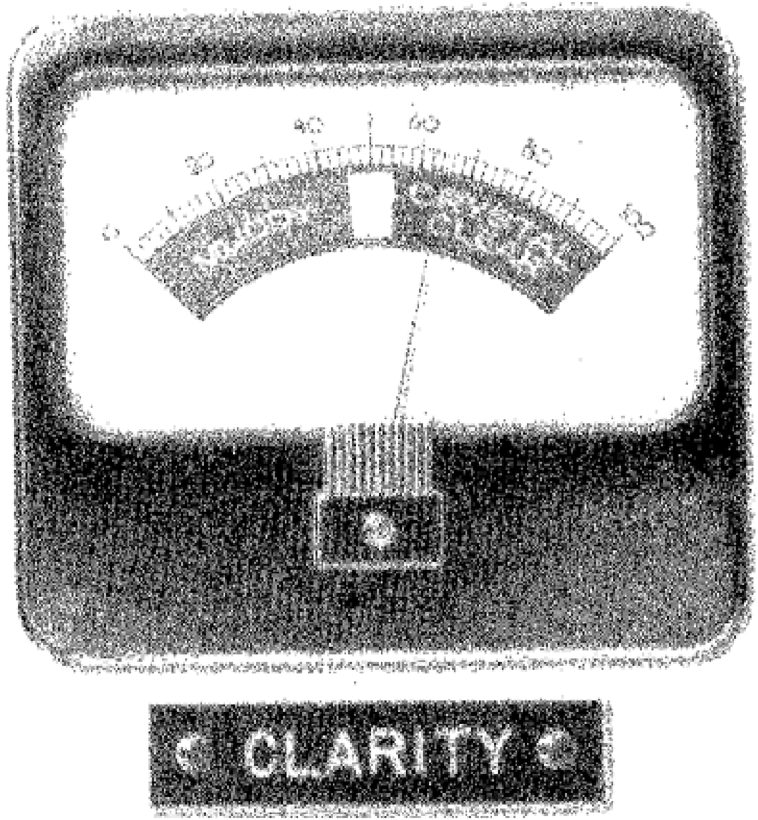
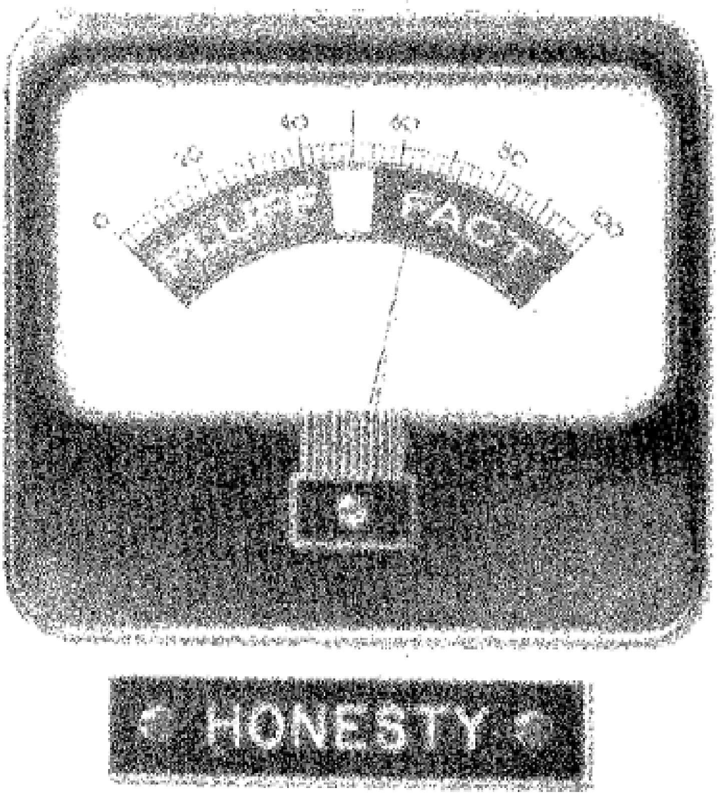
ECE 562

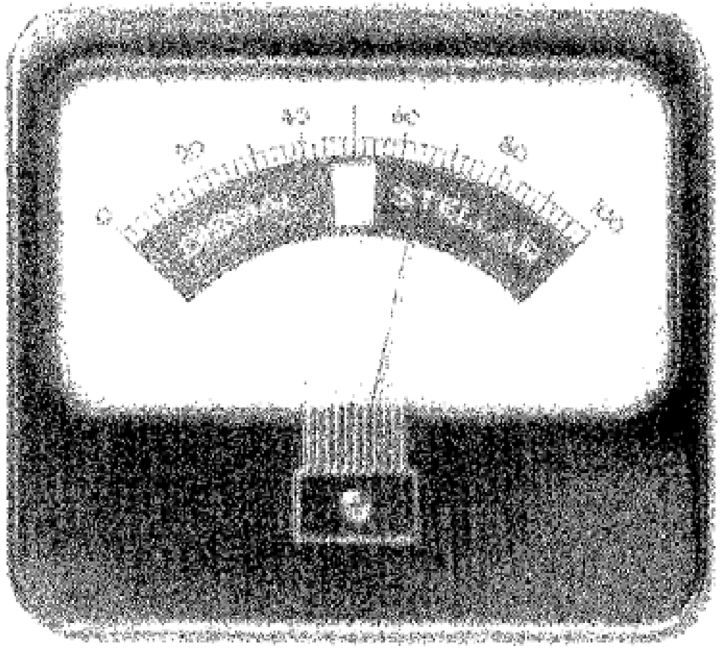
Week 3 Lecture 2

Week 3 Lecture 2 Summary

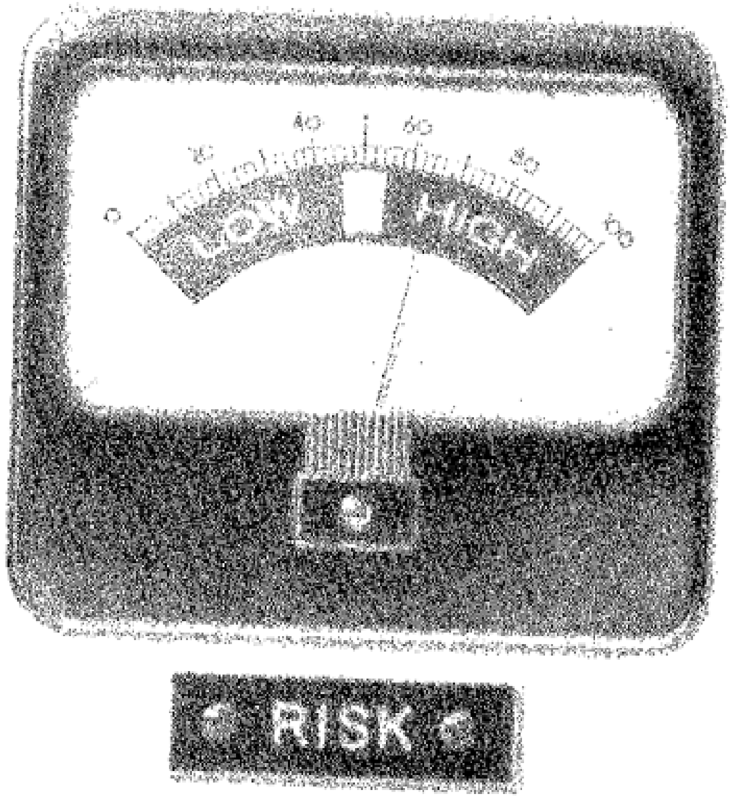
- Section notes
  - Slides 3-6 – Talk qualities
  - Slides 7-16– Capacitor realities and mechanisms
  - Slides 17-36– Capacitor impedances
  - Slides 37-40- Commercial capacitors
  - Slides 41-53 – Buck converters


