DRY FILM CAPACITORS FOR HIGH-FREQUENCY POWER ELECTRONICS

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Film Capacitor Innovation Without Limits

Presentation overview

Achieving higher frequency bandwidths for film capacitor operation is achieved by:

- Designing the capacitor winding geometry for high frequency & low ESL
- Choosing capacitor internal assembly conductors & external connections for low resistance at high frequency
- Designing the PCB or circuit buss connections to cancel ESL
- A combination of all three approaches

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Discussion Points

- Factors affecting capacitor performance at high frequencies
- Capacitor winding geometry comparison and affects on:
  - ESL & ESR
  - Peak and RMS current
  - Life and reliability
- UP37 vs. UP38 board mount coupling/decoupling – example of geometry
- Minimizing impedance, ESL, and ESR
- Skin depth and frequency
- Equations
- Skin depth vs. frequency for copper and aluminum conductors
- Conductor AC resistance vs. frequency
- Terminal selection
- Terminal option examples
- Technique review for decreasing ESL and increasing resonant frequency
- Discrete vs. Modules – system level considerations
- Capacitor vs. circuit approaches
- ECI products for high frequency
- ECI product development
- Summary
- Contact Information

Factors affecting capacitor performance at high frequencies

- Resistive factors of conductors
  - Skin depth and frequency
  - AC resistance of conductors
- Reactive factors of capacitor winding
  - Increasing resonant frequency
  - Minimizing Impedance, ESL, and ESR
- Mechanical factors of capacitor design
  - Design techniques
  - Terminal selections
- External methods vs. Internal methods of increasing capacitor resonant frequency
  - PCB parallel & reverse current
  - Concentric wind, coaxial design, incorporated laminate buss, …
- System level cost and component count of discrete vs. module capacitors
  - Assembly labor discrete vs modules
  - Reduced lam-buss and connections at system level
  - Component count and reliability

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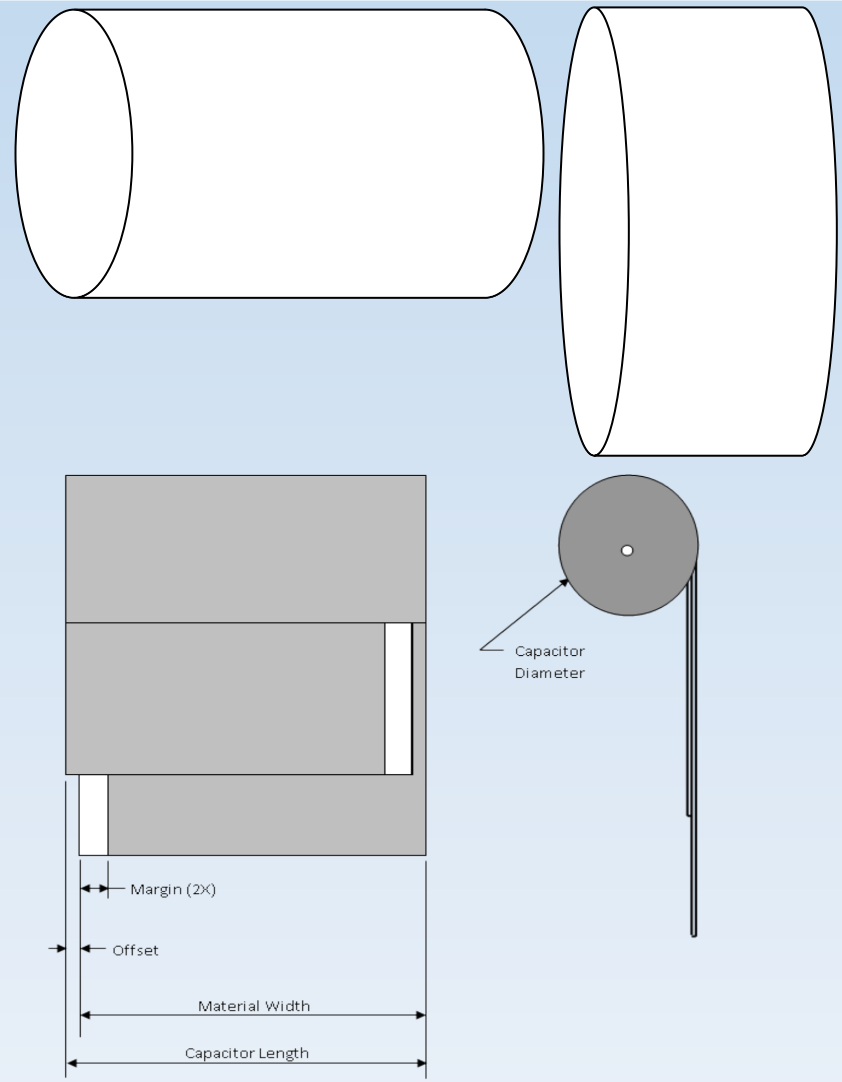
Capacitor winding geometry

