage multiplication effect). Increasing the number of capacitors in series, however, did not help much, which means the Q-factor increase was sharp. By the way, tutorially, this effect is responsible for the sad fact that most of the oscilloscope high voltage probes operated at >100MHz, marked 2 or 3 kV are already exploding at relatively low voltages such as 500-800V, and this is not a problem only to cheap imitations but even for three-digit-priced branded probes. We lost bunches of it. So, we applied the Teflon PCB for this capacitor too and got a few USD cost probe that was defect-less. What are these intriguing new materials?

3. Proposed Solutions and New Materials

We adapted the digital one-port Antennoscope PS200 to measure both i(C) and i(R) components because $tg(\delta) = i(r)/i(c)$ (formula 6). We etched the wave micro-stripline with 50 Ohm impedance, thus we may use the altered accuracy measurement method applied to shift the 25 Ohm and 100 Ohm probe loads on the end of the line, thus measuring the DF value [11] and [12] with altered accuracy. Here is the table of measurement results well passing the producer advertised data.

Table 1 The PCB capacitor materials tested

Material name	Thick (mm)	pF/cm2	Diel ε	DF @ 1 MHz	DF@ 10 GHz	Q-factor	A3 size price	f(max)***	Notes	Refer
how obtained	meas.	meas.	calc.	meas.	meas.	calc.		producer		
traditional FR4 glass textol **	1.5	2.8	4.7	0.015	na	75-95	50	50 MHz	cheap but not enough good	[13]
\`capacitor pcb\` 3M**	1.5	3100	22	0.01	na	100		1 kHz	frequency far too low huge loss	[14]
Duroid TC350	1.5	2.0	3.5	0.0015	0.002	667	115	10 GHz	matt cladding to alter natural cooling but larger Focault loss	[15]
Duroid-6035HTC*	1.5	2.2	3.6	0.0013	0.0015	770	240	40 GHz	high-T° material, conduc. 1.44 W/m/K, glossy cladding	[16]
Duroid-5880*	1.5	1.7	2.2	0.0004	0.0005	2500	325	40 GHz	0.72 W/m/K	[15]
CuClad-217*	3.17		2.2	0.0009	0.0012	1100		30 GHz	45 kV/mm	[15]
DiClad-880*	3.17		2.2	0.0009	0.0010	1100		27 GHz	45 kV/mm	[15]

(*) The plastic film glued on the surface provides the advantage that even without silver-coating the capacitor surface will not oxidize too soon to lose a penetration depth over time. Better to keep that film intact.

(**) Guess the FR4 and 3M materials suffer from multiple scattering between threads with ε=10 to best case 3.7 into the epoxy having ε=3.6. Loss is dramatic there.

(***) The DF is mostly given in catalogs at one fixed frequency, thus for any other effective work frequency of choice this pre-given DF(0) in that region where DF is changing by frequency, can be recalculated as DF(eff) = DF(0)*sqrt[f(eff)/f(0)] (formula 7). Using this formula must be considered that at frequencies far below insulator material molecular or atomic resonances, the response curve is typically flat. In the region just below that resonance (or multiple resonances) is according to the formula, but the region over the resonance capacitor may revert and become degraded "become more coil or resistor like, not a capacitor" if not affected by leads impact. From that frequency region designers try to avoid, except when large loss is the aim.

For three of those Teflon-base materials, we had a chance to measure the surface roughness with the high-class profile meter to evaluate the Foucault loss significance.

Precision profilometer printouts Fig 1 to Fig 3 help to understand that diminished roughness is part of the diminished Foucault effect and thus diminished loss factor, thus becoming obvious the dielectric material own DF impact in the heating effect is stronger

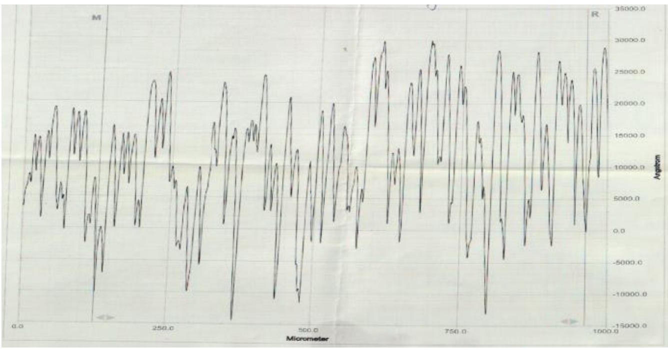

Fig. 1 Instrument printout facsimile: Duroid TC-350 profile data of copper cladding (x: lineary coordinate; y: altitude; scale: 5.0μm

than the impact of cladding. The profilometric measurements was provided as outsourced collaboration job at LU Solid State Institute (LU-CFI).