CLARITY


FAST
HONESTY



PERFORMANCE

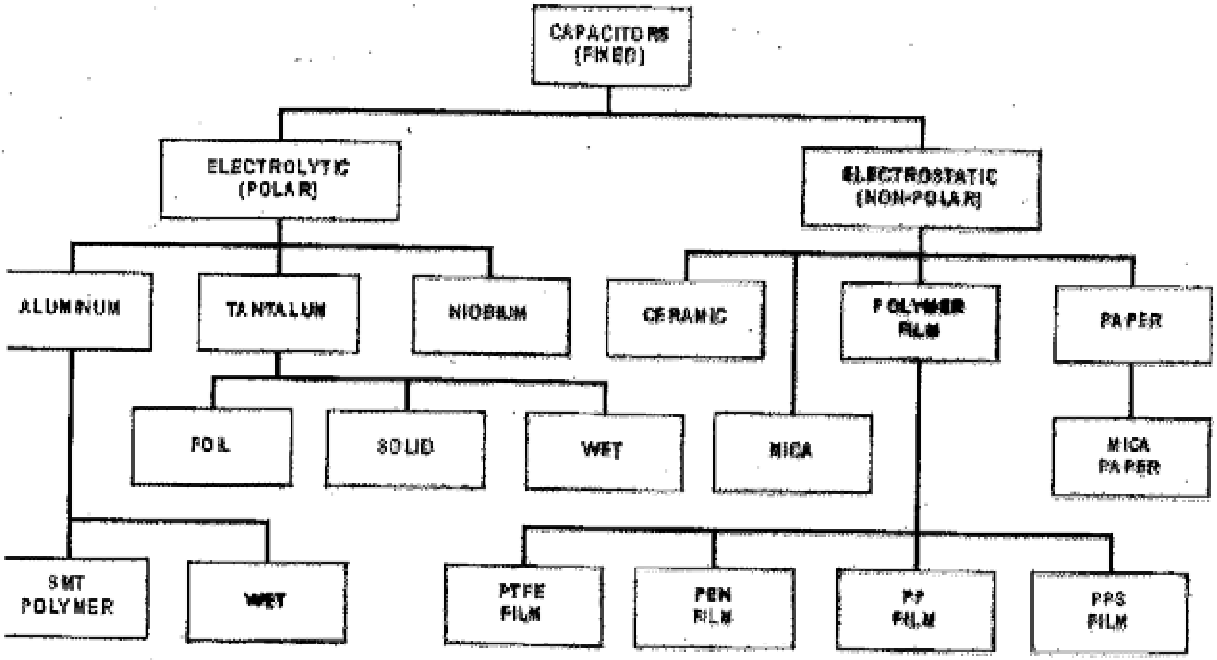

0
20
40
60
80
100
Low
High
RISK

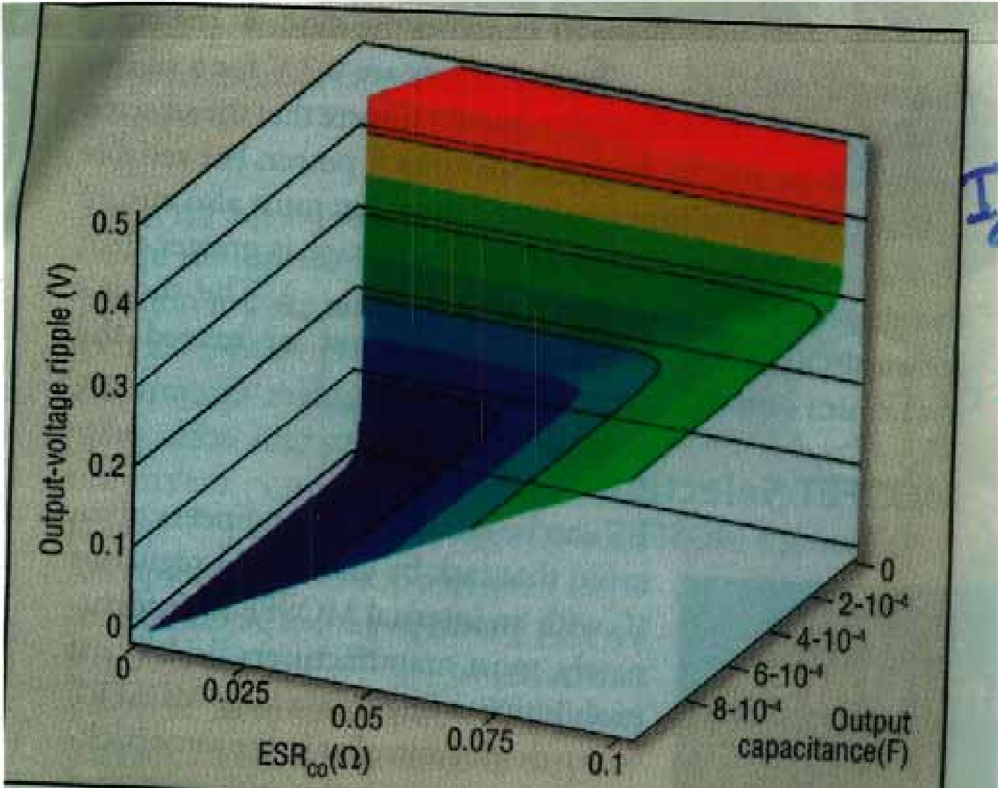
OUTLINE LECTURE 9

A. Buck-Boost Converter Design
1. Volt-Sec Balance: f(D), steady-state transfer function
2. DC Operating Point via Charge Balance: I(D) in steady-state
3. Ripple Voltage / "C" Spec
4. Ripple Current / "L" Spec
5. Peak Switch Currents and Blocking Voltages / Worst Case Transistor Specs

B. Practical Issues for L and C Components
1. Inductor: $L = f(I)$? $L = f(f_{sw})$?   Lower Q "10"
   a. Cost of Cores
   b. Inductor Core Materials Unique to Each f_{sw} Choice
   c. Core Saturation above i(crit)
      $B > B_{sat}$, $L = f(i)$
      $B < B_{sat}$, $L \neq f(i)$
2. Capacitor: $C(f_{sw}, i_c, v_c)$ Higher Q "100"
   a. Costs
   b. Dielectric Materials
      (1) $\varepsilon(f_{sw})$
      (2) E(breakdown)

Capacitor Technologies





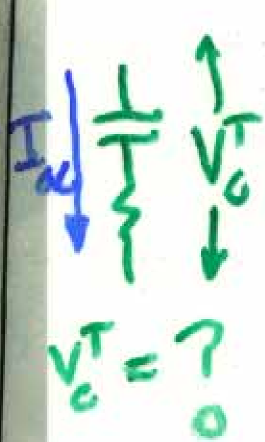
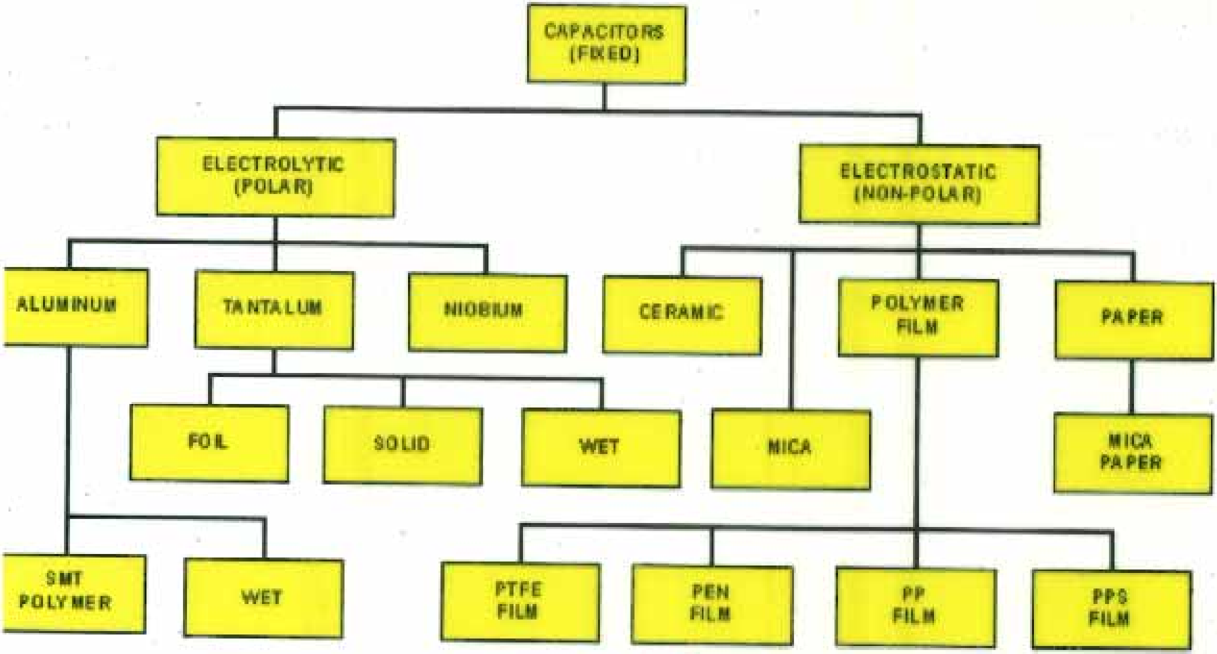


Fig. 3. *The output capacitor's equivalent series resistance (ESR) dominates the output-voltage ripple.*

Capacitor Technologies



Vacuum Cap: High Q, high f, high voltage

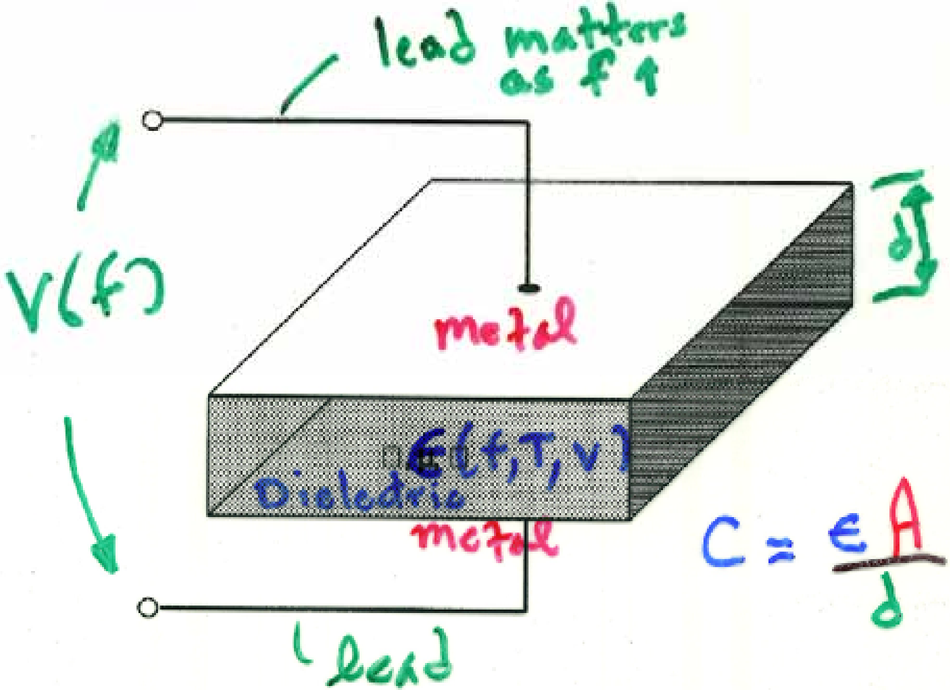
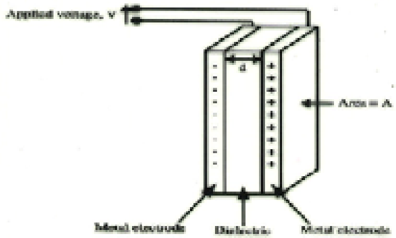


Figure 13. Generalized capacitor.

Capacitor Fundamentals

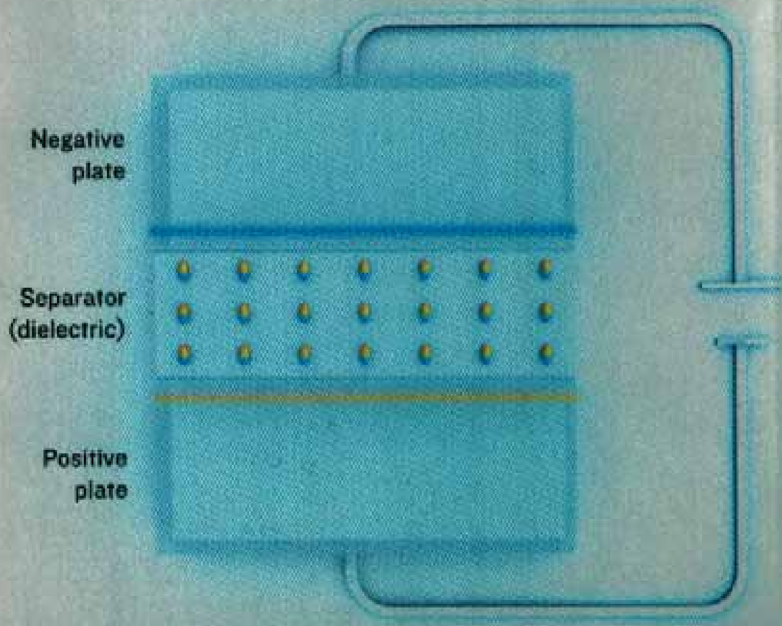
$CV = Q$

- In Conventional capacitors, capacitance is measured as the amount of charge divided by the voltage, and charge is proportional to area of the plates.
- Traditional capacitors require a large surface area plate to have more capacitance
- Ideally, to get a very large capacitance one wants a very large surface area with as little distance between the plates as possible

