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How To Improve The Efficiency of Your Switching Power Supply Design

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In spite of early design and application problems, the Switching Power Supply (SPS) is making rapid gains in popularity because of its inherent high efficiency. The SPS has already become a significant factor in the power supply technology, and its increasingly widespread usage is anticipated.

The basic operation of the SPS is illustrated in **FIG. 5**. The switching rate of the SPS will usually be between 20 and 60 KHz, often a square wave. **FIG. 5** identifies two "switching" rate filters, one at the input side of the switch and the other at the system output. The input filter serves two purposes:

- Provides EMI protection back into the line [generated by switch].
- Serves as a quasi-constant current source [turn-on] for switch.

The output filter provides DC rectification and EMI protection into the load.

Design practice in the past has been to select electrolytic capacitors for these filters. But because electrolytics have relatively high E.S.R. values, it has been common practice to parallel these capacitors to reduce the E.S.R., resulting in a high effective capacitance value. Since ripple voltages are a result of both the E.S.R. and capacitive reactance impedances, at the operation frequencies, designers have tended to relate ripple voltage magnitudes primarily with E.S.R. magnitudes. New capacitor dielectrics and technologies now offer capacitor types having significantly greater efficiency and reliability. Because of these new technologies, it is possible to use less effective capacitance and still maintain very low E.S.R. values.

CAPACITOR DESIGN CONSIDERATIONS

Capacitance reactance (X_C) is dependent on both capacitance (C) and frequency (f), as follows:

$$X_C = \frac{1}{w\,C}$$

where $w = 2\pi f$. As the equation shows, X_C is a linear decreasing function of both C and f. The physical capacitor used in a circuit, however, is not pure capacitance reactance (X_C); some component of both resistance (R) and inductive reactance (X_L) is also present. **FIG. 1** is a schematic diagram of a capacitor (any type) used in an AC (or pulse) application.

The magnitudes of the resistive and inductive components, ESR and ESL, are primarily a function of the capacitor dielectric and secondarily a function of the manufacturing processes. From those viewpoints, the plastic film capacitor offers a distinct advantage over the electrolytic capacitor, as discussed below.

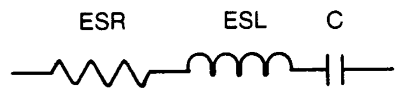
Impedance

FIG. 2 portrays impedance (Z) curves of electrolytic and plastic film capacitors. Remembering that

$$Z = \sqrt{R^2 + (X_C - X_L)^2}$$

where R = ESR, and X_C and X_L are as defined above; and that the resonant frequency (f_r) occurs when $X_C = X_L$, it can be seen that while the shape of the impedance curves of the two dielectrics are similar, the plastic dielectric has a lower Z [E.S.R.] at resonance (points 3 and 4) in **FIG. 2**.

E.S.R. is pure resistive, and it is this component that directly controls the I^2R losses of the capacitor. Typically the electrolytic E.S.R. runs in the hundred of milliohms, whereas the ASC plastic runs less than 10 milliohms, with larger cap values being less than 1 milliohm. (see **FIG. 6**)



where; C = physical capacitor
ESR = equivalent series resistance contained in C
ESL = equivalent series inductance contained in C

FIGURE 1
EQUIVALENT CIRCUIT OF CAPACITOR USED IN AC (OR PULSE) APPLICATION

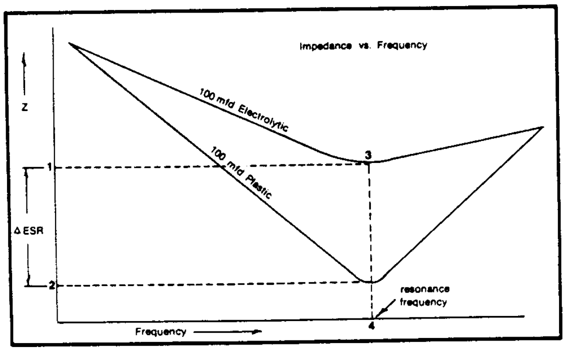


FIGURE 2.
TYPICAL CAPACITOR IMPEDANCE CURVES

Capacitance vs. Frequency

Another interesting comparison of plastic versus electrolytic capacitors is capacitance vs. frequency. Note from **FIG. 3** that electrolytics decrease in capacitance with increasing frequency, some by as much 80%, others by as little as 10%, at switching rate frequencies. Most plastics evidence no capacitance change at similar frequencies. This means that if a plastic capacitor is used, then a smaller capacitance value can be applied, and this can usually be accomplished with little or no increase in the physical size of the capacitor (plastic vs. some electrolytics).

