High Voltage Tantalum Polymer Capacitors

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Introduction

Solid tantalum (Ta) capacitors with intrinsically conductive polymers as the cathode material have been widely used in the electronics industry due to their low equivalent series resistance (ESR) and "non-burning/non-ignition" failure mode. Intrinsically conductive polymers, commonly known as conductive polymers, are electrically conductive at the molecular level. Unlike polymeric materials whose electrical conductivity is imported from the presence of foreign conductive particles (for example silver paints or adhesives), a single molecule (a polymer chain) of an intrinsically conductive polymer is conductive. Various types of conductive polymers including polypyrrole, polyaniline, and polyethyldioxythiophene (PEDT) can be applied to dielectric oxides to serve as the primary cathode material for solid electrolytic capacitors. Two methods of coating the dielectric oxide with conductive polymers are widely used in the industry, in-situ polymerization and electrochemical polymerization. In in-situ polymerization the monomer of an intrinsically conductive polymer is brought into contact with an oxidizer to drive the polymerization reaction. In electrochemical polymerization the reaction is driven by an externally supplied current. The major drawback of conductive polymer capacitors, regardless of the type or method of application, is their relatively low working voltages compared to their MnO_2 counterparts. For example, the maximum voltage rating of existing surface mount polymer tantalum capacitors is 25 volts, while that of their MnO_2 counterparts is 50 volts. When subjected to voltages exceeding 25 volts, the existing polymer capacitors have, to varying degrees, reliability issues. This limitation has restricted the use of these devices to relatively low voltage applications (<20 volts). New developments in material and process technologies have overcome these limitations leading to the introduction of a new line of high voltage tantalum polymer capacitors with excellent long term reliability.

Research and Analysis

The ability to withstand high voltage can be best characterized by the breakdown voltage (BDV) of the capacitors. Higher BDV corresponds with better reliability at a given application voltage. In an attempt to understand the differences in behavior between polymer Ta capacitors and their MnO_2 counterparts, the BDV of a wide range of Ta capacitors including both polymer (polyethyldioxythiophene, or PEDT) and MnO_2 based capacitors was measured. BDV is plotted against formation (anodization) voltage in Figure 1.

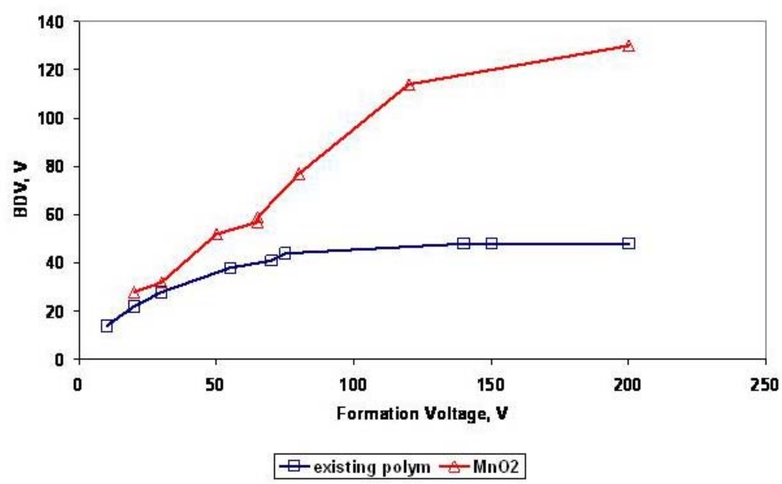

Figure 1, BDV characteristics of existing conductive polymer and MnO_2 capacitors

As shown in Figure 1, in the low formation voltage region (< 30V) the BDV of both polymer and MnO_2 capacitors are close to the formation voltage. However, as formation voltage increases above 30 volts, the BDV curves for MnO_2 and conductive polymer capacitors diverge. For MnO_2 capacitors the BDV continues to increase with increasing formation voltage, whereas the BDV of polymer capacitors levels at about 60V. Above a formation voltage of approximately 100 volts, the BDV of conductive polymer capacitors is almost unaffected by further increases in formation voltage. This explains why increasing dielectric thickness, the most important and commonly used approach to make high voltage capacitors, is virtually ineffective for making high voltage polymer capacitors beyond about 25 volt ratings. Higher voltage rated capacitors, 35V for example, would require a BDV of much greater than 60V to ensure their sound surge performances and long term reliability

