Capacitor Considerations for Power Management

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Abstract

Portable electronic devices demand maximum battery performance. This demand for ever increasing power has outpaced the rate of battery development in the electronics industry. Power management in portable electronic devices has thus become a critical area for circuit design and component selection, in the development cycle for portable electronic devices. Low energy designs improve mean time between charging (MTBC). Design in of capacitors with maximized insulation resistance (IR) and minimized equivalent series resistance (ESR) may be a useful tool in minimizing battery drain rate. In this paper, use of capacitors in typical battery operated applications is modeled with respect to leakage current and ESR for several types of capacitors available from several manufacturers. IR is measured for each and the data are used to model anticipated MTBC performance as a function of use conditions in generic applications. The effect of ESR and insulation resistance on anticipated MTBC is predicted. The use of lower ESR capacitors, which are highly consistent in capacitance and inductance from capacitor to capacitor, in the design of battery operated electronic devices is projected to improve performance significantly.

Introduction

The use of battery operated electronic goods has shown strong growth with time. Table 1 exhibits market projections for several battery operated portable devices.

Table 1. Market Estimates for Select for Portable Electronic Devices[1,2,3,4]

Product	WW Units (Million)	ASP ($ US)	WW $US (Billion)
Laptop Computer	59	$ 1,251	$ 73
Cell Phone	813	$ 142	$ 115
Personal Digital Player (MP3)	75	$ 188	$ 14
DSC (Digital Still Camera)	68	$ 265	$ 18
Overall:	1,015	$ 218	$ 221

The number of passive electronic components in each type of portable electronic device varies. For example, a typical Digital Still Camera (DSC), the Sony Cyber Shot U10 contains 169 multilayer ceramic capacitors (MLCC)[5], while at typical cell phone, the Sony-Ericsson S0505i contains 386 MLCC.[6] These numbers change with model and time, but, in general, they increase with increasing device complexity as the trend toward convergence in functionality continues. Using an assumption which is likely conservative, that the number of ceramic capacitors used per device is ~100, the annual consumption due to these 4 types of battery powered electronic devices is in excess of 100 billion units, or more than about 10% of the current world wide total available market (WWTAM) for all ceramic capacitors which is currently estimated at approximately 940 billion units annual usage.[7]

Over time, the capacitance per unit volume available in most types of capacitors has also increased due to improvements in thin dielectric layer technology as well as proportion of active of active volume as illustrated in fig 1 and as discussed in detail in numerous papers.[8,9,10,11,12,13] While this trend has been very valuable to integration and miniaturization efforts that have been drivers in the electronics industry, it has also resulted in the reduction of voltage rating for capacitor devices that each MLCC manufacturer has strived to defeat with some success. An example of the trade off between volumetric efficiency and voltage rating is shown in figure 2. Since the use voltage for most electronic devices
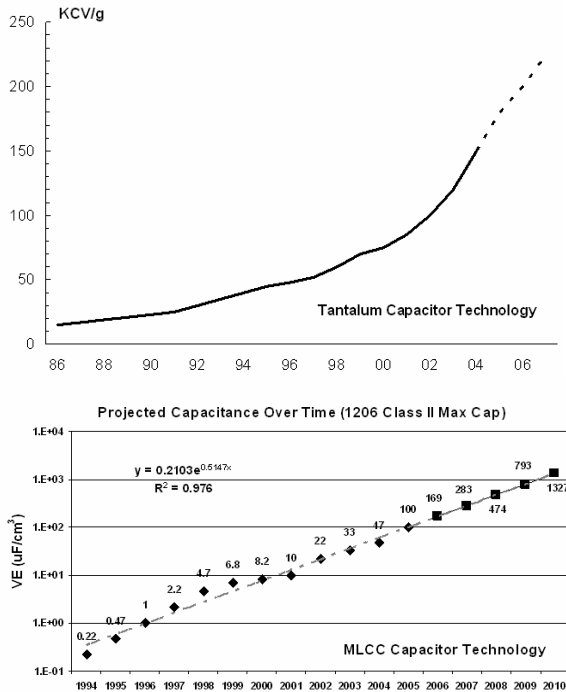
Figure 1. Increase in capacitance volumetric efficiency over time, Ta and MLCC.
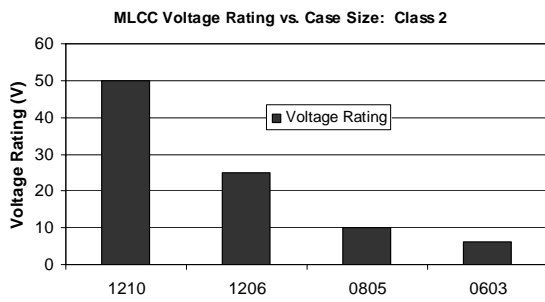