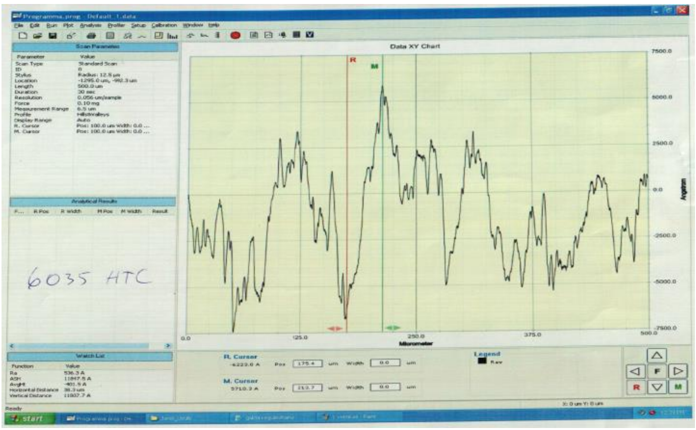

Fig. 2 Duroid 6035HTC profile data on copper cladding; scale 3.5μm

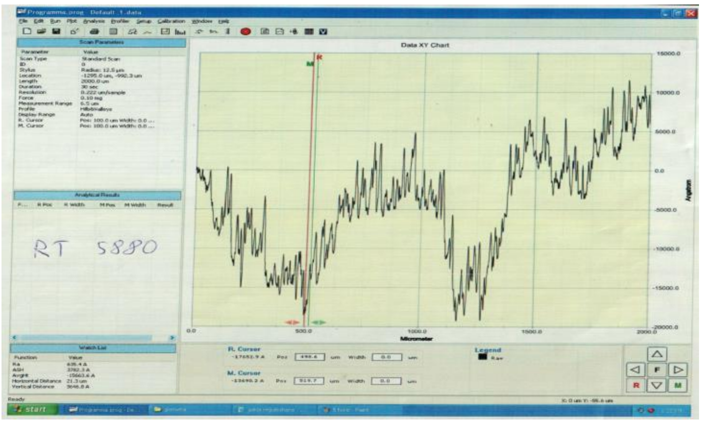

Fig. 3 Duroid 5880 profile data, scale 1.50μm

It ought to be still made bold that in spite of Focault losses surely playing the role in materials under test total losses, the dominant was dielectric losses in the insulator layer, as the following couple of Mid-range infrared pictures indicate.

Infrared experiment series we provided to measure the component temperature in tough work regimes, including the power Mosfet and resonant tank capacitor. At Facta University publications at least twice in the last years it was suggested that infrared thermography is a well-suited instrument for circuit diagnostics [17], [18].

We applied the high resolution mid-wavelength infrared camera FLIR-T62 to take the snap of serial resonance high Voltage (several kilovolts) 100 MHz generator under 10A consumption of 24V supply current. Because the human eye is not accustomized to recognize well what is what in infrared pictures, is worth to explain.

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The upper left corner in Fig 4 is the ICP coil. Under the coil, the right side wire stands the SMD array capacitor containing 3x33 pieces 2 pF 2kV, like pellets on the Teflon pad within an elastic copper cradle. The slight right of the capacitor just below the end feet of the coil is power MOSFET: IXFX42N60 with Gate input feet at the left side of it. With a surprise we got that region of Gate inside the crystal is far hotter than Drain and Source, near 200C.

Probably that is the Clapp generator circuit specialism and the reason why such generators serve several weeks and then die unexpectedly. The surprise was also that coil feet are rather cold, thus the Foucault effect is not very dominating in the temperature rise. The ICP (Inductively Coupled Plasma) lamp bulb (those, with a tail) inside the coil, of course, is hot, which is only reasonable. But the capacitor still is surprisingly hot despite so good quality factor as Q = 6666, its temperature is about 200 C. At the same time the surface area of capacitor pellets is tiny thus more troublemaking seems the Teflon keeper plate is too hot, about 100 C. That is sure not the IR rays reflection from the capacitors back, as both plate sides have similar temperatures. This means the RF Voltage raises so much that high loss happens everywhere in the insulator volume.