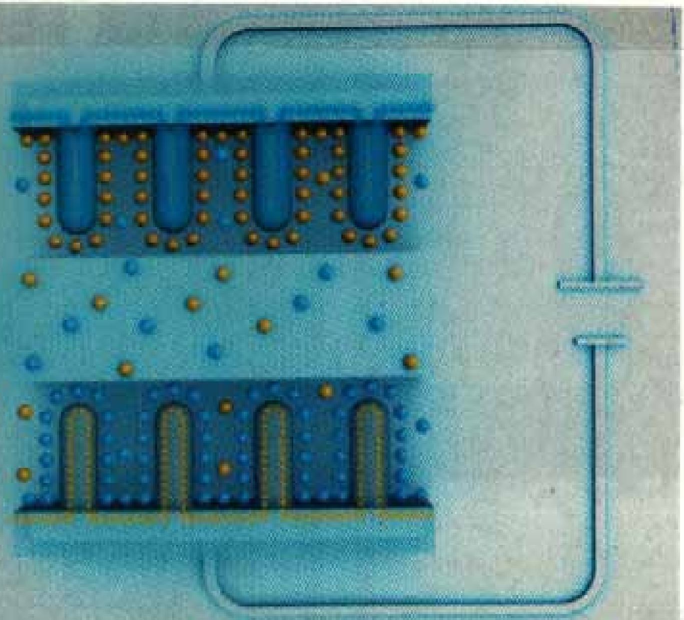


$C = ?$

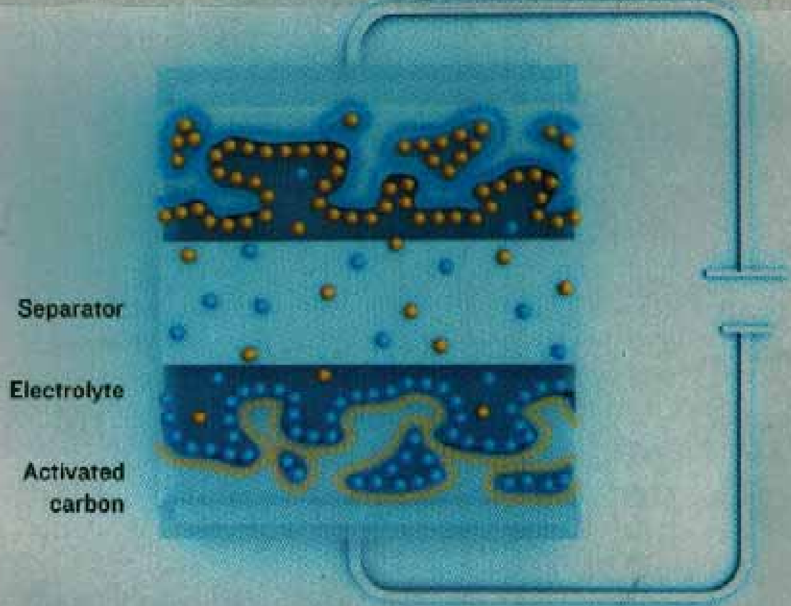
PILING ON THE FARADS



In a typical capacitor, electrons are removed from one plate and deposited on the other. Polarized molecules in the dielectric concentrate the electric field. One major factor determining capacitance is the surface area of the plates.

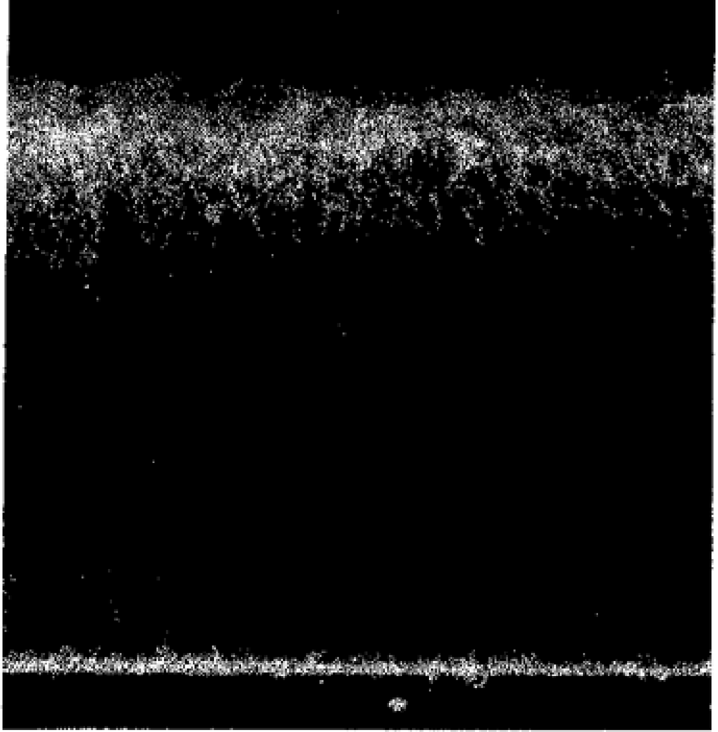


With finer dimensions and more uniform distribution, carbon nanotubes enable greater energy storage in ultracapacitors than activated carbon does.

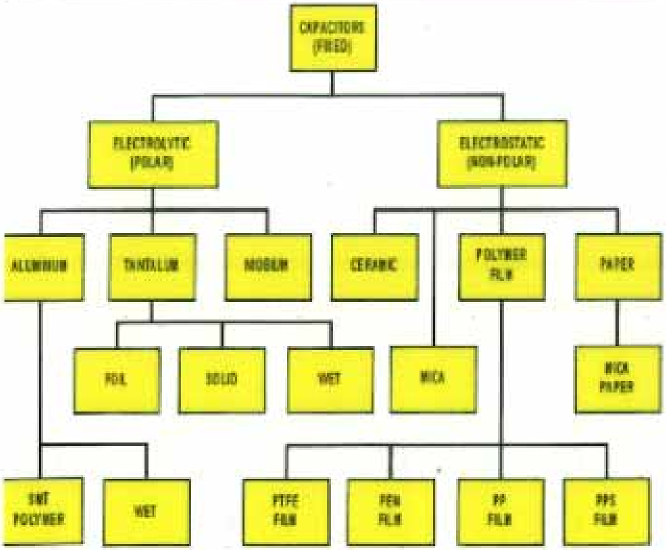


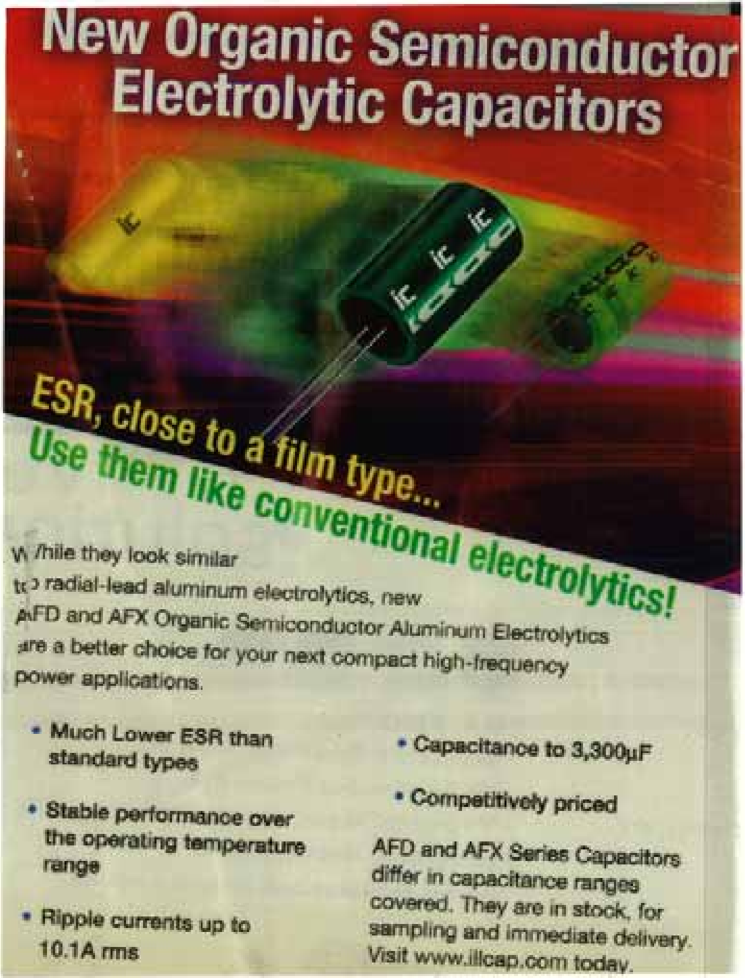
An ultracapacitor can store more charge than a capacitor can, because the activated carbon has a pocked interior, much like a sponge. This means that ions in the electrolyte can cling to more surface area.

ELECTRIC SHAG: A cross section of an electrode made with carbon nanotubes.



Capacitor Technologies




New Organic Semiconductor Electrolytic Capacitors
ESR, close to a film type...
Use them like conventional electrolytics!
While they look similar to radial-lead aluminum electrolytics, new AFD and AFX Organic Semiconductor Aluminum Electrolytics are a better choice for your next compact high-frequency power applications.
• Much Lower ESR than standard types
• Stable performance over the operating temperature range
• Ripple currents up to 10.1A rms
• Capacitance to 3,300µF
• Competitively priced
AFD and AFX Series Capacitors differ in capacitance ranges covered. They are in stock, for sampling and immediate delivery. Visit www.illcap.com today.

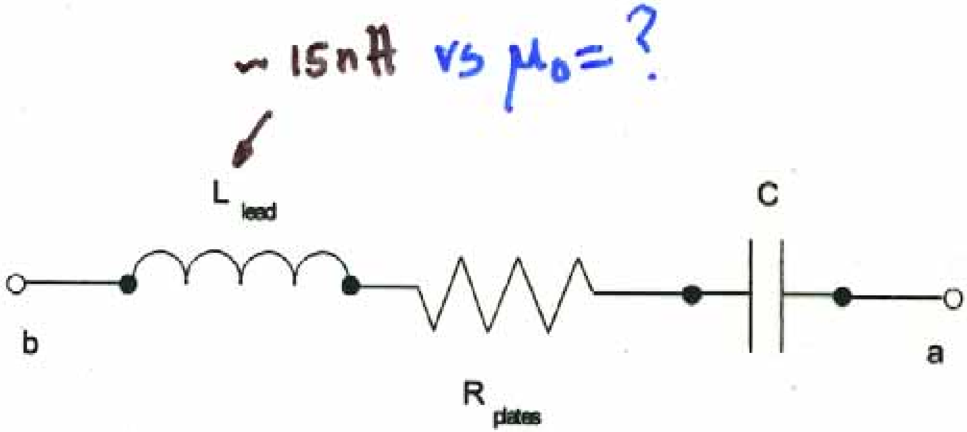
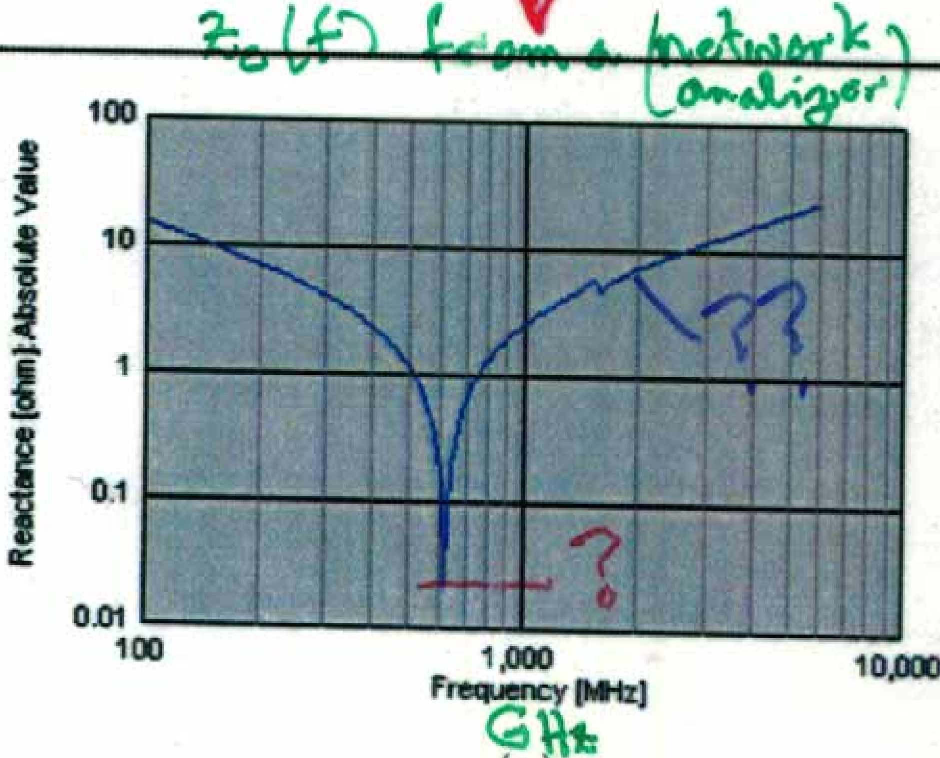


Figure 15. Simplified equivalent capacitor circuit.