The relatively low BDV of polymer capacitors suggests that the dielectric in polymer capacitors has been degraded. Efforts were made to understand the causes of this problem. Through a series of studies a breakthrough was found when comparing the BDV of 25volt-rated capacitors processed using various polymer processes. Anodes using the existing polymerization (PEDT) process (Std.) were evaluated and compared to anodes with a new/alternative PEDT and or PANI polymer process. As illustrated in Figure 2, a higher BDV was obtained with the new polymer process regardless of the polymer compositions (PEDT or PANI).

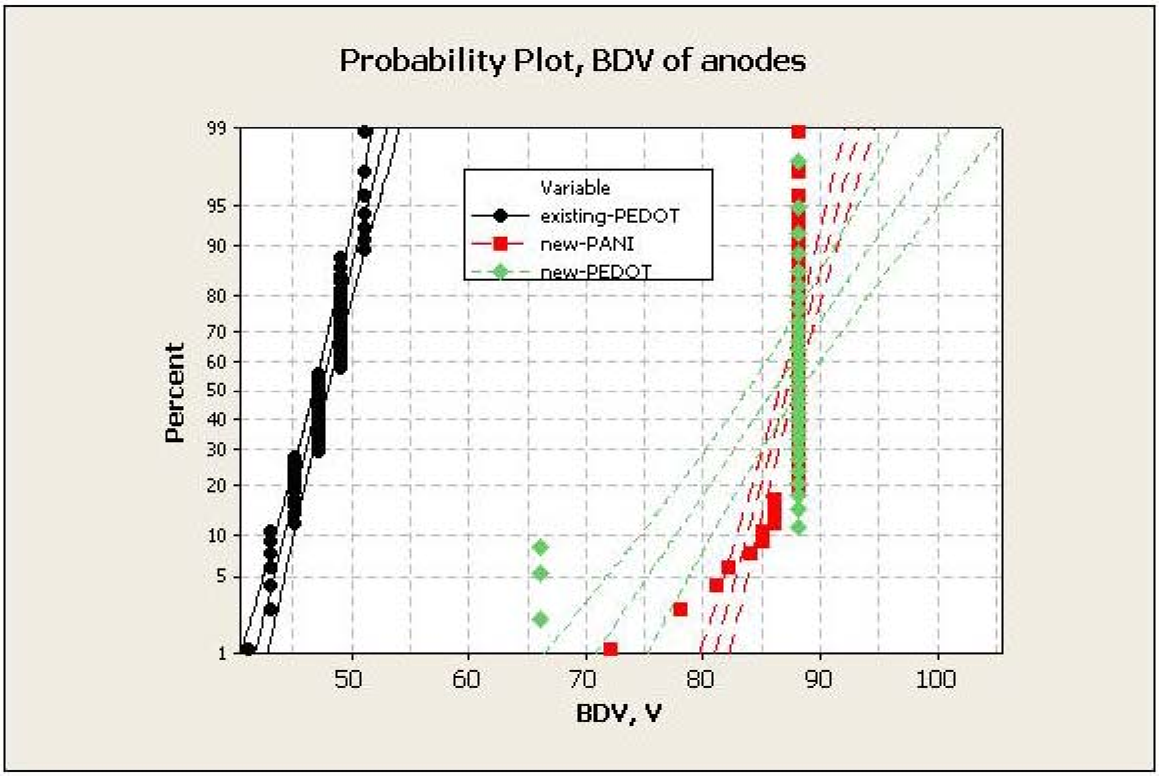

Figure 2, BDV of polymer anodes using alternative PEDT and PANI process*
***BDV test stopped @88V**

In addition to high BDV, the anodes processed with the alternative polymer process also showed excellent "self-healing" behavior, which is illustrated in Figure 3. As the applied voltage increased, the current passing through the anode decreased, demonstrating the characteristic 'aging' behavior attributed to self-healing in a solid electrolytic capacitor. The current spikes at about 78V indicating a partial breakdown of the dielectric. However, the consequent drop of the current under constant voltage demonstrates that the damaged dielectric was gradually "healed", possibly due to thermal degradation or de-doping of the polymer at the defective dielectric sites.

