TECHNICAL BULLETIN NO. 13

CAPACITORS FOR SWITCHING REGULATORS FILTERS

One of the most difficult tasks facing a designer of switching power supplies is the selection of the output filter capacitor. The design criteria for the magnitude of the filter capacitor are well established. Less than adequate capacitor data sheet information and a lack of understanding of the effect of higher frequencies on capacitor operation, however, often cause improper selection and misuse of capacitors in such applications.

For switching service, the correct specification for a capacitor will include the following:

1. Capacity and tolerance.
2. Maximum ambient temperature.
3. Switching frequency.
4. Maximum allowable Dissipation Factor (D.F.) at the switching frequency.
5. Peak current through capacitor.
6. Average D.C. voltage across capacitor.

The importance of correct specifications in proper capacitor selection can be seen by a short review of switching regulator characteristics. Consider the simplified circuit for a common type of regulator as shown in Figure 1.

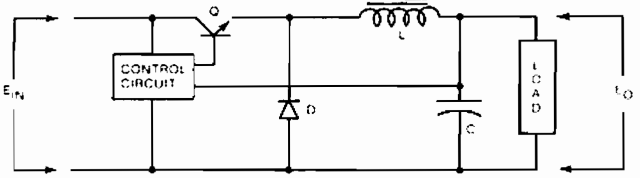


Figure 1

The Transistor (Q) is turned on and off at a fixed frequency (F), and the ratio of t_{on} to t_{off} time is determined by the control circuitry, in response to the sensed output voltage (E_O). During the time that Q is on, the input voltage (E_{IN}) is applied to the input of the LC filter causing I_L to increase, supplying current to the load and charging the capacitor (C). When Q is off, the energy stored in the inductor (L) and C, maintain the current flow via the recirculating diode (D). As the voltage begins to drop across the capacitor and load, the control circuit turns Q on again, repeating the cycle.

The output voltage will be:

$$E_O = (E_{IN})\ (t_{on}/T), \text{ where } T = 1/F$$

Figure 2 shows the wave forms for the voltages and currents associated with the circuit of Figure 1. For simplicity, voltage drops across the diode and transistor junctions are ignored. Figure 2a indicates the voltage at the input to the inductor, which is essentially the supply voltage, when transistor Q is on, and ground, when Q is off.

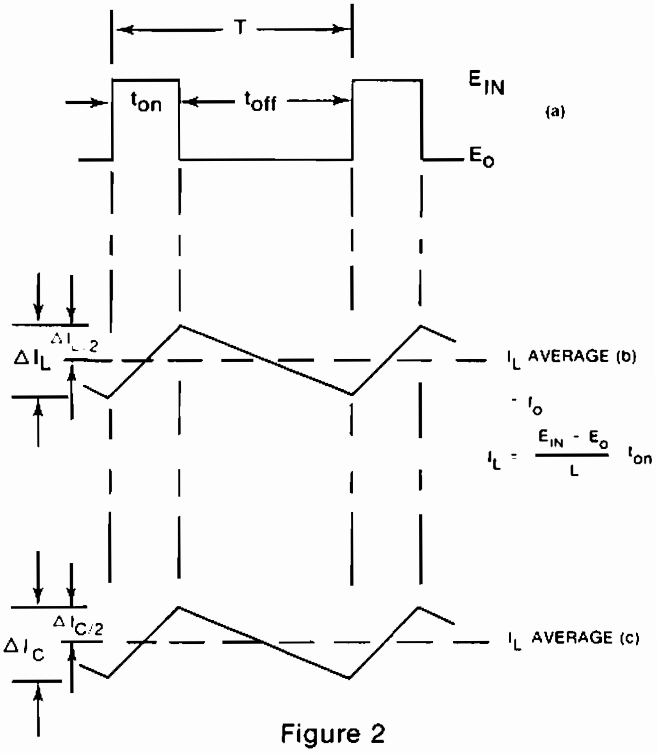


Figure 2

Figure 2b shows the current through the inductor. Under steady-state load conditions, the increase in current during t_{on}, $\Delta I_{L/2}$, must equal the decrease in current during t_{off}; the average value of the current (I_L) is equal to the load current (I_O).