E.S.R. vs. Temperature

E.S.R. is inversely proportional to temperature in electrolytics, usually by a factor of more than 100% at -40°C [referenced to 25°C]. Use of electrolytics in cold environments requires the designer to examine the application very closely to assure adequate and reliable operation. The E.S.R. of plastic capacitors at cold temperature will not increase more than 10%, typically less than 5%.

Weight

Weight comparisons between plastics and electrolytics are as follows:

Plastics:
- Typically 16 grams in^3
- Will not exceed 20 grams in^3

Electrolytics:
- Typically 26 grams in^3

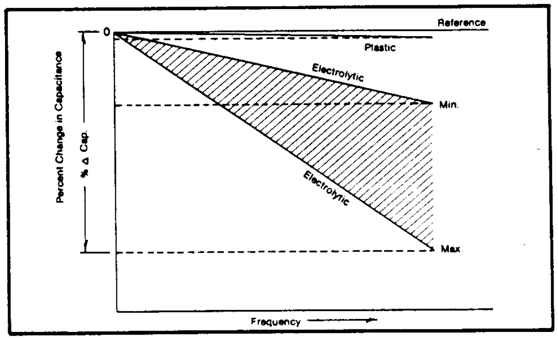


FIGURE 3
CAPACITANCE VS. FREQUENCY

Summary

COMPARATIVE PROPERTIES OF ELECTROLYTIC AND PLASTIC CAPACITORS.

TABLE 1

Parameter	Electrolytic	Plastic	Remarks
ESR	Higher than plastics (0.15 typ)	Very low (0.0005 typ)	High ESR results in power wasted (low efficiency) and heat generated.

ESL	Same	Same	Operating above f_r tends to introduce noise into the system.
Capacitance	Some derease with frequency	Very stable with frequency	Can use lower capacitance value than electrolytics.
Physical	Many contain fluids	Dry	Plastics will not evidence any liquid leakage.
Packaging	Usually round	Available round or flat	Plastics more versitile for special packaging requirements.
Cold Temperature	E.S.R. increase	Not effected	Plastic is better for cold temperature applications.

FILTER DESIGN CONSIDERATIONS

Normally used in filter designs are single-section choke input filters, as illustrated in **FIG. 5**.

In an output filter, **FIG. 4b,** C_2 is made as large as possible to reduce ripple. C_2 is usually an electrolytic capacitor with a capacitance greater than 250 microfarads. Where some degree of ripple can be allowed, this electrolytic could be replaced by a 20 or 40 microfarad plastic capacitor at some small sacrifice in size but with larger advantages in efficiency and reliability.

As shown in **FIGS. 4a and 4b,** C_1 should be packaged as close to the switch and load as possible, and must exhibit the absolute minimum E.S.R. Usually a 2 to 8 microfarad plastic will out perform the equivalent electrolytic capacitor.

While the selections of the L and C values are not exact sciences, with some trial and test usually advised, **TABLE 2** demonstrates how the theoretical values of L and C are influenced by the operating frequencies.