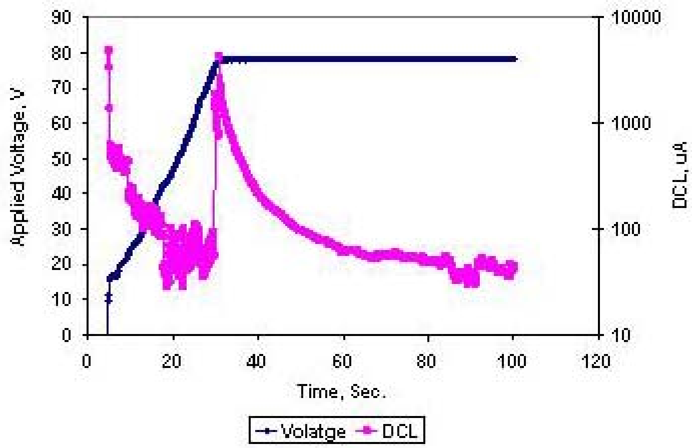

Figure 3, "Self-healing" behavior of new polymer process anode

Developing High Voltage Polymer Capacitors

As evident in the above discussions, the use of this new found process presented a solution to the low BDV problem from which the existing polymer technology was suffering. The next technical challenge was to make polymer capacitors with desired high BDV and good reliability, while maintaining other important properties such as low ESR and good stability.

The above reported new polymer process was placed into a pilot scale development project and designated as the T521 Series to differentiate the new process from the more established polymer process. The T521 Series would later be defined as a high voltage polymer tantalum capacitor that is surge robust and highly reliable for continuous operation under elevated temperature.

BDV of the T521 Series

Figure 4 compares the BDV of anodes coated with MnO_2 as the cathode, anodes processed using established polymerization processes, and anodes processed using the new process. As shown below, the BDV of capacitors processed with the new polymerization process possess a BDV performance level very similar to the MnO_2 capacitors.

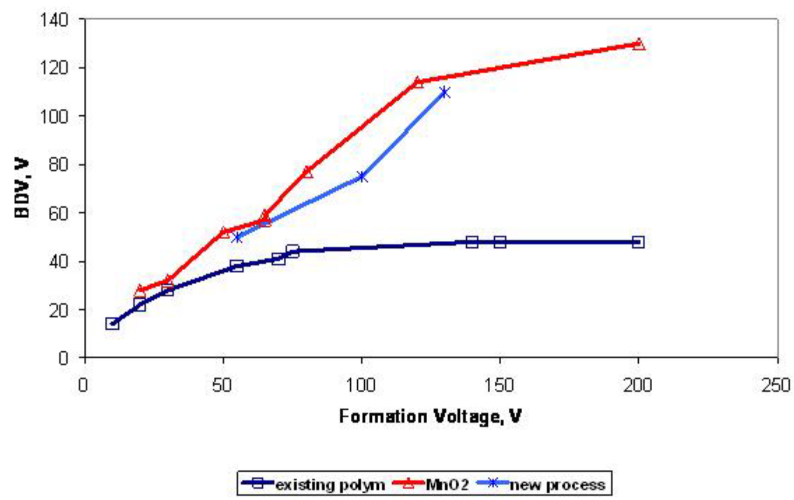

Figure 4, BDV characteristics of existing conductive polymer, MnO_2 and new process capacitors

Figure 5 is a BDV probability plot of a T521 Series 15uF/35V V7343-19 Capacitor. The median value (50%) is 78V, far exceeding BDV of any available polymer tantalum capacitors.