5µm BOPP Dry Film Capacitor Winding		
Capacitor Parameters		
CAP (µF)	100	100
DIELECTRIC (FILM) WIDTH (mm)	50	100
FIXED MARGIN / OFFSET WIDTHS (mm)	5 / 1	5 / 1
CORE DIAMETER (mm)	9	9
CAPACITOR DIAMETER (in)	2.601	1.744
DIAMETER:LENGTH RATIO	1.30 : 1	0.44 : 1
CAPACITOR SURFACE AREA (in^2)	26.8	26.4
CAPACITOR VOLUME (in^3)	10.7	9.5
ESR (Ω at F-res)	0.00206	0.00929
PEAK CURRENT I-pk (Amps)	3,256	1,427
DV/DT (V/µs)	32.6	14.3
RMS CURRENT AT 45°C AMBIENT (AMPS)	53.7	21.3
RMS CURRENT AT 85°C AMBIENT (AMPS)	34.6	13.7
THERMAL COEFFICIENT R_{th} (°C/W-dissipated)	8.20	11.60
ΔT AT 20 AMPS, 40 kHz	6.8	43.1
HOT SPOT IN 45°C AMBIENT	51.8	88.1
PROJECTECD LIFE AT HOT SPOT (Hrs.)	636,838	51,439
ESL & F-res - Standard Commercial Design		
ESL (nH at F-res)	28.1	55.7
RESONANT FREQUENCY F-res (Hz)	94,914	67,455
ESL & F-res - Low ESL Construction		
ESL (nH at F-res)	5.0	10.0
RESONANT FREQUENCY F-res (Hz)	225,079	159,155



UP37 vs. UP38 board mount coupling/decoupling – example of geometry

35µF	UP37BA0350	UP38BA035
ESR 10KHz (mΩ)	9.0	5.5
ESL (nH)	35	16
Resonant Frequency (kHz)	143	190
Amps RMS 10kHz, 45C	19	26
I-peak	861	1349
DV/DT (v/µs)	25	39
Style	Round board mount	Square board mount

Both fit the same ½" pin space, with flat copper internal tabs. The UP38 is shorter for 2" board clearance with a shorter winding width producing lower ESR & ESL and higher Ipk and F-res.

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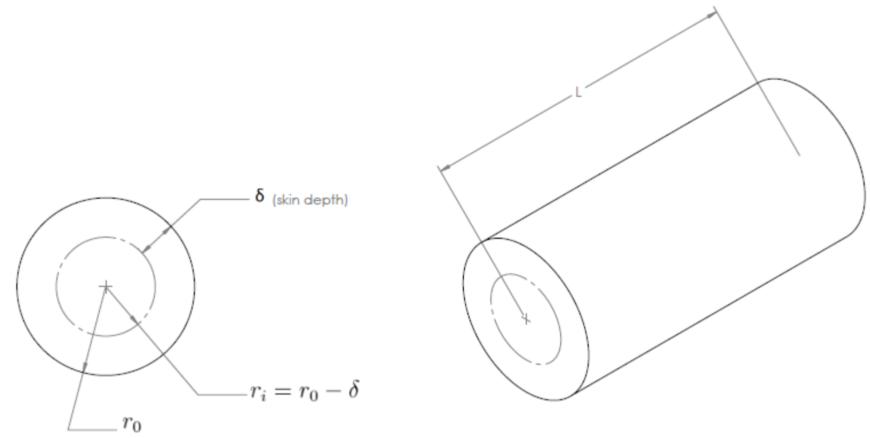
Minimizing impedance, ESL, and ESR