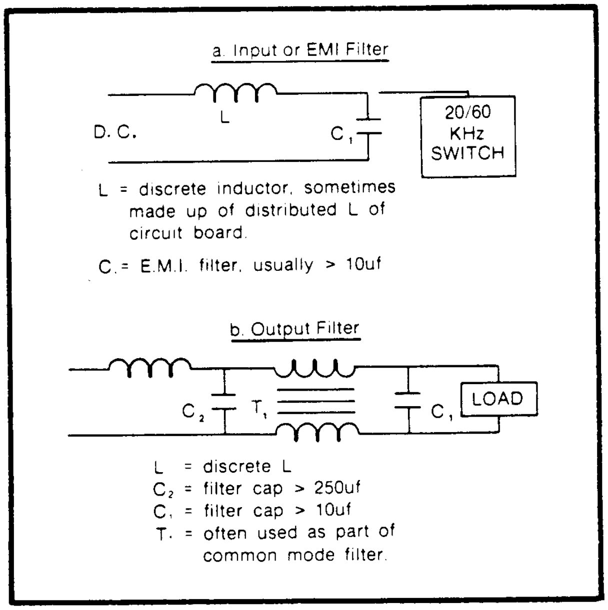


FIGURE 4
FILTER DESIGN

	Frequency (f^1)		
	60Hz	20KHz	50KHz
Case 1: $X_C <= \frac{Z_L}{5}$			
$C >= \frac{296000}{(f_1)(Z_L)}$	494 uf	2 uf	1 ufd
$L >= \frac{127000}{(f_1)^2 C}$	70 mh	159 uh	50 uh
Case 2: $X_C <<= Z_L @ f_1$			
$C >= \frac{159000}{(f_1)(Z_L)}$	265 uf	1 uf	1 uf
$L >= \frac{127000}{(f_1)^2 C}$	130 mh	318 uh	50 uh

Notes: (1) Z_L assumed to be 10 ohms, c in ufd, L in uhenry.
(2) See **Electronic Designers Handbook**, Landee, Davis & Albrecht, McGraw Hill, 1957, pp 15-2 through 15-20.
(3) All L and C values rounded to next highest integer.

TABLE 2.
FILTER DESIGN VS. OPERATING FREQUENCY

The L and C values shown in **Table 2** are the minimum values required for a load impedance of 10 ohms. Higher load impedances naturally will reduce the computed values of L and C. Good design practices, however, have usually dictated L and C values of something greater than the minimum calculated. Obviously, higher values of C will reduce the ripple and possibly ease the regulator design limits, and higher values of L will reduce EMI energies back into the line (or DC bus). An article in **Solid State Power Conversion**, May/June 1975, "Simplifying the Switching Regulator Input Filter" (D. Silbur), suggests a simplified technique for selecting L and C based on EMI prevention criteria.

The above guidelines, together with a conservative design philosophy, seem to suggest minimum values of C, of 4 uf for 20 KHz, and 2 uf for 50 KHz operation - remembering, however, that each power supply design is separate and unique, and what may be suitable for one may not be suitable for another.

Another important design consideration is the current carrying capacity of the filter capacitors. Most electrolytics are limited to less than 1 amp, (some types of electrolytics greater than 100 mfd. can approach 2.5 amps), thus common design practice is to parallel electrolytics to increase the load current. Plastic capacitors are rated up to 9 amps ripple current, therefore paralleling caps is usually not required. The following comparison table, comparing a better grade of electrolytic with a ASC plastic, points out the differences in the I^2R losses, the current values selected represent the design limits of the electrolytic capacitors.

Recommended Capacitor Type

ASC Capacitors has developed a "metallized Polypropylene" capacitor ideally suited for high-frequency filter applications. The specification for these capacitors is shown in **TABLE 4.**

The capacitors can be operated at 100% of rated voltage, AC or DC or any combination thereof, provided that the AC + DC ≤ rated DC up to 105°C.

These devices contain no oil, impregnate, or electrolytic, and therefore there is no possibility of contaminating associated circuitry and PC boards due to "leaky" capacitors. The capacitor configuration is available in either round or flat pack, thereby providing the packaging engineer with options in his system packaging requirements.

Capacitance range:	Up to 20uf
Operating voltages	100 and 200 VDC or VAC
Operating temperature:	105°C
Maximum current:	9 amps up to 105°C
Series Inductance:	Less than 20 uh [½" Leads]
Resonant frequency:	1 mfd >.5 MHz
ΔC with frequency:	-1% maximum
Failure Rate:	0.01% maximum at rated voltage at 105°C
Case:	Wrap and fill; no oil, impregnates or electrolytics used.