Z0 (f) from a network analizer
100
10
1
0.1
0.01
Reactance [ohm]: Absolute Value
100
1,000
10,000
Frequency [MHz]
GHz
(a)

- Most of the parasitic inductances that we are concerned with here are those associated with traces, bond-wires, lead terminations, etc. From an applications point of view, we need to be concerned about *PCB trace inductances* in particul --- for that is what we can minimize easily.

- But not all PCB trace inductances are "trouble-makers". For example, the traces in series with the inductor are "benign" --- because they can be looked at as jus being lumped together with the main inductor. A freewheeling path is available f them too --- the same as the freewheeling path of the main inductor.

- However, certain other trace inductances do not have any freewheeling path, ar will therefore "complain" --- in the form of voltage spikes across the board, as pe the basic equation V=LdI/dt. These traces are considered "high-frequency" or "critical traces" from the viewpoint of PCB layout, and their associated inductances are considered to be "uncoupled" or "leakage" inductances.

nect small RF-bypass capacitors across

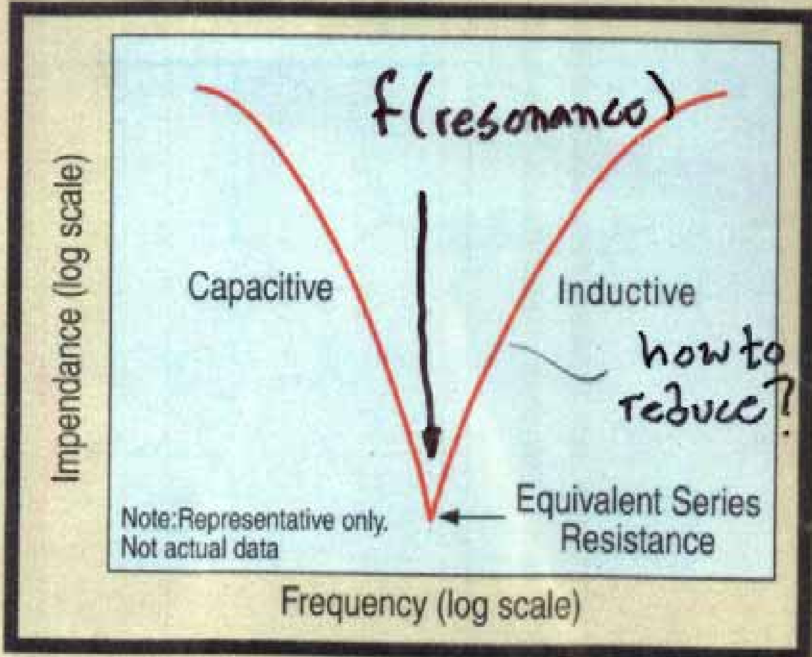
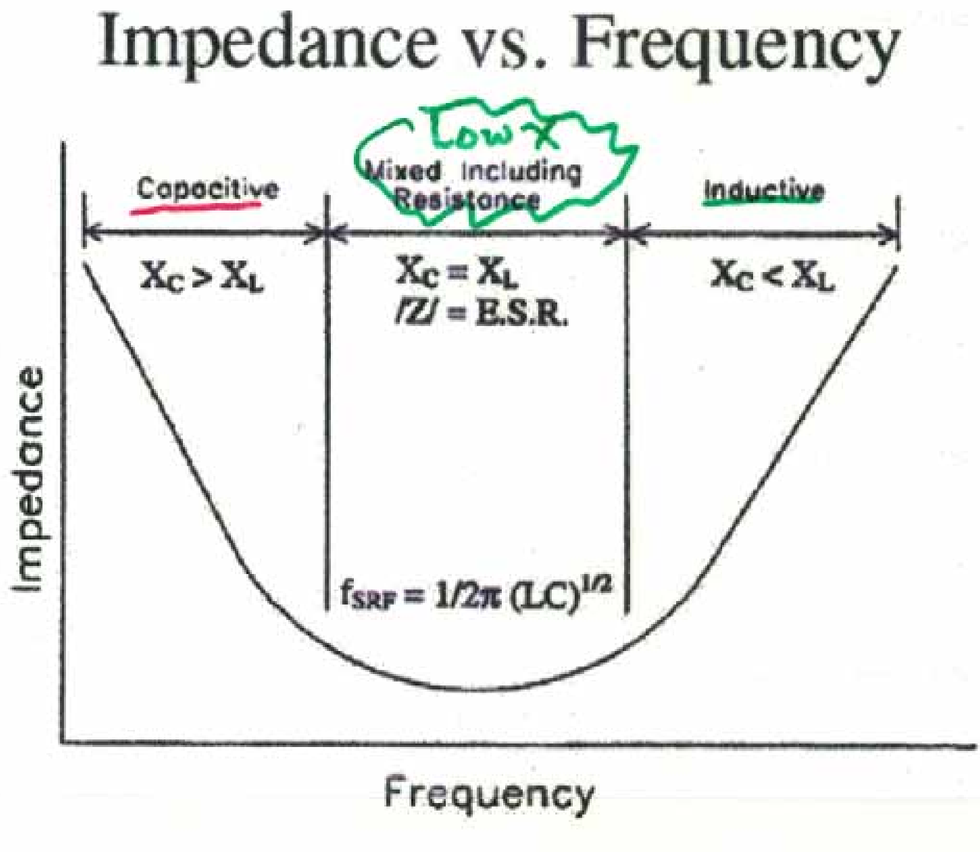


Fig. 3. *As frequency increases, the parasitic inductance of a capacitor becomes dominant.*

Following graph illustrates how characteristic of some capacitors vary ove frequency.



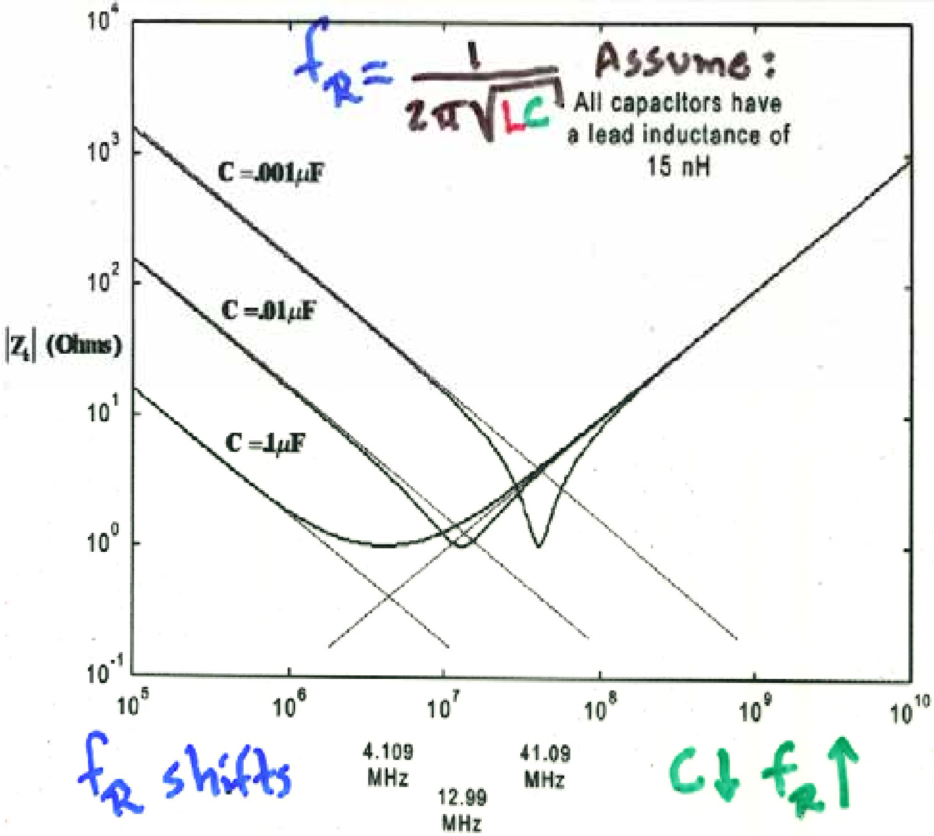


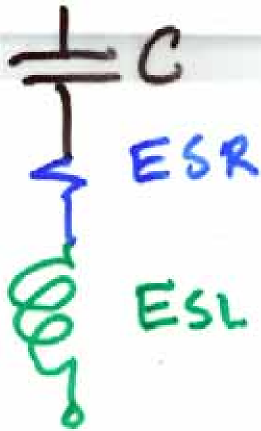
Figure 16: Plot of frequency dependent behavior of equivalent circuit for various capacitors.

ESR
R(f)

Capacitance vs Frequency

The sheet resistance of the conductive plates of the capacitor and the wires that link these conductive plates to the terminals of the capacitors lead to a parasitic resistance that is called the ESR (Equivalent Series Resistance). The termination loop of the terminal wires also lead to a small and often negligible parasitic inductance called the ESL (Equivalent Series Inductance). Thus, the total impedance of a capacitor varies over the frequency at which it is used.

ESL small but
$\sim \frac{di}{dt} \uparrow$ as $f \uparrow$



achieved in the last 10 years. With tantalum, the main ripple component comes from ESR.