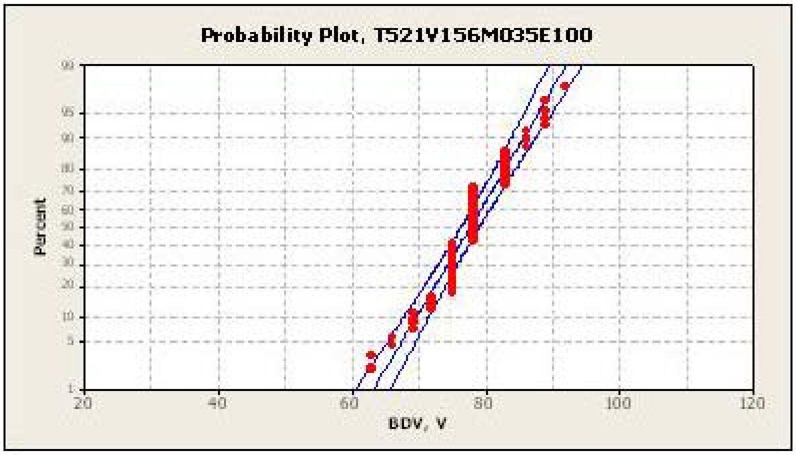

Figure 5, BDV behavior of a 15uF, 35V, 100mOhm, 7343-19 Case Size Polymer Device

<u>Reliability Testing of the T521 Series</u>

In recent years, multiple studies have been conducted to compare and quantify the reliability of polymer tantalum devices (including PEDT) to their MnO_2 predecessors [2,3]. These studies have reached similar conclusions in that the polymer cathode systems are, at the least, as reliable as the well established MnO_2 cathode design when used within their recommended operating ranges. In order to qualify the new polymer process additional reliability studies were conducted. Components were placed on a conventional 85° C Life Test and charged at rated voltage for 1000 hrs. Initial measurements were taken immediately following board mounting of the devices. The devices were measured again after 250, 500 and 1000 hours of testing. The reliability of the polymer tantalum capacitor can best be determined from assessing the DC Leakage and ESR performance of the capacitor over the duration of the life test. Following 1000 hrs of testing, the dielectric showed no signs of degradation, as evidenced by the reduction in DC Leakage shown in Figure 6. In addition, the ESR performance was found to be stable throughout the 1000 hrs of testing (Figure 7). This initial study demonstrates that the new polymer process has, at a minimum, reliability characteristics similar to that of the currently available low voltage PEDT polymer tantalum products.

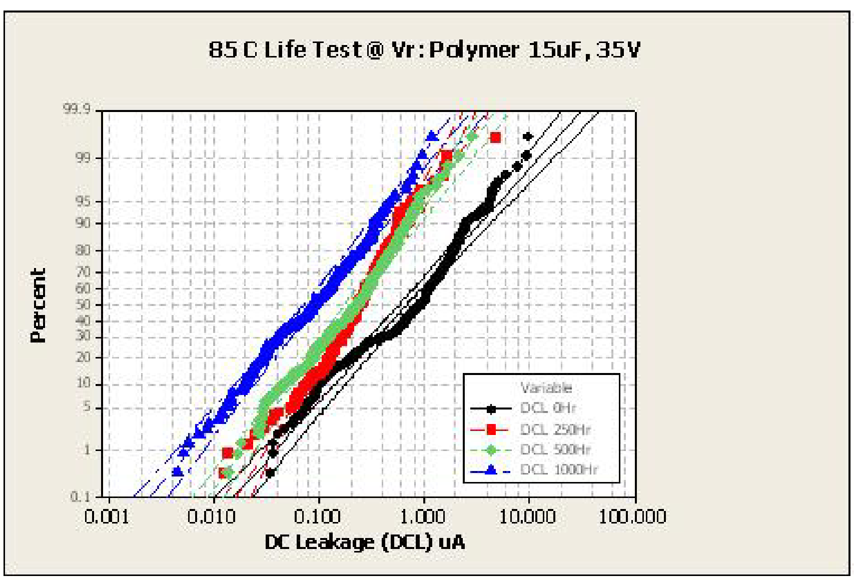

Figure 6: 85 C Life Test for New Polymer Process (DC Leakage)