TABLE 4
ELECTRICAL CHARACTRICS

ELECTROLYTIC				ASC PLASTIC	
Cap Value	I (Amps)	E.S.R @ 100 KHz (ohms)	I^2R (milliwatts)	E.S.R. @ 100 KHz (ohms)	I^2R (milliwatts)
4.7	.1	3	30	.00703	.07
6.8	.12	2.4	30	.004	.06
8.2	.15	1.8	40	.003	.06
27.0	.68	.4	180	.001	.05

TABLE 3
COMPARATIVE PROPERTIES

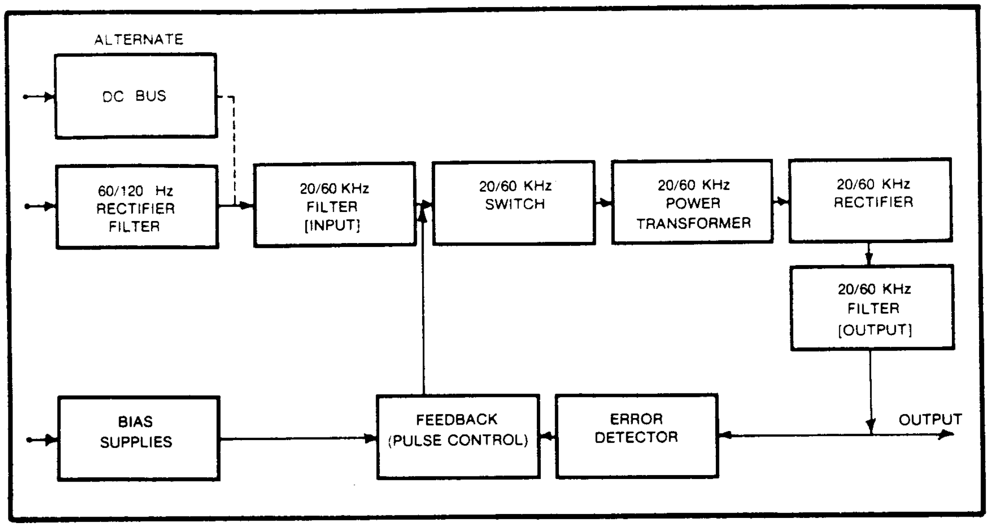


FIGURE 5.