- Capacitor winding design optimized for geometry
- Capacitor ESL & ESR decrease as winding length decreases
- Mechanical methods to reduce ESL employ the cancellation techniques of coaxial cable and laminate buss
- Internal capacitor conductor construction for high frequency; tab vs. wires, hollow vs. solid

Skin depth and frequency

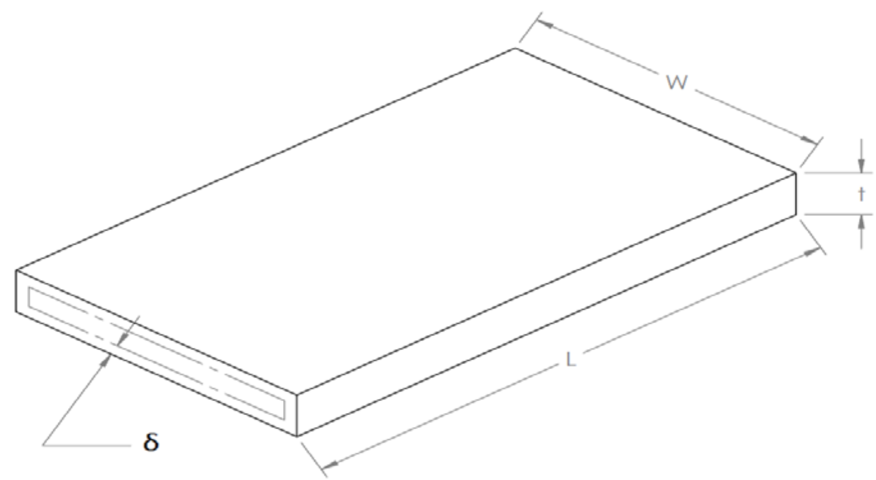
Round Conductors

The cross-sectional conducting area is a function of the skin depth and circumference. As frequency increases the skin depth decreases, and the cross-sectional conducting area decreases leading to higher resistance, losses, and heating. Tubes have better frequency range then solid round conductors.



Flat Conductors

The cross-sectional conducting area is a function of skin depth and perimeter. As frequency increases the skin depth decreases, and the cross-sectional conducting area decreases leading to higher resistance, losses, and heating. Thin wide conductors have better frequency range then thick narrow conductors.



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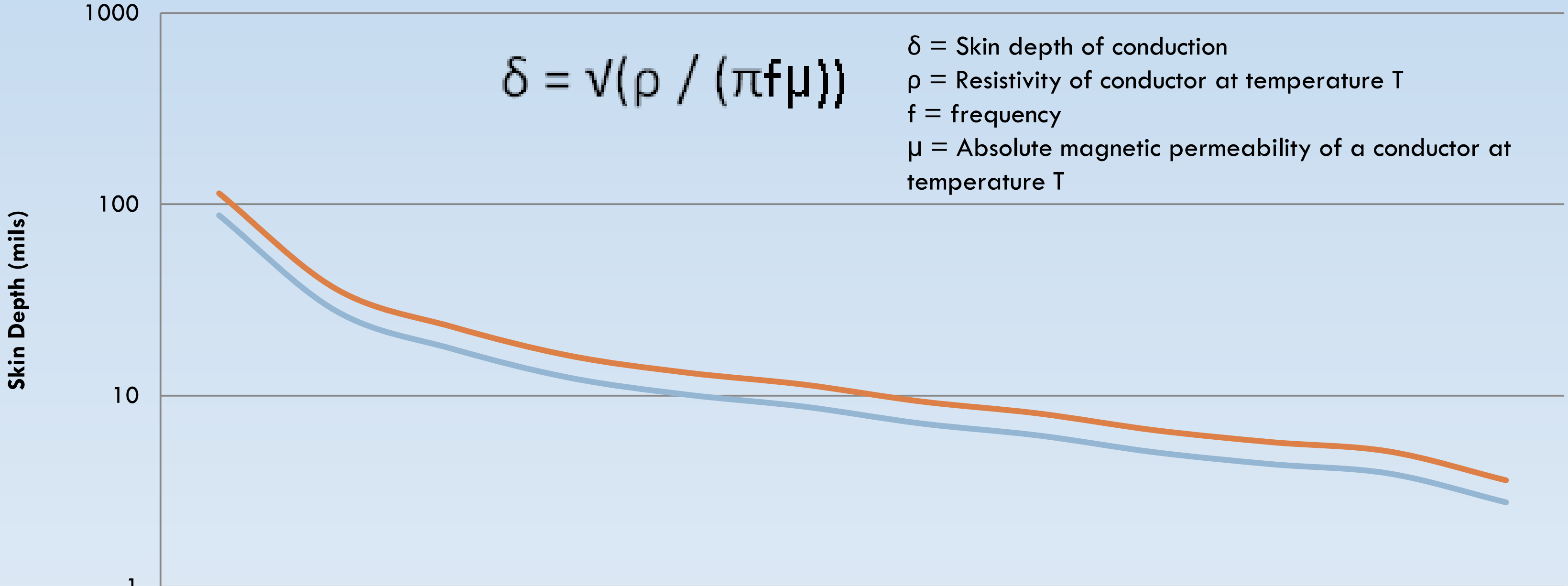
Equations