Figure 2. Representative trade-off of voltage rating for smaller case size MLCC.

has also dropped with time, and due to technology improvements in MLCC technology over time, this typically has not been an issue. However, with the reduction in voltage rating an associated reduction in breakdown voltage (BV) has also occurred. Figure 3 illustrates this effect for representative X5R dielectric MLCC as a culmination for 4 different manufacturers over time. The drop in BV is apparent. This reduction is also observed, albeit with poorer correlation with respect to IR both at room temperature (RTIR) and at elevated temperature (HTIR) as indicated in fig 4. The poorer correlation is likely due to process

improvements that have occurred over time at each manufacturer as the data for the larger case size parts is considerably older (~3-6 years) than the data for the smaller case size parts.
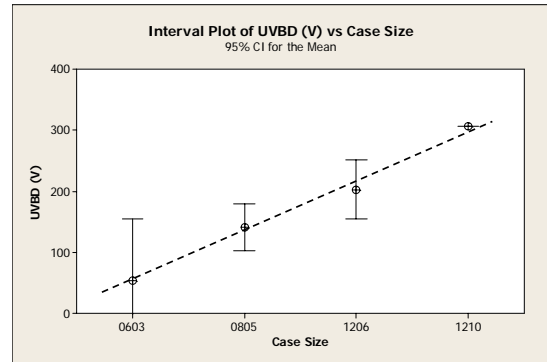

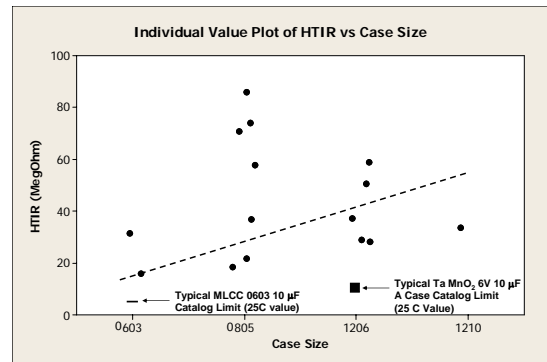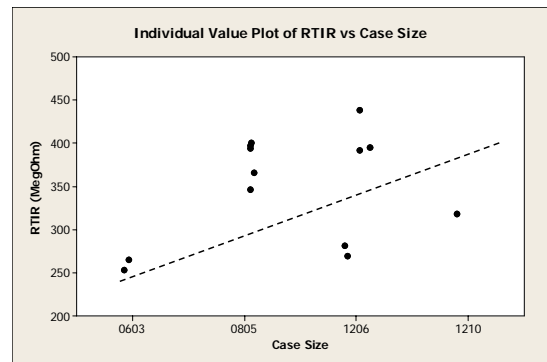Figure 3. Breakdown voltage of 10 µF class 2 MLCC as a function of case size.

Figure 4. RTIR and HTIR vs. case size for 10 µF X5R MLCC.

For reference, a typical minimum HTIR for an A case (1206) 6V rated MnO_2 Ta capacitor at 25°C is about 10 MΩ, or about one third to one half that of an equivalently sized MLCC and is about one

third less than the lower of the 0603 X5R 10 μF MLCC values.[14] Additionally, a typical catalog minimum IR value for an 0603 10 μF MLCC is 5 MΩ at 25°C.[15] These points are included on the HTIR slide even though the specifications for these two part types is at 25°C in order to show that the actual IR values are typically considerably higher than the specification.

Median time between charges (MTBC) is a major consideration when designing battery powered devices. Leakage current, or inversely IR is important in that a low IR or high leakage current will adversely affect MTBC if the capacitor is configured across the battery as in a decoupling or bypass configuration as illustrated in fig 5.
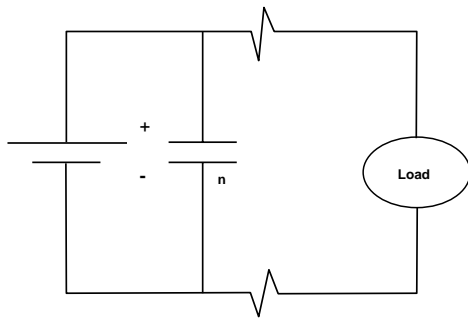

Figure 5. Generic decoupling or bypass circuit. n indicates the possibility of more than one capacitor in parallel.