TYPICAL 'SWITCHING' POWER SUPPLY BLOCK DIAGRAM

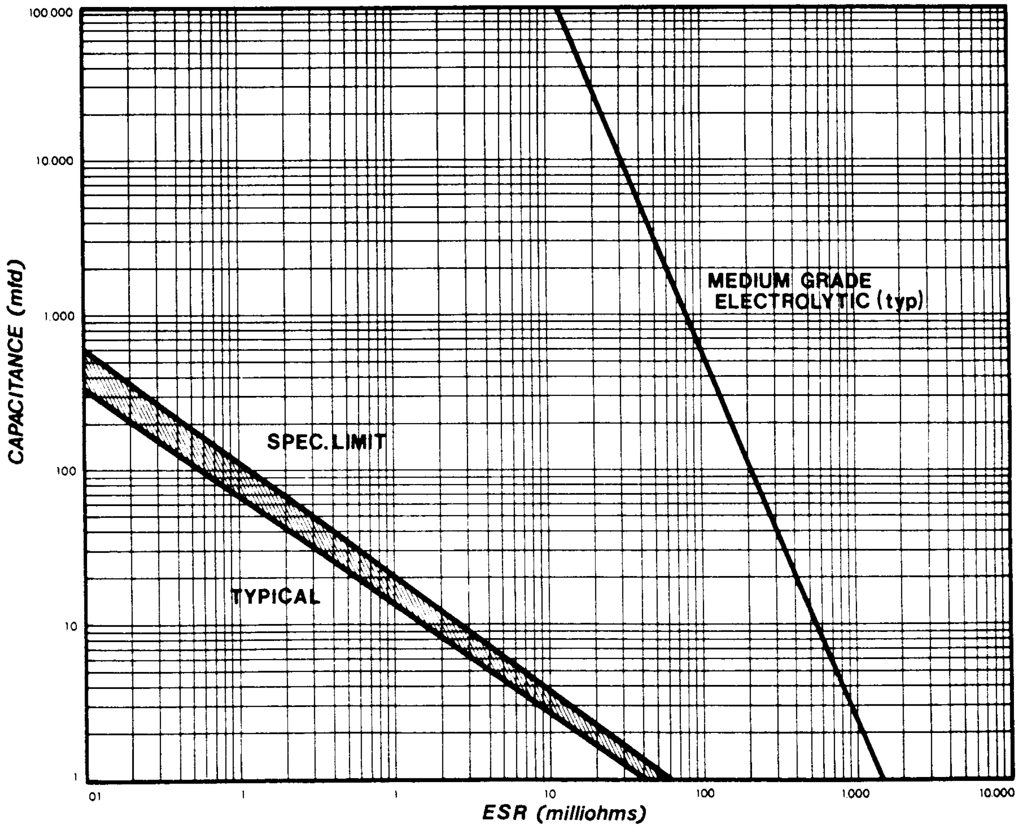


FIGURE 6.
PLASTIC VS. ELECTROLYTIC ESR LIMITS

DESIGN COMPARISONS OF PLASTIC VS. ELECTROLYTIC CAPACITORS

The design criteria for E.M.I. and Common Mode Rejection filters is usually single-fold; to develop the MINIMUM ripple voltage across the filter capacitor due to direct or reflected ripple currents. It follows then that the design analysis techniques of these filters would focus on the 'impedance' characteristics of the filter capacitor.

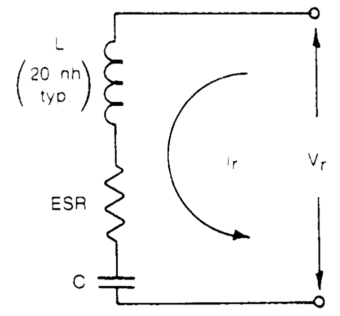
The magnitude of the ripple currents are a function of:

a) The specific SPS design, efficiency, and output power.
b) The load at any particular moment.
c) The switching rate frequencies and duty cycles.

A rigorous analysis of the filter circuits would require some analysis under nonsinusoidal waveforms. But since this analysis is looking at the apparent capabilities of the capacitors only, and is not addressing system comparisons, only sine voltages will be considered. The equivalent circuit of the filter capacitor is as shown in **FIG. 7.**

Assume, for this analysis, that the ripple current is 2 amp, and that the SPS is operating at either 20KHz or 40KHz. The following analysis, see **TABLE 5,** is for the fundamental frequencies only, and does not consider the influences of harmonics, which could be significant depending on the internal design of the SPS.

The following observations are made on the data shown in **TABLE 5:**



Where
L = Series inductance, body and leads
ESR = Series resistance
C = Ideal capacitance
i_r = Ripple currents (s)
V_r = Ripple voltage (s)
Z = Impedance = $ESR^2 + j(Xc + XL)^2$

FIGURE 7.
EQUIVALENT CIRCUIT, FILTER CAPACITOR

a) Z for plastics is considerably less, and phase angle remains a near constant -90° indicating absolute minimum ESR losses.
b) With a constant 2 amp ripple current the I^2R losses are orders of magnitude less for plastic capacitors.
c) With a constant 2 amp ripple current the ripple voltages for plastic capacitors is significantly less, particularly so if EMI requirements for the SPS are stringent. (As is usually the case).

In summary, in filter designs where capacitance values less than 50mfd are adequate for system performance, plastic dielectric capacitors offer impedance characteristics that can significantly enhance the overall system design.

		PLASTIC				ELECTROLYTIC			
f	Cap	(ohms) E.S.R.	(ohms) Z	(watts) I^2R	(mv.) Vr	(ohms) E.S.R.	(ohms) Z	(watts) I^2R	(mv.) Vr
20KHz	1	.06	7.98∠-90°	.24	15,960	1.5	8.12∠-80°	6	16,240
20KHz	5	.007	1.6 ∠-90°	.028	3,200	.72	1.75∠-66°	2.88	3,500
20KHz	10	.0018	.8 ∠-90°	.0072	1,600	.55	.97∠-55°	2.2	1,940
20KHz	20	.001	.4 ∠-90°	.004	800	4	.56∠-45°	1.6	1,120
20KHz	50	.0003	.16∠-90°	.0012	320	.28	.32∠-30°	1.12	640
40KHz	1	.06	3.98∠-89°	.24	7,960	1.5	4.25∠-69°	6	8,500
40KHz	5	.007	.8 ∠-89°	.028	1,600	72	1.07∠-48°	2.88	2,140
40KHz	10	.0018	.39∠-90°	.0072	780	.55	.68∠-36°	2.2	1,360
40KHz	20	.001	.19∠-90°	.004	380	.44	.44∠-26°	1.6	880
40KHz	50	.0003	.07∠-90°	.0012	140	.28	.29∠-14°	1.12	580

TABLE 5
CAPACITOR COMPARISONS PLASTIC VS. ELECTROLYTIC