It must be noted to measure 10 kV 100 MHz RF voltage is not possible more exactly like plus/minus wide margins. So, we don't know the precise value, but sure that value was over 5 kV and less than 20 kV. That is a magnificent result with resonant voltage multiplication out of 24 Volt power supply.

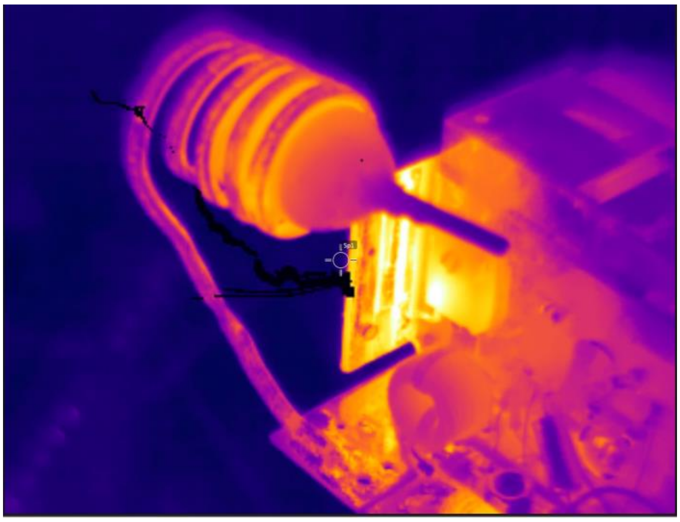

Fig. 4 The 5A 3kV battery of 1206 size SMD capacitors of 10pF 2kV (see just under the coil, 3 vertical stacks). Capacitors are notably warmer than ICP plasma lamp in midst of the coil. Power mosfet has thermal problem into gate region (right from capacitors), instead of more logical-to-think drain or source be warmest

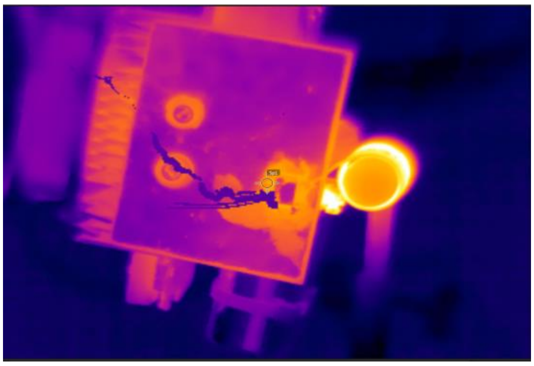

Fig. 5 PCB capacitor thermogram under tough load

Then the SMD array was shifted to the PCB capacitor consisting of 3x4 cm large Rogers "Duroid 5880" material with an etched perimeter to diminish the probability of high voltage discharge through the air (Fig 5). Is notable, that the dielectric layer there is brighter (hotter) than the copper and the dielectric is still hot even at the perimeter zone where the Foucault effect is absent but the electric field is diminished just slightly because of the fringent field currents.

This means that the Foucault effect is sure not dominating the heat build source but the dielectric heating. Contraycan be seen Fig.5 at right side where wire cross section clearly indicates the temperature function by the surface where the warmest point in the thermogram is the "shiny ring" on the right side, which is the coil wire. Just the view worth illustrating in the student textbook on the skin effect topic.

By the way, if more raise the current, the wire may come desoldered - thus the temperature went over 300 C. The capacitor cladding was kept stable at 60-80ºC which is in a reasonable range. The light frame around the capacitor in Fig.4 is cladding etched off zone for high voltage over the side discharge suppressing. Left side wavy pattern is transistor cooler ribs.