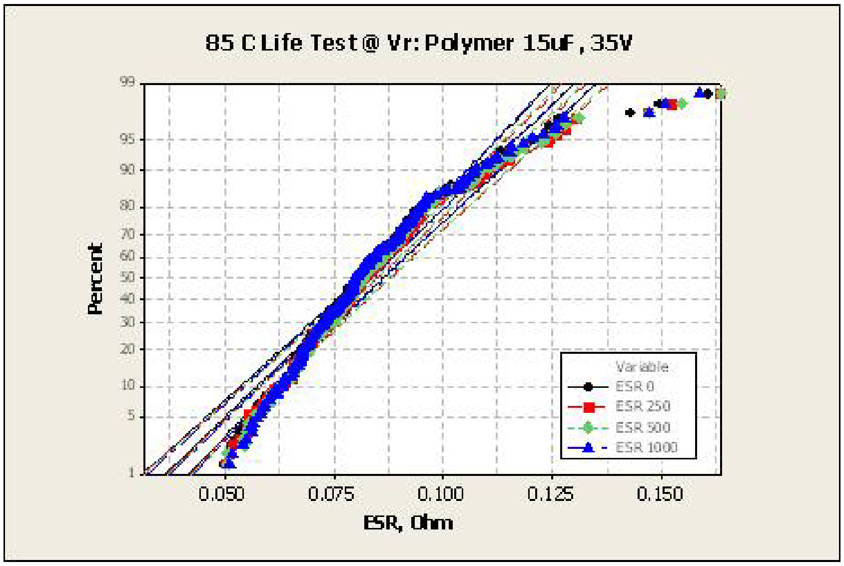

Figure 7: 85 C Life Test for New Polymer Process (ESR)

Electrical Performance

The primary goal for developing a polymer formulation for higher voltage polymer tantalum capacitors was to improve the electrical performance. While the benefits of a "non-burning/non-ignition" failure mode and a much improved voltage derating factor resulted from the use of intrinsically conductive polymers as a replacement for MnO_2, these polymers were originally developed as cathode systems for solid electrolytic capacitors in the early 1990's in order to reduce ESR and the RC-Ladder effect. To quantity the benefits this technology would bring to higher voltage applications, a comparison study was conducted using several MnO_2 tantalum capacitor technologies commonly used for higher voltage applications such as decoupling 20-24V power input rails.

<u>Component Selection</u>

For this comparison, component selection was based on the highest capacitance value and lowest ESR that has been achieved in a 50V MnO_2 tantalum chip design. Today, the highest CV ratings commonly available in a standard Commercial Series design offers up to 15uF of capacitance in a 7343-43 package size with advertised ESR limits of around 700mOhms. Low ESR designs are also commonly available with ESR offerings as low as 200mOhms. In addition, a more costly multi-anode design of the same capacitance value and case size was offered with an ESR limit of 75mOhms.

Due to the polymer devices ability to perform more reliably closer to its rated voltage (20% recommended voltage derating vs. a 50% recommended voltage derating for MnO_2), a 35V rated polymer component was selected with an ESR limit of 100mOhms. The advantage of using a lower rated voltage polymer device yielded the additional benefit of a much smaller package size as well (low profile 7343-19). Table 1 below summarizes the list of components that were selected for this evaluation.