Figure 2c shows the current through the capacitor. The current (I_O) to the load must be the sum of the current I_L and I_C. Therefore, at the time I_L equals the load current, there can be no current in or out of the capacitor and I_C = O. At the end of the t_{on}, the inductor current exceeds the load current by $\Delta I_{L/2}$. This excess current charges the capacitor. At the start of the t_{on}, the current from the inductor is less than the average load current by $\Delta I_{L/2}$. The makeup current is supplied by the capacitor. Therefore, $\Delta I_C = \Delta I_L$ and the current wave forms are in phase.

This triangular current wave produces a ripple voltage which is $\Delta V_C = 1/C \int_{T_1}^{T2} idt$, which can be expressed as

$$V_{P-P} = \frac{V_O T^2 (V_{IN} - V_O)}{8\ V_{IN}\ LC}$$

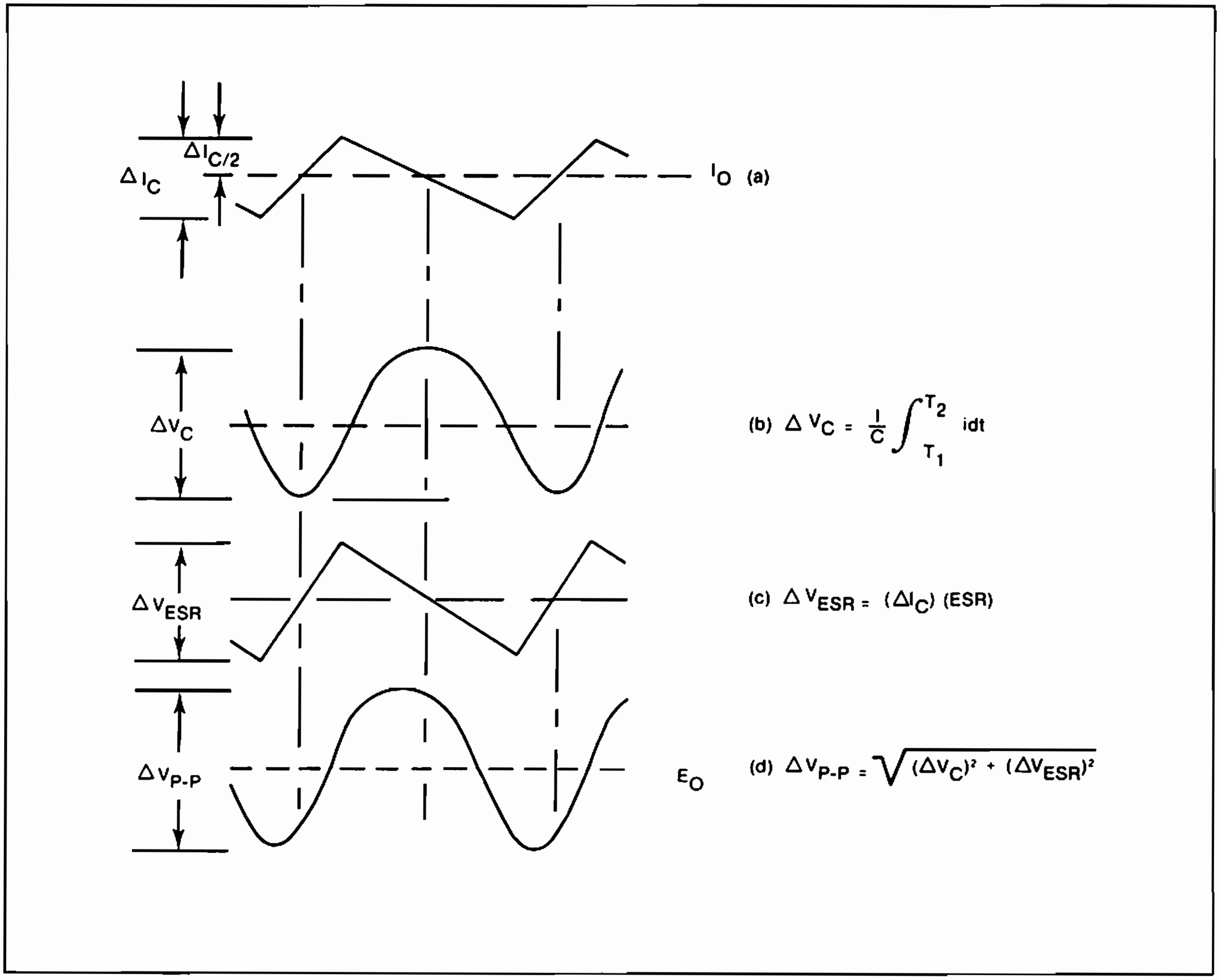


Figure 3