According to these tests we suggest the new material allowable power load be about 10 A per 10 cm2 (one side) area and too much value is 20A or a very mild regime is 5A. These figures are important when the designer is weighing how large the resonant tank is

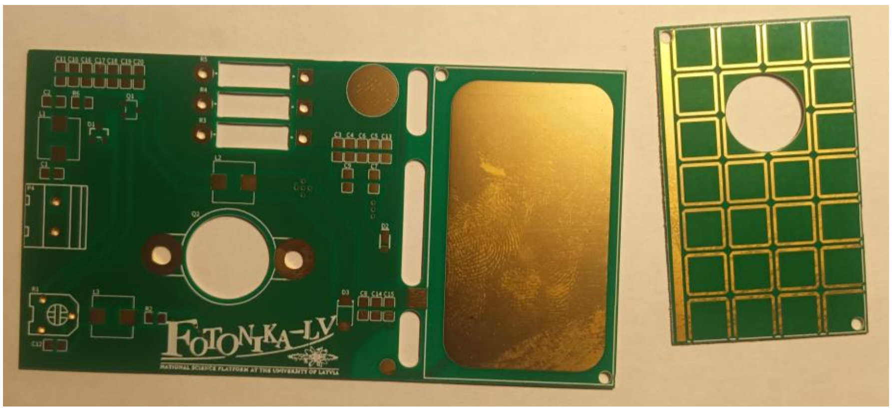

Fig. 6 Rogers (C) material PCB used three layer capacitor at right side

optimal. Fig. 6 shows the 10 Amperes 100 MHz generator PCB designed with the abovementioned capacitor, containing down-side layer GND, a middle layer with high voltage, and separate gluable-on platelet with upper layer GND.

4. CONCLUSIONS

Duroid bi-clad materials serving as a capacitor were installed and tested in the Clapp generator feeding ICP reference spectra source lamp. The Duroid-5880® was identified as the most appropriate designer choice. Cladding warmed up to 60-80 ºC, exhibited a good Q-factor storing enough circulating energy in the tank and low heating, naturally not permitting the voltage step-up too much when the lamp is not yet ignited or is taken out.

Each capacitor in most circuits has one pole under high voltage and the other near the ground potential. Then in the case of a PCB capacitor is wise to divide one plate into a pair of equal parts, thus the outer sides near the Earth potential hide the high-voltage and RF field into the capacitor body for safety reasons and to decrease the radio interference (acting like fringent field antenna). Note that the popular belief the RF current is innocent and may not kill is not true when a multiple kV tank provides significantly more than 5 Amperes RF. Know our experience, touching such (DC-less) capacitors with RF is potent to cut severe and deep necrotic burnouts into flesh.

In the first case study - 3MHz, 30kW induction heater, we tried a PCB capacitor for a resonant tank of 20nF. Applying the cheapest Rogers Duroid TC350 resulted in the cost of the device being far below $1000. In comparison, built by Vishay capacitors the device would demand 30-fold bigger funding. As the resonant current is about 400A there, each of the 70 parallel PCB boards receives 5-7 A which is well in the safe range even not demanding the forced cooling. Only due to the sum of heat fluxes, we applied the small-size simple fan. Thermal losses here were: (30 kW) x (resonant Q factor when full load = 100) x ($tg\delta = 0.0015$) resulting in the 4500 W of heat (or 1200 W using 5880 material). The best Vishay capacitor ceramics may give a thermal flux as low as 450 W in the extreme but then the interplay with the self-cost is less favorable.

For large, powerful, and overall costly custom-produced devices and instruments the best professionally made capacitors are still 2.6-fold less lossy than the best 'Duroid'. However, for small RF power sources, the Duroid alternative gives huge savings with just an insignificant loss of Q-factor or without loss of it. If the surface temperature is limited, the cheapest Duroid with Q = 667 is optimal because of its strong natural cooling, but if the quality factor is the most substantial - then the most expensive one with Q = 2500 is the best choice. In both cases, the surface temperature of the PCB capacitor is expected to be similar. When capacitance is desired lesser and voltage is very high, the BiClad and CuClad materials are the best choice.

Disclaimer: *Authors have no mercantile interest in Rogers production advertisement and receive no benefit from their business welfare*.
Data availability statement: *The data that support the findings of this study are available upon reasonable request to the authors.*

Acknowledgement: *The research was financially supported by EU ERDF Project No ESS2020/381, CFLA 1.1.1.1/19/A/144 and in many ways supported by the scientific platform FOTONIKA-LV*

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