Component Type (Common Trade Names)	Capacitance	Category Voltage	Voltage Derating Recommendation	ESR Specification Limit	Case Size (L x W x H)
Polymer Ta (T521 Series)	15uF	35V	20%	100mOhms	7.3 x 4.3 x 1.9 (Low Profile)
MnO_2 Ta (Commercial)	15uF	50V	50%	700mOhms	7.3 x 4.3 x 4.3
MnO_2 Ta (Low ESR)	15uF	50V	50%	200mOhms	7.3 x 4.3 x 4.3
MnO_2 Ta Multi-anode (MAT)	15uF	50V	50%	75mOhms	7.3 x 4.3 x 4.3

Table 1: Component Selection for Performance Comparison

ESR Performance

Initial ESR measurements were taken from 10 kHz to 1 MHz to establish a baseline for ESR comparison of the four component types (Figure 8). The resulting ESR measures below demonstrated the advantages of the polymer cathode when compared to the Commercial and Low ESR MnO_2 devices. In addition, the polymer design was found to have only slightly higher ESR than the much larger and more costly multi-anode MnO_2 design when operating at frequencies below 30 kHz and showed no significant difference in ESR at frequencies above 30 kHz.

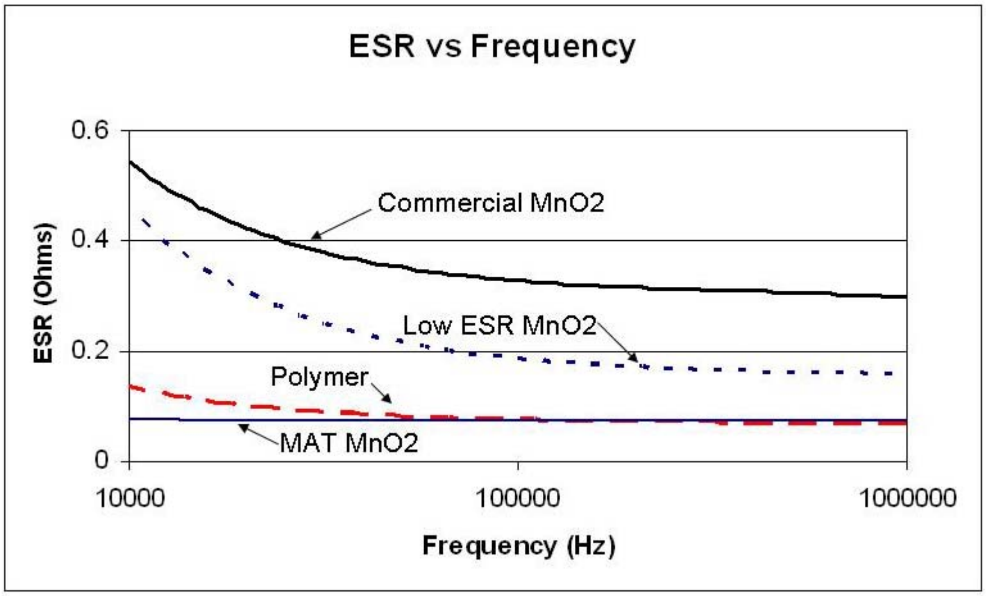

Figure 8: ESR vs Frequency for Tantalum Capacitors

Capacitance vs Frequency

With ESR behavior documented, the RC-Ladder effects were then analyzed to determine the effect on capacitance with frequency. As shown in Figure 9, the Commercial and Low ESR MnO_2 technologies lose 67% and 40% of capacitance respectively at around 300 kHz while the MAT device loses only 14% of initial capacitance. The polymer device demonstrates a capacitance response similar to that of the MAT device with only 13% drop in capacitance at 300 kHz.