Vin = +5V	L = 8µH (10µH nom)	F = 650 kHz
Vout = +1.8V	ton = 0.7µs	ΔIL = 0.24A
Iout = 600mA	toff = 0.9µs	Ipeak = 0.72A

Nominal C	Minimum C	Dielectric	ΔVc	ΔVesr	ΔVesl	ΔVout
			$\Delta I_L/8Cf$	$ESR*\Delta I_L$	$ESL*\Delta I_L*(1/ton+1/toff)$	Graphic estimation
10µF	7µF	MK	6.5mV	2.6mV	0.4mV	≈ 8mV
22µF	16µF	MK	2.8mV	1.9mV	0.7mV	≈ 5mV
47µF	34µF	MK	1.4mV	1.4mV	0.7mV	≈ 3mV
33µF	27µF	TPA	1.7mV	17.7mV	3mV	≈ 20mV

Table 3. *Ripple characteristics of output capacitor in a step-down converter.*

Real $V_c(f)$

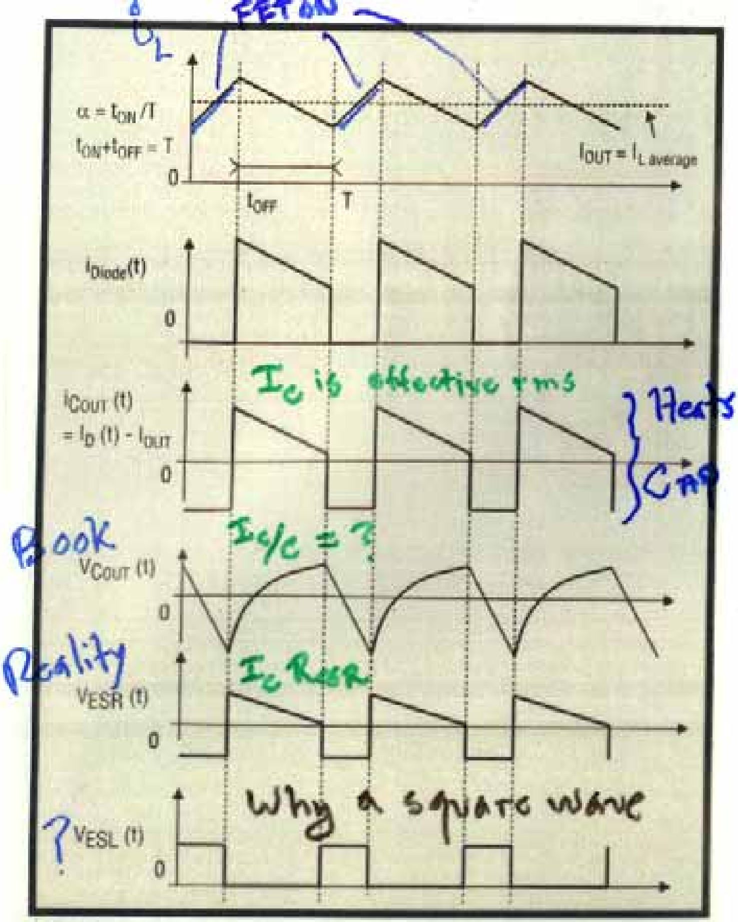


Fig. 5. *Currents in the inductor and tank capacitor (Cout) of a step-up converter.*

- Several factors affect the ESR:
  - Thickness and material of the electrodes
  - Area and aspect ratio of the electrodes
  - Number of layers and parallel termination that form the electrodes
  - Electrode surface flatness and metallization density
  - Distributed resistance of the dielectric
  - Frequency of operation

Below is a plot of ESR for various capacitors. Note that the ESR for ceramics can be as small as 1% of that of the Tantalum capacitors.

$$ESR(\text{ceramic}) \sim \frac{1}{100} ESR(\text{Ta})$$

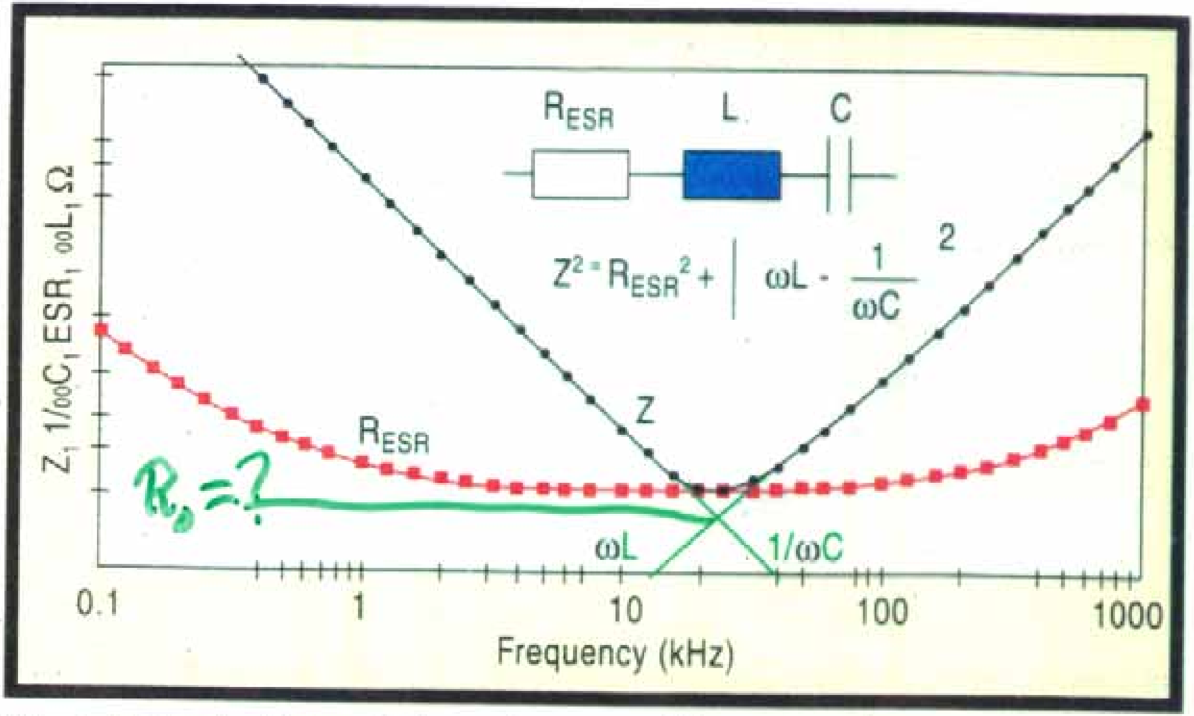
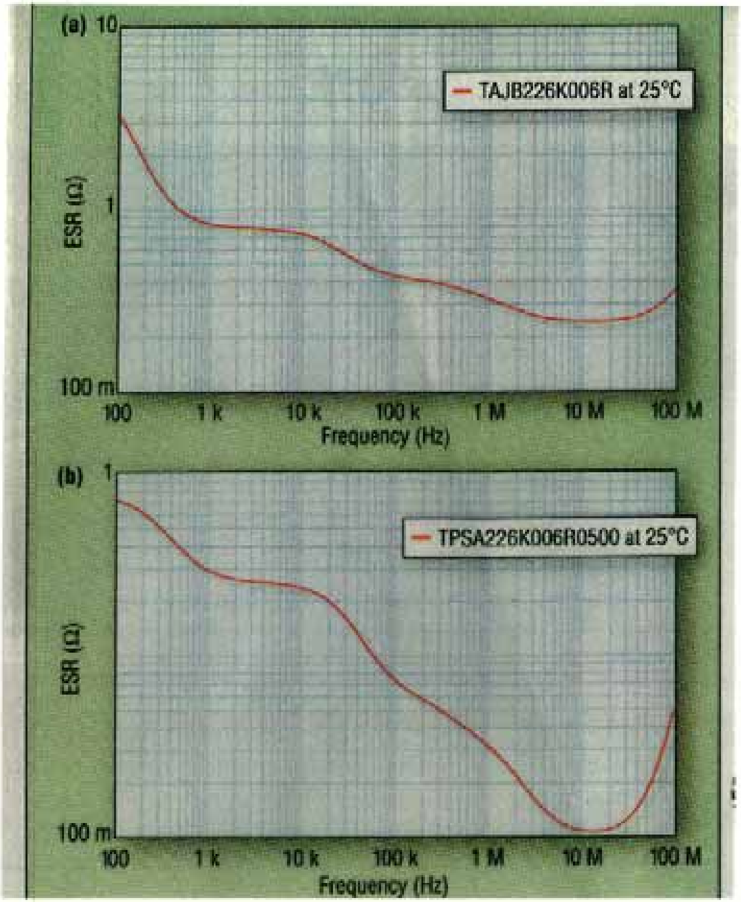


Fig. 5. *Equivalent circuit, impedance and frequency dependence of bulk capacitors.*

$$R_0 = \sqrt{\frac{L}{C}} = X_C(f_R) = X_L(f_R)$$



(a)
TAJB226K006R at 25°C
ESR (Ω)
10
1
100 m
100
1 k
10 k
100 k
1 M
10 M
100 M
Frequency (Hz)
(b)
TPSA226K006R0500 at 25°C
ESR (Ω)
1
100 m
100
1 k
10 k
100 k
1 M
10 M
100 M
Frequency (Hz)