Additionally, equivalent series resistance (ESR) is important in a portable electronic device as a high ESR may be detrimental to power transmission when the capacitor is configured in series with the load as depicted generically in fig 6. In a coupling application, the AC conduction properties of the capacitor are used to pass a specific frequency range, while excluding frequencies above and below that range as illustrated in fig 7.
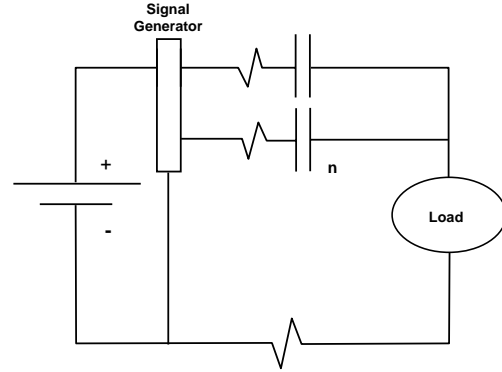

Figure 6. Generic capacitor coupling circuit. n indicates the possibility of more than one capacitor in circuit.
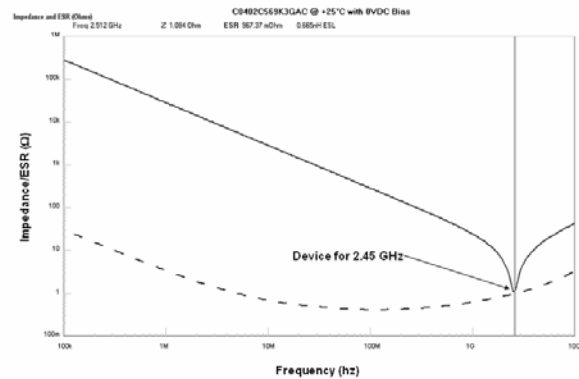

Figure 7. Representative ceramic capacitor impedance curve.[16]

For this application, the capacitor is typically selected such that the resonance frequency of said capacitor is centered at the frequency of interest. The resonant frequency of the capacitor may be calculated using the relationship:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

where:
f_0 = resonance frequency (Hz)
L = inductance (H)
C = capacitance (F)

Resonance frequency values for various capacitance and inductance values are illustrated in fig. 8 and may be easily calculated utilizing KEMET's Spice program.[16]
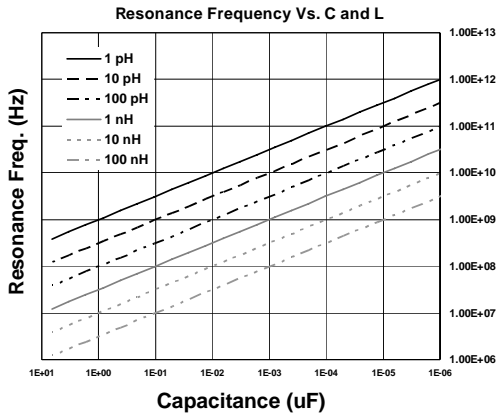
Resonance Frequency Vs. C and L

Figure 8. Resonance frequencies for various capacitance and inductance values.

For these types of applications, the frequencies are typically high (>100 MHz) and the capacitors involved are typically of lower value (i.e., 100 nF or less). It is important that these devices have a low ESR with respect to the impedance of the load so that little energy is dissipated by the capacitor in the series configuration. Quality factor (Q) is typically used as a measure of steepness and depth of the impedance curve and is a valuable consideration for this application. Q is defined as:

$$Q = \frac{1}{df} = \frac{X_C}{ESR} = \frac{1}{2\pi f \cdot C \cdot ESR}$$

where:

Q = Quality factor
df = dissipation factor (tan(δ), where δ is loss angle)
X_C = Capacitive reactance = $1/(2\pi f \cdot C)$
f = frequency (Hz)
C = Capacitance (F)
ESR = Equivalent Series Resistance (Ω)

From the Q equation above, it is evident that Q increases as frequency, capacitance and ESR are reduced. Combining these factors with the effect of inductance on f_0 indicates that the best solution for this type of application has f_0 centered on the frequency of interest, and that f_0 is achieved using the lowest inductance (L) possible in order to enable the lowest C possible to achieve the f_0 of interest, all combined with minimized ESR.