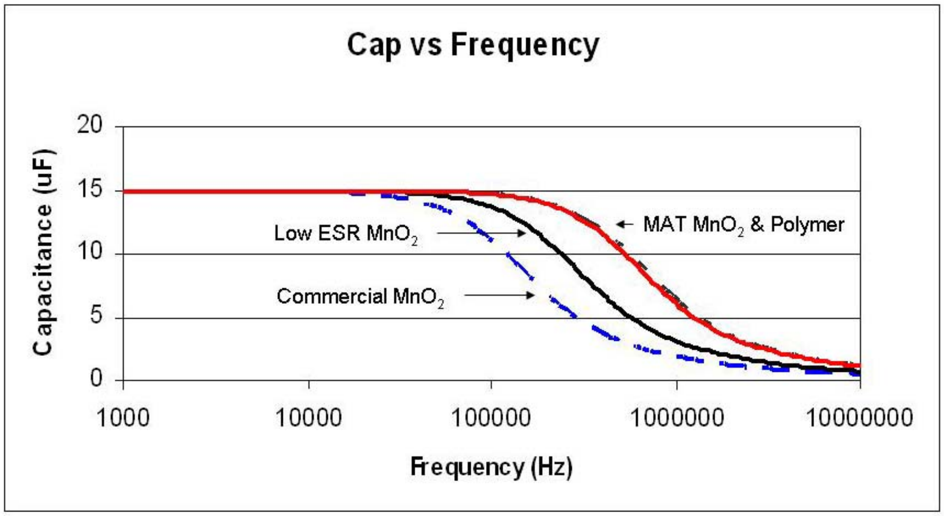

Figure 9: Capacitance vs. Frequency for Tantalum Capacitors

dv/dt Response

Once this initial assessment of component performance was completed, the next objective was to demonstrate how this technology would be of benefit on higher voltage input rails when compared to MnO_2 technologies. The improvements in ESR and capacitance roll-off can be viewed in a time domain as shown in the dv/dt plot in Figure 10. Using the same four tantalum capacitor technologies as above, a dv/dt plot was constructed to demonstrate this element. The dv is expressed as volts per ampere, as the current is another independent variable with this response. The dt is expressed in µS. We can see that there is no discernable difference in dv between the polymer and multi-anode MnO_2 device up to and beyond 100µS. However, the Commercial and Low ESR MnO_2 technologies demonstrate a more rapid decline in voltage almost immediately. If we look at a time interval of 30µS, we see that the MAT MnO_2 and Polymer experience a voltage drop of around 2.5 volts per ampere. However, the Commercial MnO_2 and Low ESR MnO_2 experience a dv of 4.3 and 3.2 volts per ampere respectively within the same time domain.

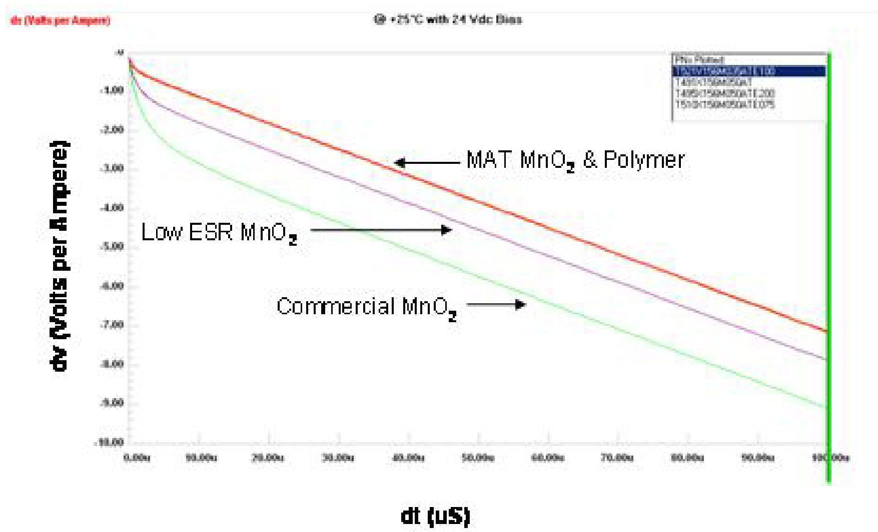

Figure 10: dv/dt Plot of Tantalum Capacitors

By targeting a specific application need, a piece count assessment can be conducted. For this exercise, a dv/dt of less than 1 volt per ampere/30µS was selected. To maintain this requirement, the piece count of each capacitor technology was increased until the dv/dt was met. As shown in Figure 11, the minimum piece count necessary to maintain this dv/dt was 5x Commercial MnO_2, 4x Low ESR MnO_2, 3x multi-anode MnO_2 and 3x Polymer capacitors.