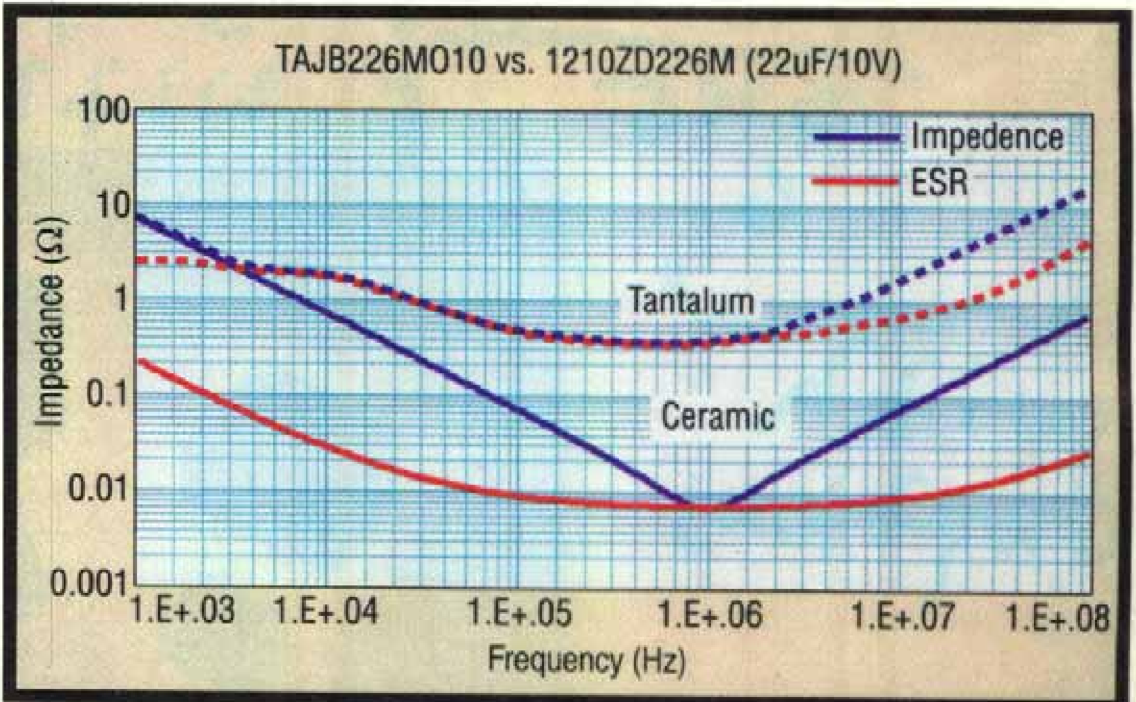


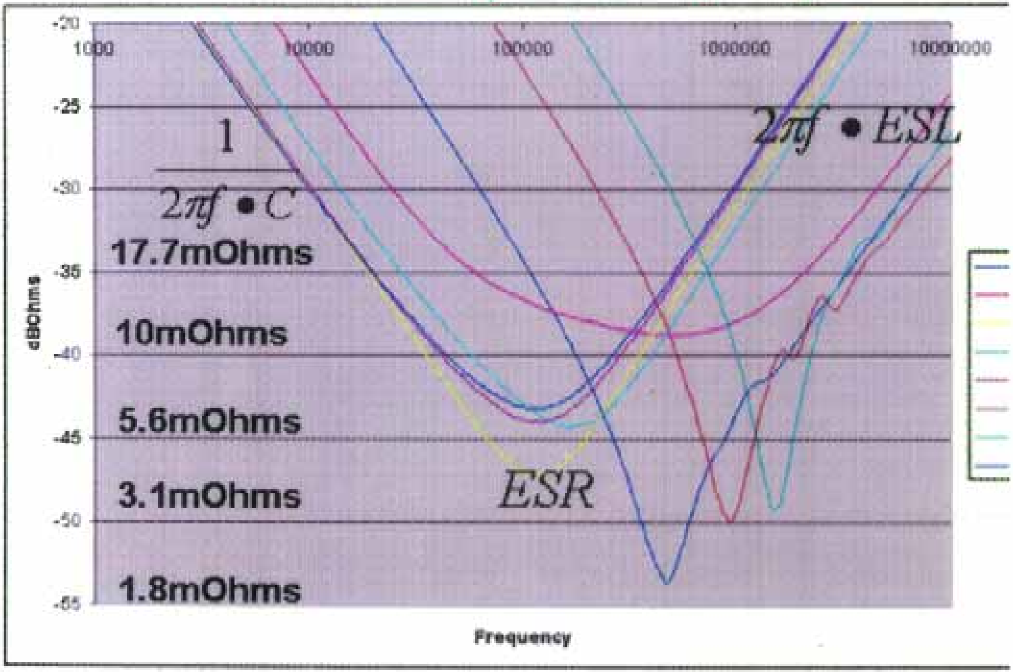
Fig. 1. *Impedance versus frequency*.

ESR

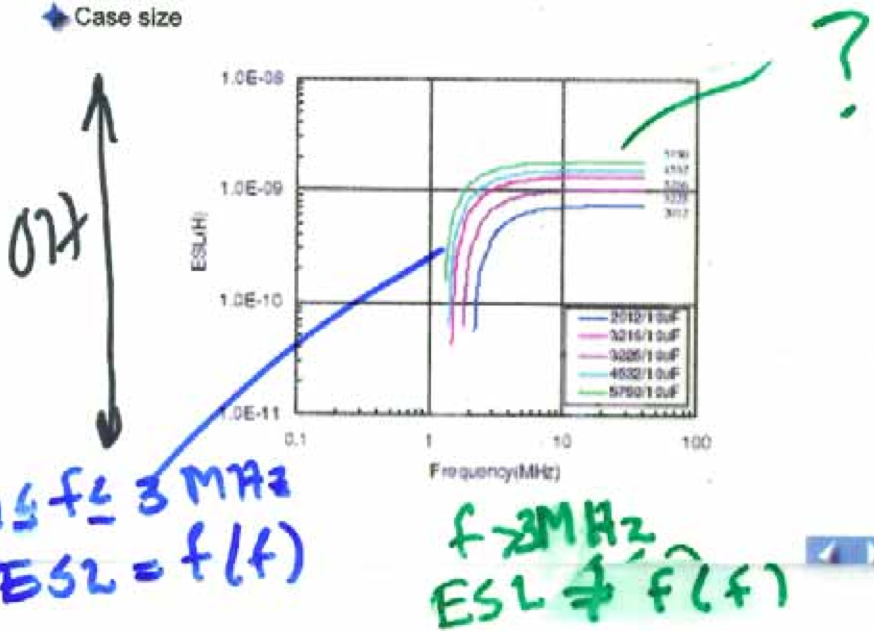
Technology	Capacitance Range (µF)	V_R Range (V)	ESR(min) (Ω)	Leakage nA × µF × V	Temperature Range (°C)
Standard MnO_2	0.1 to 1000	4 to 50		10	-55 to +125
Low-ESR MnO_2	3.3 to 1000	4 to 50	0.1	10	-55 to +125
Standard 3f Multianode	330 to 1000	4 to 50	0.03	10	-55 to +125
Polymer	150 to 470	2.5 to 10	0.035	100	-55 to +105
Polymer Multianode	470 to 1000	2.5 to 6.3	0.01	100	-55 to +105

Capacitor characteristics.

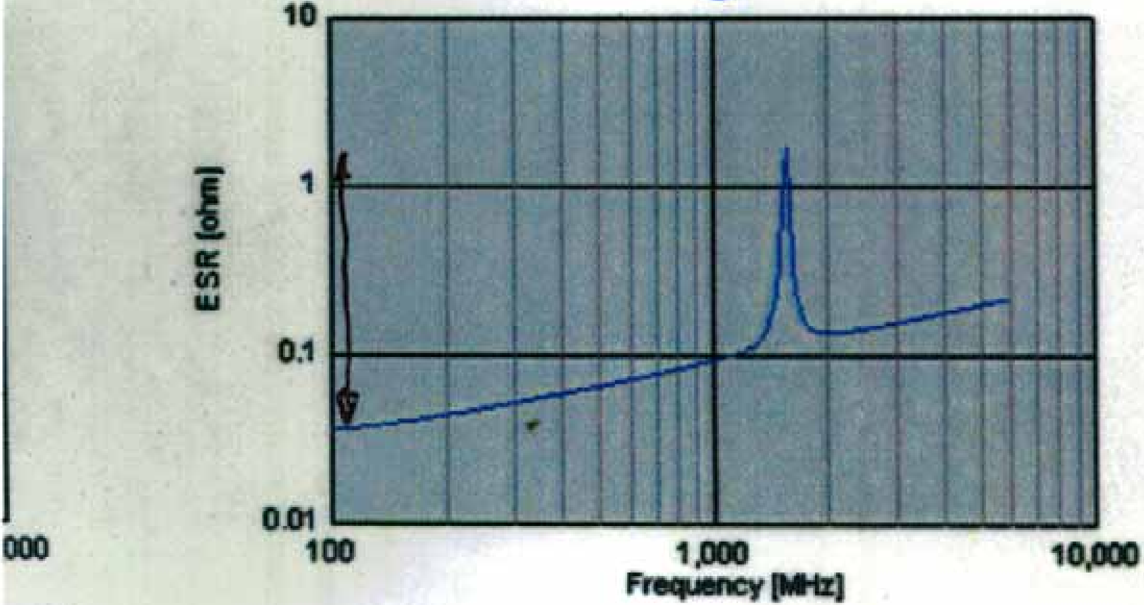
Various C all show ESL, ESR, f_R



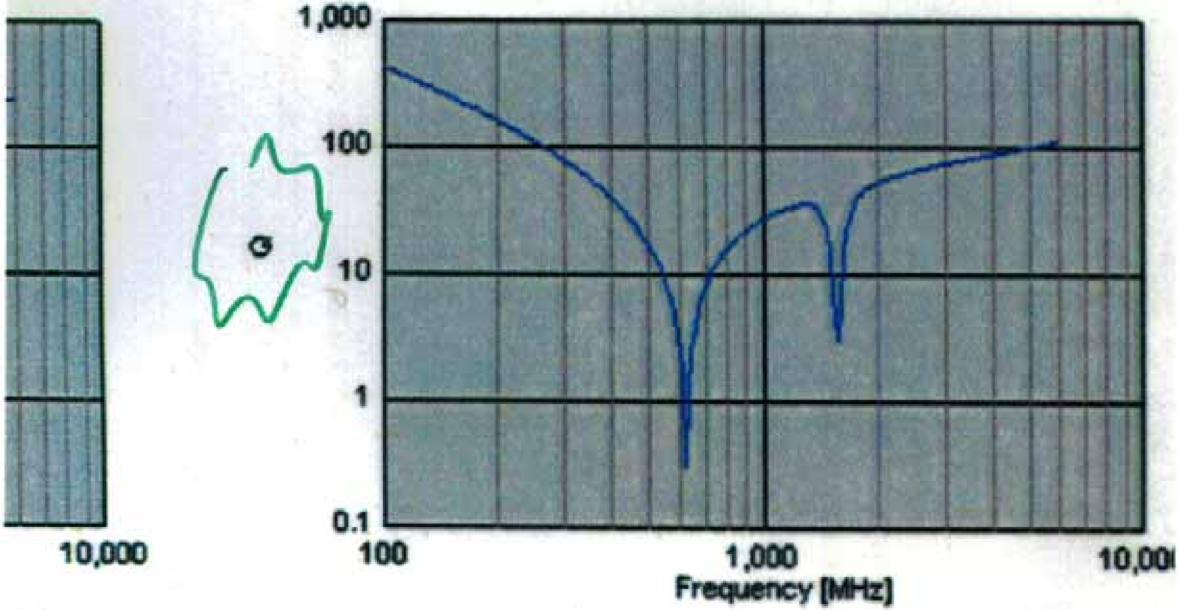
- Area and aspect ratio of the electrodes
- Number of layers and parallel termination that form the electrodes
- Cover layer thickness
- Case size



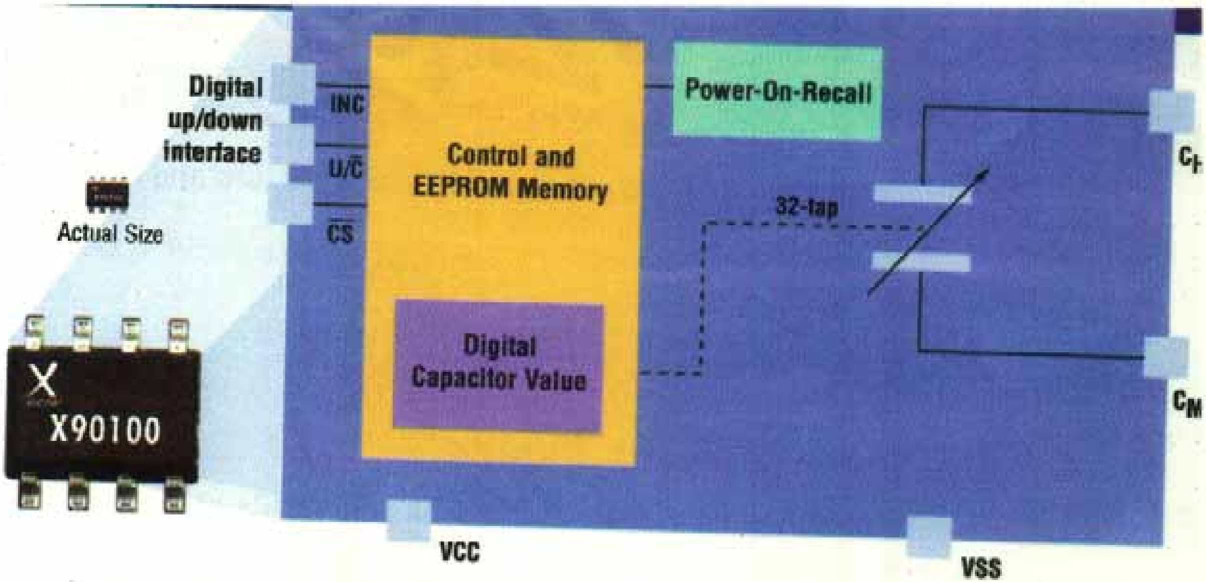
Why ESR peaks



(c)