Figure 3b is the time integral of the capacitor current (I_C). Note that it is in quadrature with the current, and since the current is triangular, the voltage is not sinusoidal. There is a second component of the ripple voltage (V_{P-P}), which is caused by the resistive components of the capacitor.

This resistance is the sum of many physical aspects of the capacitor and is called the Equivalent Series Resistance (ESR). The current I_C through the ESR causes the second component of the ripple voltage to be developed, which is triangular in form and in phase with the current (Figure 3c). The voltages of Figures 3b and 3c are added vectorialy to produce the true ripple voltage shown in Figure 3d.

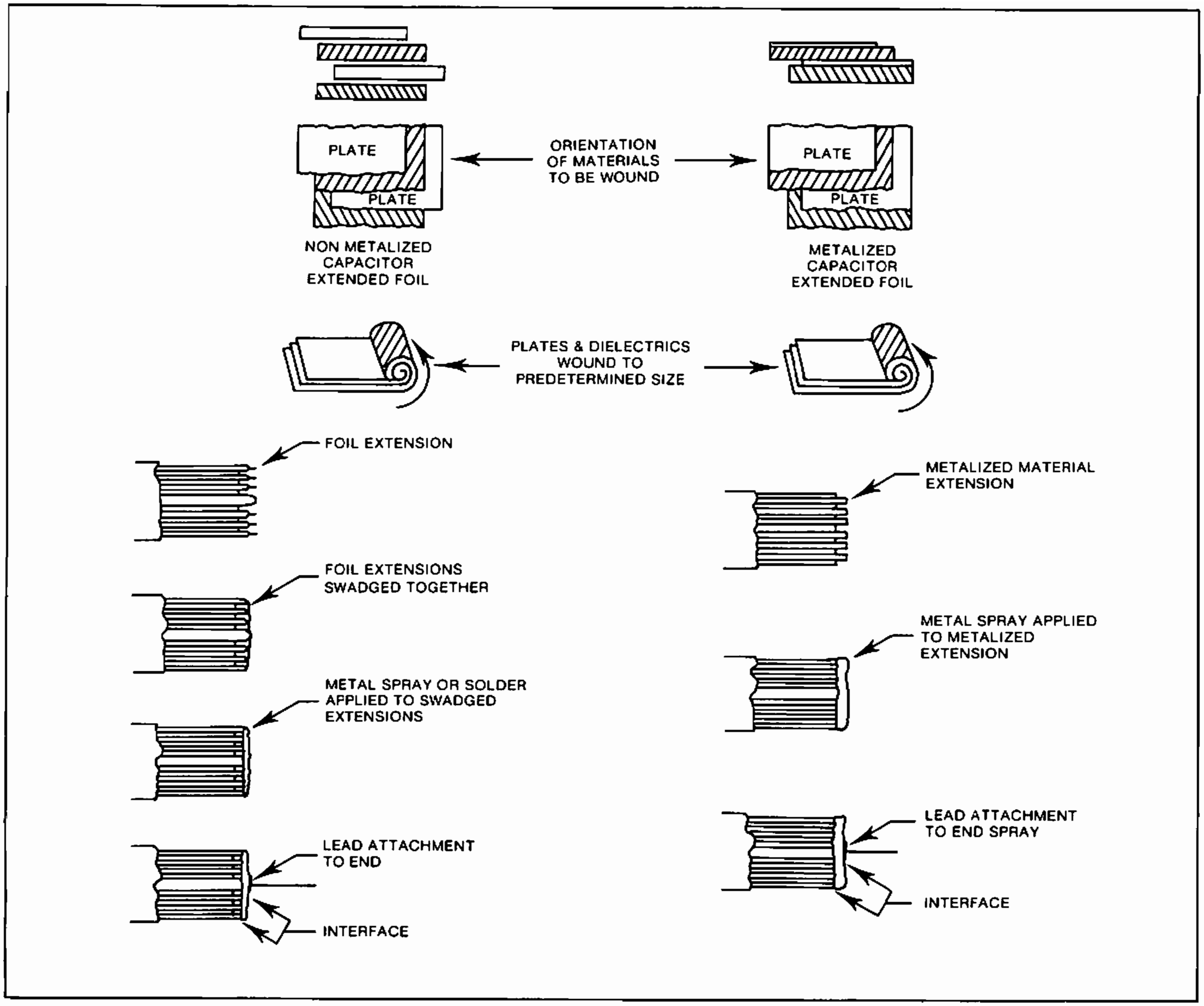
The magnitude of ΔV_{ESR} is significantly larger than ΔV_C, and it is quite common to specify larger capacitor values than would otherwise be required to obtain a reasonably low value of ESR.