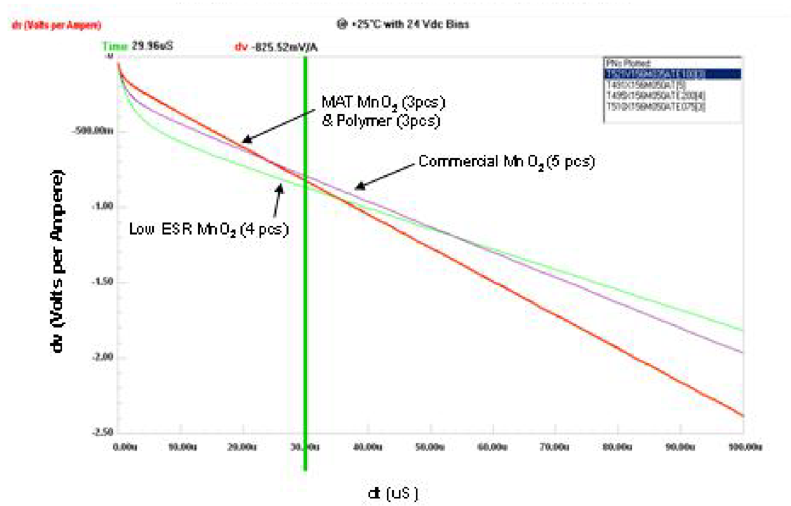

Figure 11: dv/dt Plot of Multiple Pc Count Tantalum Capacitors
dv=1V dt=30uS

COST FACTORS

Regardless of the improvements seen in the performance of polymer technology, the bottom line is the total cost for the solution. To conduct a cost analysis, the dv/dt requirements analyzed above were used to construct a cost model. In addition, a commercially available high cap MLCC structure was added to account for other volumetrically efficient package designs being considered today. The commercial MLC was selected as the state-of-the-art capability of an X7R dielectric 22uF/25V design in a 2220 SMT chip. The total cost solution for each of these component technologies is reached in Figure 12. As shown, the polymer solution represents the lowest cost solution between the selected technologies given the lower piece count and smaller case size requirement. From this point, the cost increases significantly for the Commercial MnO_2 and Low ESR MnO_2 solutions due to the higher piece count required and larger case size. The high cap ceramic solution maintains the next highest solution cost due to poor dv/dt performance which resulted in a much higher piece count as well as the higher premium placed on high cap ceramics. Finally, while the MAT MnO_2 design maintained the same piece count as the polymer design, an even higher premium is required due to the higher manufacturing cost of MAT products and the larger case size.

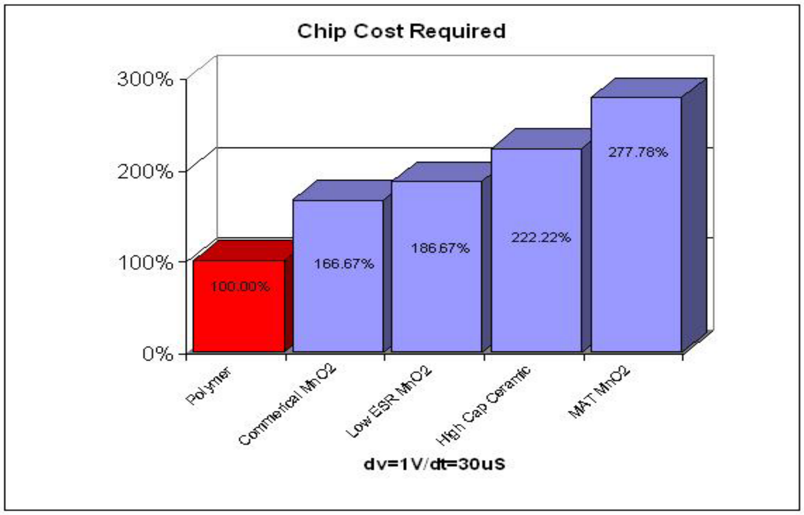

Figure 12:Capacitor Cost for dv/dt Solution

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