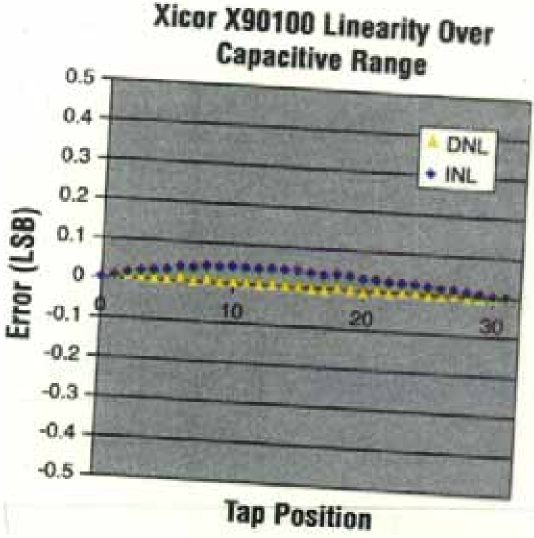
(b)



X90100 Replaces variable capacitors used to tune the frequency response of electronic systems up to 400MHz

Features

- 32-tap Digital capacitor
- Non-volatile EEPROM Storage of capacitor value with Power-On-Recall
- Fast setting time of 5µsec
- Excellent Linearity
- Simple Digital interface to program & store
- X90100M8I: $0.99 each in 10k units



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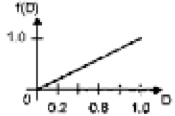
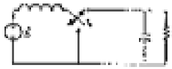
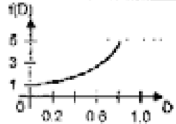
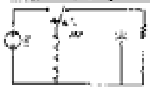
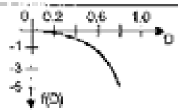
Milpitas, CA 95035-7493
Call: (408) 432-8888

L2

SIMPLE SWITCH MODE CONVERTERS

 BUCK The buck is limited in that $V_{out} < V_{in}$ only		$V_L = V_o$ or $V_{DC} - V_o$ •f(D)=D •Never get negative output •$V_o(min) = 0$
 BOOST The boost is limited in that $V_{out} > V_{in}$ only		•f(D)=1/(1-D) •Never get zero output: $V_o(min) \neq 0$ $V_L = V_{DC} - V_o$ or V_o
 BUCK-BOOST The buck-boost is limited to negative voltages		•f(D)=-D/(1-D) •Inverting output w.r.t. V_g $V_L = V_o = -V_{DC}$ for D = ½

4. UNSYMMETRIC i_L AND v_C WAVEFORMS OF EQUAL INTEGRATED AREA IN THE ABOVE THREE CONVERTERS

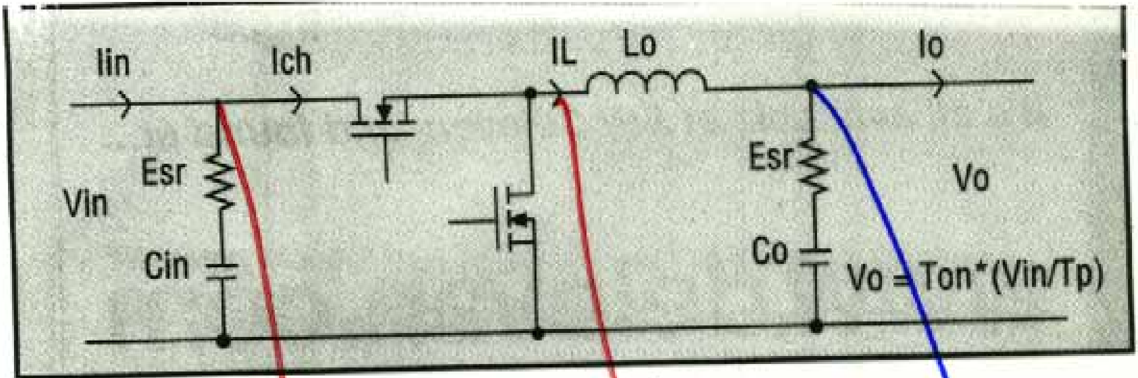


Fig. 1. *Conventional buck converter topology.*

The shunt transistor remains on during the time pe-

V_{peak}^{IN}

I_{peak}

V_{peak}^{out}

IGBT, FET Choice
Thyristor

C_{IN} Choice

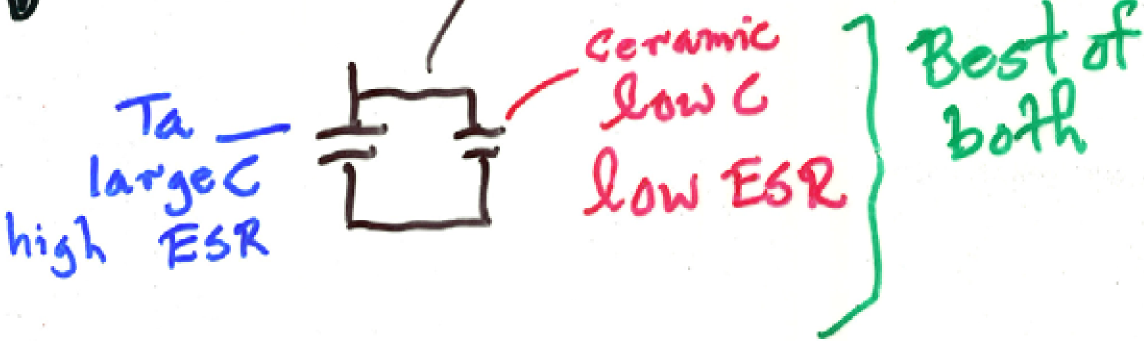
C_{out} Choice

Decoupling is a DUAL requirement!

In general, the decoupling requirements at the input of a power converter should be visualized as dual requirements:

- Decoupling for the **power stage** (buck and buck-boost in particular).

- *Irrespective of the topology*, the **IC control sections** (and switch drivers --- which also draw spikes of current to drive the Mosfet switch), need good input decoupling t prevent noise from infiltrating the IC and causing malfunction. This is usually provide by ceramic capacitors placed very close to the IC --- **right next to the supply and ground pins of the IC.**



Decoupling and the SIMPLE SWITCHER family

For example:

- In a buck converter driving a Mosfet, we need a large "bulk capacitor" (e.g. a low-grade Aluminum Electrolytic) in parallel to a low-ESR ceramic.

- In a buck converter driving a BJT, we can usually get away with a single low-grad bulk cap close to the IC (no ceramic).

The third generation SIMPLE SWITCHER (buck) family (LM267x) uses a (high-speed) MOSFET as the switch. Therefore, because of the high crossover speed (typically 30ns), the noise is relatively worse (more *"customer complaints"* too!). ***We therefore always need a 0.1uF to 0.47uF capacitor right next to the pin of the IC.*** This component is in fact the most important component in the entire PCB layout (the second being the diode, which has to be very close too, to reduce the trace length from SW pin to switching node). In fact, customers have reported anomalous behavior even if the ceramic decoupling capacitor was very close, but on the other side of the PCB --- i.e. the intervening vias apparently ha enough stray inductance to cause the IC to malfunction, especially under abnormal situations like overloads and output shorts.

The second generation SIMPLE SWITCHER (buck) ICs (LM259x) use a BJT switch , so we can usually combine the input decoupling requirements of the power stage and IC into one single low-grade (e.g. aluminum electrolytic) bulk capacitor. It seems that not only this particular series of ICs has a higher level o

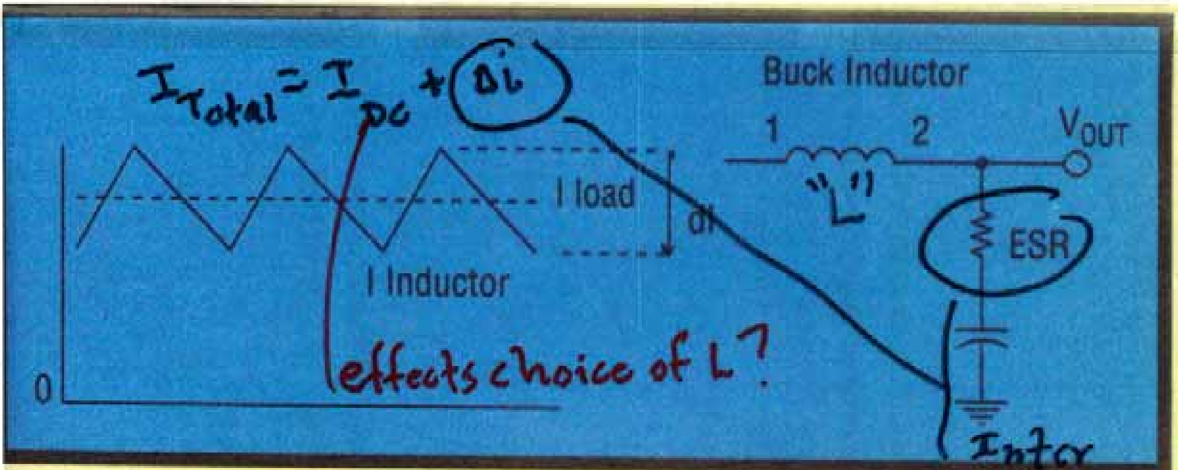


Fig. 1. *Inductor ripple current and Buck output circuit.* Related

① "L" is doing energy storage $E = \frac{1}{2} L i^2$

② "L" sets Δi (ripple) into Cout : Chapter 2

$\Delta V_{out} \approx \Delta i \, R(ESR)$ } want 1–50mV

L (chosen) by $\geq \frac{V_{in}(max) \, dt (\approx 1/f_{sw})}{\Delta i (ripple)}$ ← customer spec