From the above, it can be seen that the characteristics of the capacitor, in particular the ESR, are critical to the performance of the switching regulator.

The Equivalent Series Resistance for electrolytic and tantalum capacitors is dependent on the detailed internal construction of the capacitor. How connections are made to the equivalent capacitor plates, the nature of the dielectric, the capacity value and physical size and voltage rating effect the internal construction. This is also true for wound plastic dielectrics, however the effect of the dielectric material itself is overshadowed by the method of construction, particularly, the lead attachment to the capacitor plates.

Consider the typical wound dielectric as shown in Figure 4.

Note that each layer of the dielectric and the plate, whether foil or a metallized deposit on the dielectric, has a distributed resistance to the current flow. In addition, at each end of the capacitor there is resistance in the end-spray alloy, the solder, the lead and at each of the interfaces between the different



CAPACITOR PHYSICAL CONSTRUCTION
Figure 4

materials. These interfaces are composed of the oxides of the alloys used in making the end connections.

The total sum of all of these series resistance is the ESR. The magnitude of the ESR is most commonly determined by reading the Power Factor (PF) at the same time the capacity is measured.

By definition, the PF is the ratio of power lost in the capacitor to the total power passed by the capacitor. The power loss is real and is expressed as I^2R; the total power is equal to I^2Z, where R is the ESR and Z is the vectorial sum of R, X_C and any present X_L. In capacitors where the ESR is small compared to the reactance and the cosine of the vector angle is less than 0.1, the reactance is substituted for Z. Thus:

$$PF = \frac{R}{Z} = \frac{R}{X_C}$$

In the capacitor industry, this ratio is more commonly known as the Dissipation Factor (DF), and is expressed as a percent.

$$DF = \frac{R}{X_C} = 2\pi fCR; \text{ where: } X_C = \frac{1}{2\pi fC} \text{ and } R = ESR$$

$$\therefore ESR = \frac{DF}{2\pi fC}$$

The DF will vary with frequency, capacity, resistance and any condition, e.g., temperature or moisture, which causes C or R to change.

It can be seen then that when the DF value for a capacitor is used to determine the ESR, the DF measurement should be made at the frequency at which the capacitor is to operate.

It can also be shown empirically that the DF or ESR of a capacitor increases significantly as the operating frequency increases. This is due to the increased resistance of the dielectric to changes in polarization, and more importantly, the increase in the resistance of the metal oxides at each of the interfaces.

The factors controlling the resistance are summarized as:

1. The resistance of each of the metals used for the leads, plates, solder and end spray; this is fixed at the design stage by choice of materials and does not vary significantly with changes in operating frequency.
2. The inherent Equivalent Series Resistance (ESR) of the dielectric material, which is fixed by the choice of material.
3. The resistance of the oxides resulting from the interface connections between the various materials; this is minimized principally by manufacturing processes and workmanship.