The batteries used to power portable electronic devices vary significantly from device to device. Table 2 depicts key battery data for several portable electronic devices. From this, a general assumption about power consumption can be made for each device, even though power consumption varies greatly with use conditions.

Table 2. Battery Data for Representative Portable Electronic Devices

Mfg	Type	Product	Voltage (V)	Capacity mA-h	Capacity W-h
Dell	Laptop	D600	11.1	4320	48.0
HP	Laptop	DV1000	10.8	8800	95.0
Motorola	Cell Phone	V265	3.6	780	2.8
Motorola	Cell Phone	T-Series	3.7	1000	3.7
Motorola	Cell Phone	T-Series (Extended Life)	3.7	1600	5.9
Apple	MP3	Ipod (Gens. 1 and 2)	3.7	2100	7.8
Apple	MP3	Ipod (Gen. 3)	3.7	850	3.1
Sony	DSC	Cyber Shot	3.6	720	2.6
Sony	DSC	Cyber Shot (High Capacity)	7.2	2000	14.4

From table 2 it is evident that most of the portable applications of interest use batteries in one of 3 voltage categories (~10-12V, ~7-8V and ~3-4V), and that the mA-h ratings vary widely from ~500 to 10,000 depending upon the application.

Power management in portable electronic devices is becoming more important as consumer demand for performance, functionality and maximized MTBC is addressed by the design community. Numerous clever and elegant solutions, both hard and soft, have been introduced that enable improved power management.[17,18,19] Entire symposia have been dedicated to this subject.[20] These developments vary in scope from throttling of frequencies to hibernation of the power consuming components. This study focuses on the impact of capacitor leakage current, or inversely, IR as well as the impact of ESR, or inversely and qualitatively, Q on the MTBC of generic portable electronic devices.

Discussion

For the generic configuration illustrated in fig. 5 IR is the most important parameter to consider for impact on MTBC. Using Ohm's law:

$$V = I \cdot R$$

where:

$\quad$ V $\;=\;$ voltage (V)
$\quad$ I $\;=\;$ current (A)
$\quad$ R $\;=\;$ resistance (R)

Assuming that IR = R, it is possible to estimate the potential impact on MTBC using with respect to the number of bypass capacitors and the IR of each based upon the voltage of the device and the MTBC.

Figures 9-12 illustrate the projected effect of IR, number and the number of bypass capacitors having similar IR on the MTBC of four typical battery applications (laptop computer, cell phone, MP3 player, high output digital still camera as depicted in Table 1) assuming that the capacitors are on the battery side of any switches. The region of concern depicted in the figures is set to 200 hours. This region is arbitrarily set to be more than 1 week.
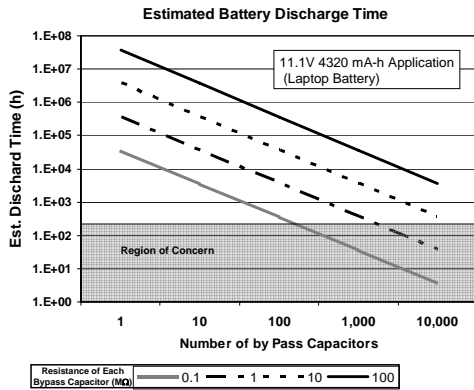
Figure 9. Projected discharge times for typical laptop computer as a function of bypass capacitor IR.
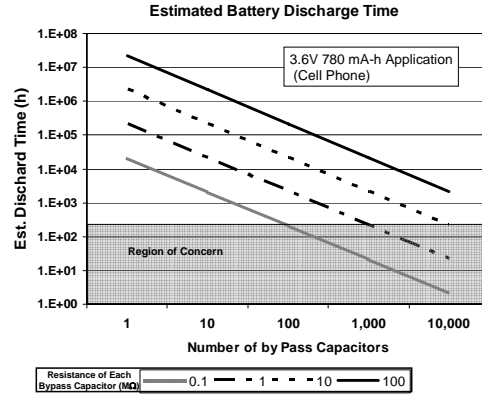
Figure 10. Projected discharge times for typical cell phone as a function of bypass capacitor IR.