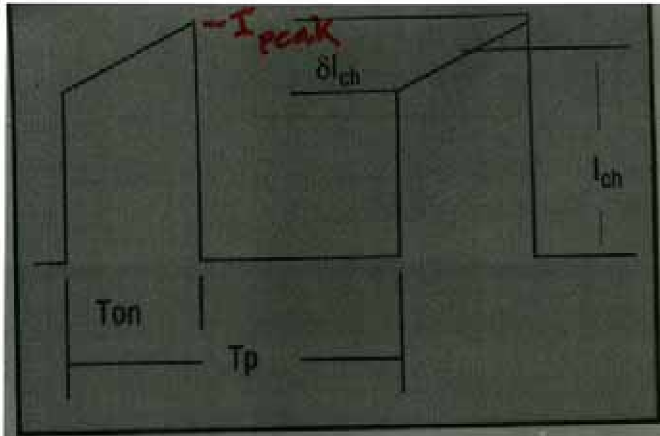


Fig. 2. *Input pulse current.*

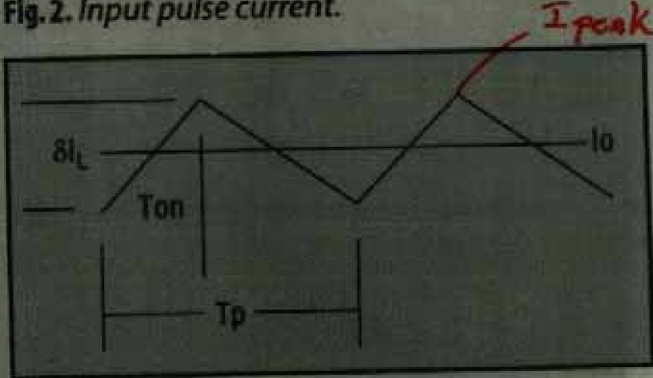
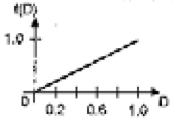
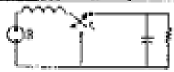
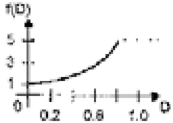
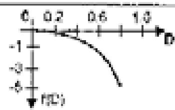


Fig. 3. *Output inductor ripple current.*

wer distribution system, this current

L2

SIMPLE SWITCH MODE CONVERTERS

 BUCK The buck is limited in that $V_{out} < V_{in}$ only		$V_L = V_o$ or $V_{DC} - V_o$ •$f(D) = D$ •Never get negative output •$V_o(min) = 0$
 BOOST The boost is limited in that $V_{out} > V_{in}$ only		•$f(D) = 1/(1-D)$ •Never get zero output: $V_o(min) \neq 0$ $V_L = V_{DC} - V_o$ or V_o
 BUCK-BOOST The buck-boost is limited to negative voltages		•$f(D) = -D/(1-D)$ •Inverting output w.r.t. V_s $V_L = V_o = -V_{DC}$ for $D = ½$

4. UNSYMMETRIC i_L AND v_C WAVEFORMS OF EQUAL INTEGRATED AREA IN THE ABOVE THREE CONVERTERS

We thus conclude

:

- A buck converter draws spikes of input current (i.e. with sharp edges). That produces a high dI/dt --- and therefore lots of noise originating at the input.
- Same for the buck-boost.
- The only exception is the boost, in which the input is in series with the inductor, and therefore the input current waveform is a slowly rising and falling ramp (no "sharp edges"). This makes *the boost topology reasonably insensitive to input decoupling (no significant dI/dt on input side).*

Therefore, **providing effective input decoupling (for the power stage) is a very important goal of good PCB layout --- *especially for the Buck and the Buck-Boost*** .

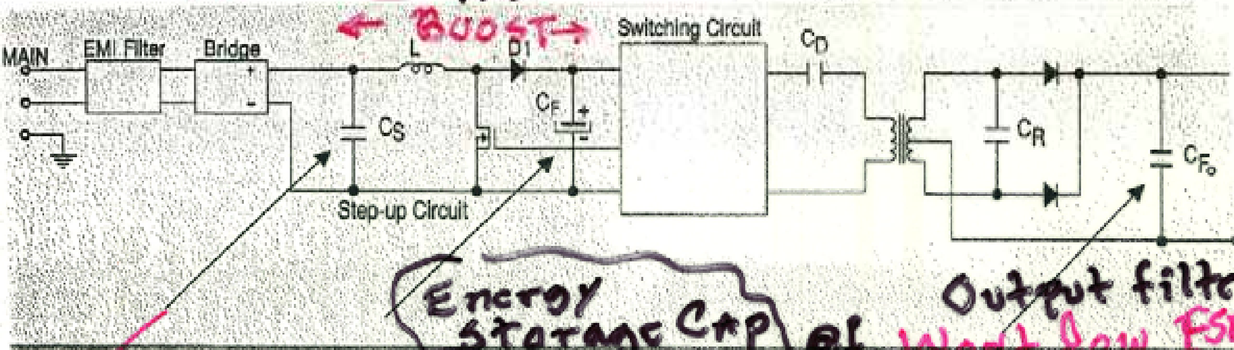
OH

"Lytics" for $f < 100$ KHz

Why? Al_2O_3 ↕ $d = 1000$ Å $\Rightarrow C = \frac{\epsilon A}{d}$

Al

← BOOST →



Capacitors in switchmode power supply.

Energy Storage Cap

Output filter @ f_{sw} Want low ESR to avoid $\Delta I_c R_{ESR}$
Not too low or oscillation occurs

largest C ("lytic")
- filter mains to acceptable DC
- Handle V_{ac} sag / surge
- I_{sw} shunt

} Very low ESR, ESL ← i_{stress} high

EIA Class 2 TCC Designations

First Character: Defines the low temperature limit.

X = -55 °C   Y = -30 °C   Z = +10 °C

Second Character: Defines the high temperature limit.

5 = +85 °C   7 = +125 °C

Third Character: Defines the maximum capacitance change in percentage.

V = +22, -82%	R = ±15%
U = +22, -56%	P = ±10%
T = +22, -33%	F = ±7.5%
S = +22%	E = ±4.7%

Snubbers

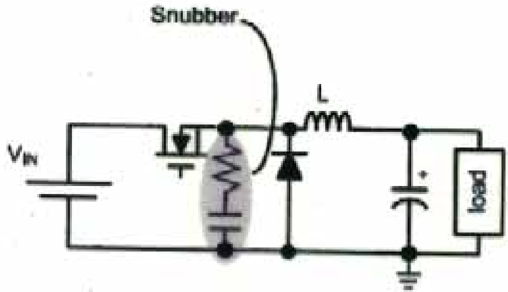
A small RC snubber from Switch Node to Ground helps as shown below

Typical Values:
C=470pF to 4.7nF
R=10 ohms to 100 ohms

Dissipation in resistor is:

$C \times V^2 \times fsw$

where fsw is the switching frequency and V is the voltage that appears across the capacitor when charged up (equal to V_{INMAX})



Buck regulator

What do you get?

ck-
ra-
ent
ci-
as
ip-
ice
he
is
ic-
bit
os

ent
he
is-
of
ic-
ro-
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ise
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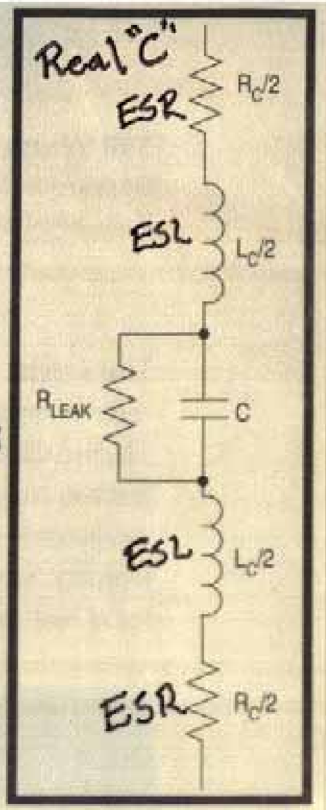


Fig. 2. *Actual capacitors have parasitic inductance and resistance.*

low f

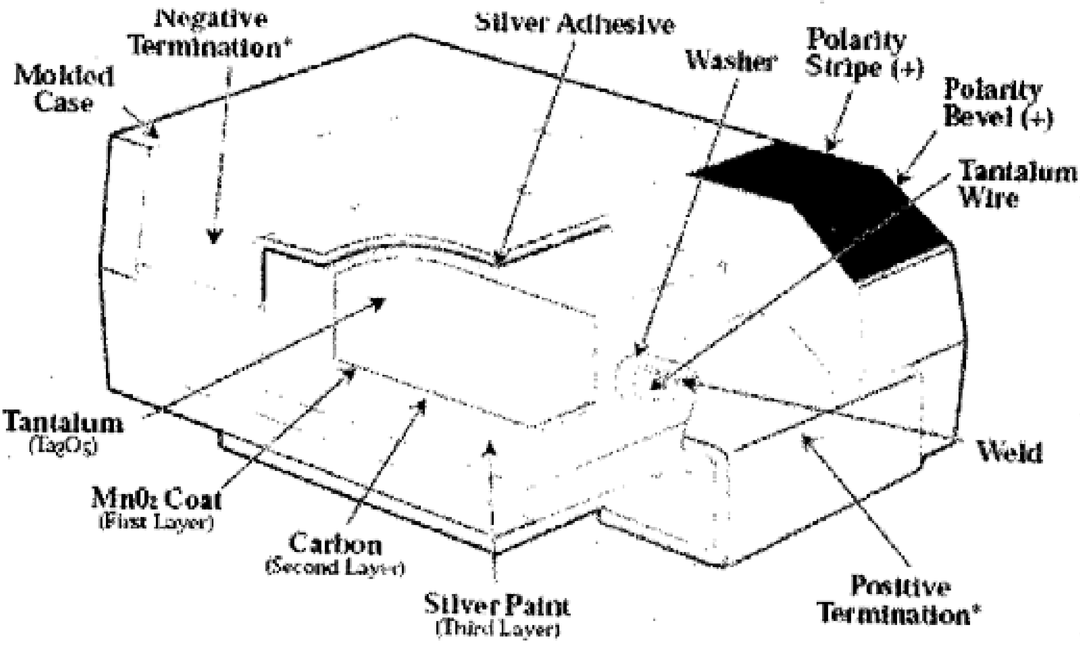
rent is linear and equal to ΔIL/ton:

$$Vesl1\ (0 < t < ton) = ESL * \frac{\Delta I}{ton}$$

Vin = +5V	L = 8µH (10µH nom)	F = 650 kHz
Vout = +1.8V	ton = 0.9µs	ΔIL = 0.24A
Iout = 600mA	toff = 0.7µs	Ipeak = 0.72A

Nominal C	Minimum C	Dielectric	ΔVc	ΔVesr	ΔVesl	ΔVout
			Iout*toff/C	ESR *(Iout+ΔIL/2)	ESL *ΔI_L/ton	Graphic estimation
10µF	7µF	MK	77mV	7.9mV	0.2mV	≈80mV
22µF	16µF	MK	33.8mV	5.8mV	0.4mV	≈36mV
47µF	34µF	MK	15.9mV	4.3mV	0.4mV	≈18mV
33µF	27µF	TPA	20mV	54mV	1.7mV	≈75mV

Table 5. *Ripple characteristics of input capacitor in a step-down converter.*



*Termination Solder Coating 90 Sn/10Pb