Symbol	Description	Units	Equation/Note	Copper	Alum
δ	Skin depth of conductor based on AC frequency	mm	$\delta = \sqrt{\rho / (\pi f \mu)}$		
ρ	Resistivity of conductor at temperature T	$\Omega \cdot m \times 10^{-8}$	$\rho(T) = \rho_0[1 + \alpha(T-T_0)]$	1.9492	3.3059
ρ_0	Reference resistivity of conductor at temperature T_0	$\Omega \cdot m \times 10^{-8}$		1.6780	2.8200
α	Temperature Coefficient of resistivity	1/°K		0.004041	0.004308
σ	Conductivity (inverse of resistivity) in Siemens	$S/m \times 10^{7}$	$\sigma(T) = 1 / \rho(T)$	5.9595	3.5461
μ	Absolute magnetic permeability of a conductor at temperature T	H/m	$\mu(T) = \mu_0 \times \mu_r$	1.2564	1.2567
μ_0	Permeability of free space at T_0	$H/m \times 10^{-6}$	$\mu_0 = 4\pi \times 10^{-7}$	1.2566	1.2566
μ_r	Relative magnetic permeability	None	Vacuum = 1	0.999834	1.000022
T	Conductor temperature	°C		60	60
T_0	Reference temperature for ρ_0 and μ_0	°C		20	20
f	Ripple frequency	Hz			

Skin depth vs. frequency for Cu and Al

Skin Depth (mils) vs Frequency (kHz)



	1	10	25	50	75	100	150	200	300	400	500	1000
Copper	87.49	27.67	17.50	12.37	10.10	8.75	7.14	6.19	5.05	4.37	3.91	2.77
Alum	113.93	36.03	22.79	16.11	13.16	11.39	9.30	8.06	6.58	5.70	5.10	3.60

Material	Resistivity at 20 °C (nΩ·m)	Density at 20 °C (g/cm³)	Resistivity-density at 20 °C		Conductor cross-section/volume, at same conductance relative to copper
			(nΩ·m·g/cm³)	Relative to copper	
Copper	16.78	8.96	150	100%	1
Aluminium	26.5	2.7	72	48%	1.5792

Conductor AC resistance vs. frequency

- AC resistance function of:
  - Surface area
  - Skin depth
  - Cross-sectional area perpendicular to current flow
  - Length parallel to current flow
  - Frequency of current
  - Temperature
  - Conductor material
- Maximum conductor frequency when AC and DC resistance is equal
- Conductor and terminal design optimized for $R_{AC} \leq R_{DC}$ for frequencies ≤ capacitor self-resonant frequency (F_{res})