Other levels may be more appropriate depending upon the application as well as customer expectations. Designers should avoid designs in this region as the designs would likely lead to unacceptable leakage.
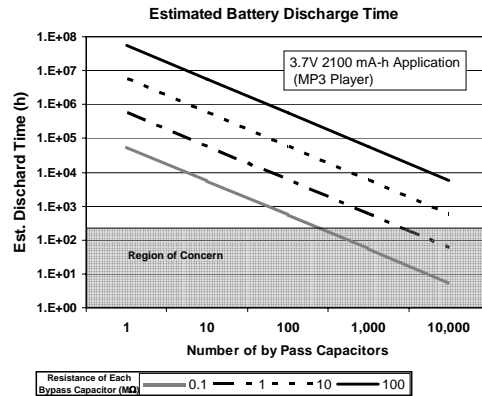
Figure 11. Projected discharge times for typical MP3 player as a function of bypass capacitor IR.
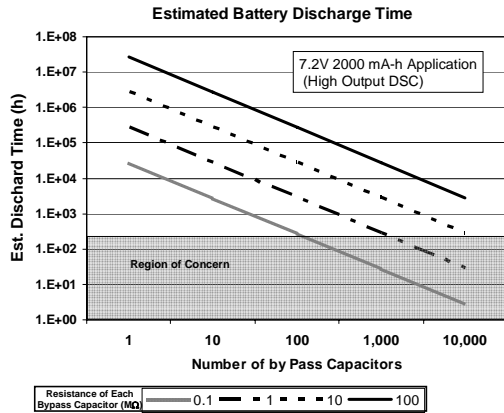
Estimated Battery Discharge Time

Figure 12. Projected discharge times for high output DSC as a function of bypass capacitor IR.

The estimates for each of the applications indicate that use of capacitors in a bypass configuration for the battery powered applications discussed should not be an issue with respect to MTBC until IR drops below ~1 MΩ or until the number of devices across the battery encroaches 1000 for the IR values >=1MΩ. This should not be an issue even for the highest volumetric efficiency (i.e., lowest IR) Ta or MLCC capacitors available. While the number of capacitors continues to increase in each of these applications over time, it is likely that the number of bypass capacitors in each will not encroach 1000 for quite some time. The model indicates that IR for capacitors designed into bypass these types of designs should probably exceed a minimum of 1 MΩ for under all conceivable application conditions (voltage, temperature, etc.). At this time all commercially available MLCC and Ta capacitor products known to the authors exceed this level by a significant amount.

For the generic series configuration illustrated in fig. 6, the important factor is the ESR at the frequency(ies) of interest with respect to the impedance of the load at the frequency of interest. Typical load impedance for the loads in fig 6 is 50Ω.[21] For applications near and above 1 GHz, ESR may have values as high as 300 mΩ to 2 Ω at or near resonance (see fig. 7). Transmitting power through these devices will dissipate additional energy, thereby limiting the amount of signal energy sent to the load. This power dissipation shows up as a reduced amplitude signal, limiting the ability of the respective portable electronic device. Taking this into consideration, the designer must either choose to use the lowest impedance (highest Q) capacitor in the range of frequency of interest, or to "over design" the circuit to provide additional signal to compensate the power loss of the higher impedance capacitor.

For the above case, insertion of each 1 Ω device in series with one or more load(s) will not necessarily reduce batter life, but will reduce signal amplitude by ~2% for each device.

Additionally, it is important that the designer choose a capacitor solution that is stable in capacitance, inductance and ESR. Changes in any of these values may significantly reduce the signal to the load by increasing the overall impedance of the circuit. This effect is illustrated for a +/-10% change in capacitance from a nominal value of 5.6 pF in fig. 12 as well as for a +/-10% change in inductance from a nominal value of 750 pH in fig. 13, both situations with capacitors having ESR values at resonance of 300 mΩ. The figures indicate that a +/-10% change in either C or L can increase the impedance (Z) significantly at the target frequency (f_T) of 2.45 GHz for this example. The associated in Z may be as much as from 300 mΩ to ~1.4 Ω in this situation. These effects are much more dramatic than the effect of changing ESR +/- 10% (i.e., impedance change at resonance of only +/-30 MΩ). The increase in Z associated with the changes in C or L above may reduce signal amplitude as much as 2.2% for a 50 Ω impedance load, and as much as 10.7% for a 10 Ω impedance load.
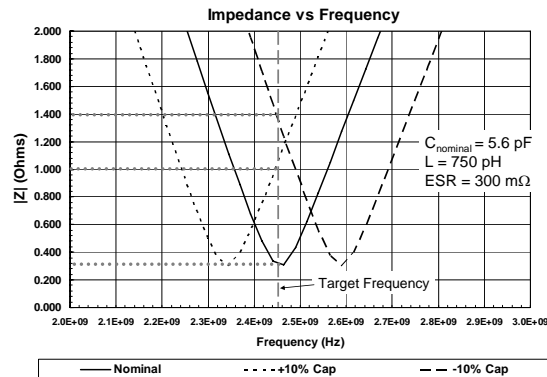

Figure 13. Effect of a +/-10% change in capacitance upon impedance at target frequency.