With the above information, the design engineer can specify the required capacity and DF for his application. Note that it is not necessary to define the dielectric as long as the maximum allowable DF is specified at the operating frequency and temperature. A problem can exist here in that the standard test frequency is 60 Hz for capacitors of 1.0 Mfd. and larger. Some of the new test facilities have instruments to measure the DF of capacitors at frequencies up to 10K Hz. Fortunately, the DF measured at 10K Hz is reasonably representative of the DF up to 20K or higher.

For electrolytic, tantalum, and capacitors wherein the DF exceeds 10%, the direct measurement of ESR is the normal method of measurement. Once again, the frequency for testing should be specified.

In addition to the ripple voltage caused by the ESR, the designer must consider the heating effect of the losses within the capacitor and the current density of the end connection. The loss within the capacitor is determined by: Watts loss $W = I^2R$, where;

$$R = DF/2\pi fC$$

$$\therefore W = \frac{(I^2)\ (DF)}{2\pi fC}$$

The designer must insure that the accumulated heat added to the ambient temperature does not exceed the temperature limits specified for the capacitor by the manufacturer. Even though the DF for all dielectrics increases with temperature, most of the power loss and heating will take place at the connection interface for all but the highest frequencies. Therefore, the design engineer must consider the allowable current density in the end connections.

The plates of a non-metallized capacitor are separate thin sheets of metal, usually aluminum, wound with the sheets of dielectric. The plates extend alternately out each end of the capacitor winding, beyond the edge of the dielectric, and present a series of concentric metal rings to which the leads are attached. See Figure 4.

The plates of a metallized capacitor are usually aluminum, vapor-deposited directly on the surface of the dielectric. Once again, the edges of the metal and the dielectric film are extended, and the capacitor plates are connected by a spray of molten metal alloy on the ends. This end spray combines with the vapor-deposited metal on the dielectric to form a solid electrical connection between all concentric rings of the metallized dielectric, and to provide a surface to which the end lead can be attached.

The normal thickness of the aluminum plates is 0.00024", but can be as thin as 0.00017". The thickness of the vapor-deposited metal is specified in ohms per square foot. Typically, this is equivalent to a thickness of 4×10^{-6} inches. Assuming perfect connections, the current carrying capacity can be determined by multiplying the active length of the plate winding by the thickness of the plate to obtain the equivalent conductor area. Metal foil types will normally have at least 60 times the conducting area of the metallized dielectric. However, metallized capacitors have the capability of carrying adequate current for most applications. Because the connections are not perfect, the manufacturers must test to determine the typically allowable RMS current through the end connections. This current is based on the heat rise at the interface connections. For a given AC current, a short capacitor with a large end section area will have less loss than a long capacitor with a small end section area.

The capacitor manufacturer attempts to provide a physical size and configuration which will be satisfactory in most applications. Also, in attempting to provide data sheets which specify maximum DF or RMS current, the manufacturer cannot reasonably accommodate all possible operating conditions. Therefore, some data sheets may provide generalized information, or more often, nothing. In either event, it is advisable for the user to contact the capacitor manufacturer to determine exactly the characteristics he can expect in his application.

In summation, the most significant factors in the selection of a capacitor for use in the output filter of a switching regulator are:

1. Capacity
2. DF or ESR
3. Peak Currents
4. Average DC voltage
5. Environmental ambient conditions
6. Special physical conditions, such as size, mounting, etc.

Listed below are some typical values of DF for 5.0 Mfd, 200 volt capacitors made from various dielectrics, when tested at both 60 Hz and 10K Hz.

	DF @ 60 Hz	**DF @ 10K Hz**
Mylar* (Metalized)	.5% to .7%	3.1% to 3.3%
Mylar* and Foil	.3% to .5%	2.5% to 2.8%
Polycarbonate-Metalized	.1% to .3%	2.0% to 2.8%
Polypropylene-Metalized	.03% to .09%	1.7% to 2.0%

References: Electrocube Technical Bulletins #5, #6, #7 and #8

*TM DuPont