Terminal selection

- The higher the frequency the more surface area required for skin depth and conducting cross-section
- Hollow round conductors are better than solid conductors (tubes, through bushings, etc…)
- Thin flat conductors provide large surface area for high frequency impulse response
- AC resistance ≤ DC resistance at capacitor self-resonant frequency

Terminal option examples

Board mount multiple leaded smaller discretes or spade tab terminals

Spade lugs or bolt down

Bolt through bushings and tabs direct to buss or IGBT

Buss connected DC links or direct to IGBT

Modules

Technique review for decreasing ESL and increasing resonant frequency

- Capacitor intrinsic ESL is defined by the mechanics of the capacitor design
  - ~14nH/inch of material width without cancellation techniques
  - “Coax” methods of ESL cancelation
  - Concentric wind method of ESL cancelation
  - Internal and external conductor & terminal design
  - Internal laminate buss to array of canceling windings

- Extending the frequency range requires minimizing ESL to increase resonant frequency by the capacitor designer or circuit designer
  - Intrinsic to the capacitor design – winding geometry, mechanical cancellation techniques
  - As arranged by user on PCB’s or laminate buss – multiple discrete capacitors arranged physically parallel with equal and reverse current flow through each on PCB

Discrete vs. Module – system level considerations

Weighing the trade-offs:

- Discretes – higher part count and assembly labor cost but lower capacitor cost
  - Customer employs ESL cancellation techniques to increase resonant frequency and band width
  - Extra board, buss, or cable costs and complexity
  - More connections and mountings to assemble

- Modules – volume efficient, low part count, minimized assembly labor, possibly higher total capacitor cost offset at system level
  - Lower volume then multiple discrete capacitors
  - Minimizes buss and cable connections, complexity, and assembly cost
  - Significant reduction in assembly labor and materials offsets module cost

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Capacitor vs. Circuit approaches

- Capacitor Designer
  - Winding geometry
  - Concentric winding
  - Coaxial construction
  - Flat tabs – no solid wires
  - Wide surface area terminals
  - Multiple isolated caps in a housing
  - Modules of bulk capacitance and ESL cancellation mechanics
- Circuit Designer
  - Use double sided PCB
  - Lay-out discrete capacitors parallel and closely spaced
  - Reverse current flow through every other cap
  - Use laminate buss structures with caps
  - Use modules minimizing connection materials and labor

Board and direct mount ripple filters, snubbers & resonant capacitors

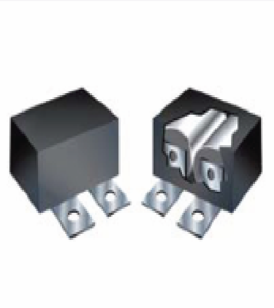
UP2 Series (high energy density BOPP)

Key Features

- Higher voltage ratings
- Simple construction
- Two types of terminals
- RoHS compliant

UP37 Series- Unlytic® Miniature Series

- Operating Temperature Range: -55°C to +105°C
- Capacitance Range: 4.7µF to 35µF
- Voltage Range: 500VDC to 1500VDC
- High voltage ratings & RoHS compliant
- Dry construction (no harmful electrolytes)
- Non-polar
- Voltage ratings convenient for Euro designs
- Terminal style, high current carrying ability



MP88-PT88 Series- Metallized Polypropylene

- Operating Temperature Range: -55°C to +105°C
- Capacitance Range: 0.10µF to 2.5µF
- Voltage Range: 460VAC to 920VAC, 800VDC to 3000VDC
- No internal wire connections, improves frequency response
- Direct-to-element tab attachment
- Terminals spacing 23-28mm
- Reversed current through unique dual element design minimizes ESL

UP38 Series- Unlytic® Miniature Series

- Operating Temperature Range: -55°C to +85°C
- Capacitance Range: 3µF to 40µF
- Voltage Range: 600VDC to 2400VDC
- Less than 2 inches in height
- High peak current
- High dv/dt
- Lowest ESR
- Low ESL
- Maximum energy density