Impedance vs Frequency

C = 5.6 pF
$L_{nominal}$ = 750 pH
ESR = 300 mΩ

Target Frequency

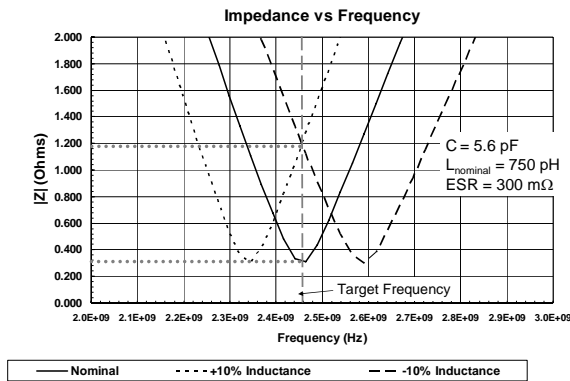— Nominal   - - - - +10% Inductance   — — -10% Inductance

Figure 14. Effect of a +/-10% change in inductance upon impedance at target frequency.

An element of research and development in capacitor industry is directed toward increasing IR as well as reducing impedance and improving consistency in C and L. Gains in IR are achieved mainly through advancements in materials selection, green processing and thermal processing of the dielectric, internal electrode and external electrode composite comprising the MLCC. Gains in IR for valve metal type capacitors (Ta, Al, and the like) are typically made via improvements in the associated anodization process. Improvements in consistency of C and L are typically made via improvements in process capability. This may be achieved effectively through the use of Six Sigma (6σ) methodologies or the like.

Use of Design for 6σ or DFSS tools have been utilized at KEMET in order to improve IR (ΩF product) and capacitance values offered as indicated in Table 3, as has the rest of the MLCC industry.

Table 3. Representative Properties of State of the Art X7R Capacitors Offered by KEMET and Other Suppliers

Part Type	Samples	CAP (µF)	DF (%)	TCC -55°C	TCC 125°C	Breakdown Voltage	R.T. RC (ΩF)	125°C RC (ΩF)
0805-2.2µF	Vendor A	2.25	1.94	1.6%	-14.4%	256	1813	79.0
	Vendor B	2.30	3.00	-2.2%	-10.2%	295	1553	47.4
	KEMET	2.20	3.02	-1.3%	-12.9%	342	2150	107.8
1206-10µF	Vendor A	10.54	9.15	-8.61	-15.2%	266	4247	518.2
	Vendor B	10.31	2.96	-3.5%	-21.1%	252	2031	76.9
	KEMET	9.89	3.05	-0.70	-14.3%	331	1464	86.8

Furthermore, KEMET has been very successful in its efforts to reduce ESR in valve metal products through evolutionary improvement in Ta MnO2 ESR as well as revolutionary improvement exhibited by its organic polymer (KO) and aluminum polymer (AO) introductions and offerings. Reducing ESR/increasing Q is also a focus of the MLCC industry in order to improve signal integrity as described above.

Summary

Power management is a major consideration in the design of today's battery powered portable electronic devices. Numerous methods of power management now exist in hard device solutions as well as in software solutions for these devices.

Capacitors may influence power usage in portable electronic devices in at least two ways, through excessive leakage when used in a bypass configuration and through excessive power dissipation when used in series manner. All known Ta and ceramic capacitors have adequate IR for these applications assuming that the device must not discharge in an arbitrarily set time frame of ~200 hours and when the number of devices placed across the battery are less than 1000 units which is all known designs currently for battery operated devices. Concern is not warranted now with respect to low IR for either of these types of devices.

ESR and Q are significant design considerations for portable electronic devices as significant variations in these capacitor properties may affect signal amplitude by several percent or more. A very important consideration in the selection of a capacitor for AC coupling is the consistency in C and in L from device to device as a change in either of +/-10% may affect signal strength by >10%. Accordingly, the capacitor industry continuously strives to improve consistency and performance of capacitor devices.

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