MP80 Series- Metallized Polypropylene

- Operating Temperature Range: -55°C to +105°C
- Capacitance Range: 0.5µF to 50µF
- Voltage Range: 400VDC to 3300VDC
- Reduces inductance up to 90%
- Uses screw down terminals vs. lead wires
- Rugged monolithic construction
- Continuous current carrying capacity
- ESR as low as 0.003 OHMS

5PT Series- Polypropylene & Foil

- Operating Temperature Range: -55°C to +105°C
- Capacitance Range: 0.010µF to 0.100µF
- Voltage Range: 230VAC to 460VAC, 400VDC to 1500VDC
- Higher current carrying capability
- Minimum inductance lower impedance and ESR
- Five case sizes
- Compact configuration
- Direct plug-in spade lugs

Discrete DC link building blocks & modules

UL3 Series- Unlytic®

- Operating Temperature Range: -55°C to +105°C
- Capacitance Range: 6.5μF to 300μF
- Voltage Range: 500VDC to 2200VDC
- Inductance as low as 25nH (<12nH available)
- Low ESR
- Current carrying capability to 110 amps
- Withstands hostile environments
- Integrated mounting flanges
- RoHS compliant

UL9 Series- Metallized Polypropylene

- Operating Temperature Range: -40°C to +85°C
- Capacitance Range: 380μF to 17100μF
- Voltage Range: 700VDC to 3000VDC
- Long Life > 100,000 hours
- Cost effective
- Low ESL & ESR
- High RMS current capability
- Flexible construction
- RoHS compliant

MP3 Series- Unlytic® Polypropylene

- Operating Temperature Range: -40°C to +85°C
- Capacitance Range: 85μF to 1350μF
- Voltage Range: 500VDC to 2400VDC
- Long Life: > 100,000 hours
- Low ESR
- High RMS current capability
- High surge voltage capability: 1.5 x VDC
- Integrated mounting flange
- Cost effective design

EV/HEV Series – Metallized Polypropylene

- Direct connect to IGBT
- High RMS current 100A to 200A
- Operational to 110°C
- Low ESL: 20nH
- Life expectancy: > 15,000 hours
- RoHS compliant

LH3 Series- Unlytic®

- Operating Temperature Range: -55°C to +105°C
- Capacitance Range: 30μF to 1600μF
- Voltage Range: 500VDC to 2400VDC
- Low ESL <10nH
- Compact terminal arrangement
- Low ESR <0.20 mOhms
- High RMS current capability >400 Arms
- Integrated mounting flange to withstand high shock and vibration environment

High-temperature, high-frequency caps

5HT Series- High Temperature

- Operating Temperature Range: -55°C to +175°C
- Capacitance Range: 0.010µF to 0.100µF
- Voltage Range: 230VAC, 400VDC
- Compact configuration
- Direct plug-in spade lugs
- Low ESL and ESR
- High dv/dt
- High peak current

HT1 Series- High Temperature

- Operating Temperature Range: -55°C to +150°C
- Capacitance Range: 0.12µF to 2.2µF
- Voltage Range: 600VDC to 2400VDC
- Highest peak current capabilities
- Low loss factors that decrease with temp.
- Tight capacitance stability vs. temperature
- Volume efficiency comparable to MP88
- RoHS compliant

UH3 Series- High Temperature

- Operating Temperature Range: -65°C to +125°C
- Capacitance Range: 25µF to 325µF
- Voltage Range: 600VDC to 1200VDC
- Low ESR and ESL
- Low cost
- Withstands hostile environments
- Integrated mounting flanges
- RoHS compliant

ECI product development

- Wave solderable film caps with plug in bases and multiple pin-outs
- Low ESL Feed through capacitive line filters
- 125°C hermetic sealed AC filter caps for 400Hz aerospace generator sets
- Continuous development of customer specific designs – please contact us with your application request

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Summary

- Film capacitors for high-frequency power electronics offer advantages in self healing, no liquids, very efficient (low loses), and flexible design options.
- Capacitor geometry influences ESR, ESL, power efficiency, RMS current, peak current, capacitor heating, and life projection/reliability.
- Lowering ESL and increasing resonant frequency is accomplished through capacitor winding design, internal and external conductor choice, capacitor assembly design, and system level cancellation techniques.

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