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Battery and capacitor technology for uniform charge time in implantable cardioverter-defibrillators

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Abstract

Implantable cardioverter-defibrillators (ICDs) are implantable medical devices designed to treat ventricular fibrillation by administering a high-voltage shock directly to the heart. Minimizing the time a patient remains in fibrillation is an important goal of this therapy. Both batteries and high-voltage capacitors used in these devices can display time-dependency in performance, resulting in significant extension of charge time. Altering the electrode balance in lithium/silver vanadium oxide batteries used to power these devices has minimized time-dependent changes in battery resistance. Charge-interval dependent changes in capacitor cycling efficiency have been minimized for stacked-plate aluminum electrolytic capacitors by a combination of material and processing factors.

Keywords: Applications/medical; Lithium/vanadium oxide batteries; Electrolytic capacitors

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1. Introduction

Fibrillation is a condition of irregular, spontaneous contraction of the individual muscle fibers of the heart. In ventricular fibrillation, the heart ceases to pump effectively, creating a potentially lethal condition. Implantable cardioverter-defibrillators (ICDs) are medical devices designed to treat cardiac arrhythmias, including ventricular fibrillation, by application of an electric stimulus directly to the heart. Implanted in the chest with leads extending into the heart, these devices operate by sensing and analyzing the electrical activity of the heart and responding appropriately to any detected arrhythmias. If ventricular fibrillation is detected, the device will administer a high-voltage shock directly to the right ventricle. These shocks may be as much as 30–40 J delivered at 700–800 V.

Minimizing the time a patient remains in fibrillation is an important goal of this therapy. The time to charge the output capacitors of the ICD is the main determinant of the interval between detection and delivery of the therapeutic shock. This is typically less than 10 s at implant.

Charge time is, in turn, determined by several factors. These factors include the power capability of the battery, the energy-efficiency of the output capacitor and the efficiency of the overall charging circuit.

The first two factors in this list, battery power and output capacitor efficiency, can vary during the service life of the device. In traditional batteries designed for this application, the power capability may vary significantly over the service life of the device, depending on time, depth of discharge, and battery chemistry [1,2]. Reductions in power capability typically reflect characteristic reductions in open-circuit voltage with depth of discharge and increases in battery impedance with time and depth of discharge [3]. The result is increased internal dissipation of energy in the battery and increased time to charge the output capacitor.

Capacitor efficiency can depend on the interval between charges. For a 6-month interval between charges, the efficiency of some electrolytic capacitors may drop temporarily from more than 90% to less than 70% due to temporary reversible degradation or ‘deformation’ of the dielectric. This temporary loss of energy efficiency means correspondingly more energy must be taken from the battery to deliver a pulse of a given energy to the heart. The result is longer charge time and loss of some battery energy to reforming the capacitor dielectric [4]. Should further shocks be needed, subsequent charges will require time and energy characteristic of a formed dielectric. The interval-dependent loss of capacitor energy-efficiency directly affects the time to deliver therapy after detection of fibrillation.

An ICD system can be designed with a certain charge time at beginning of service for a fully formed capacitor. However, decreases in battery power capability with time and

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depth of discharge and in capacitor efficiency with interval between charges can increase the time required to charge the output capacitor. Both battery and capacitor can be designed and processed in ways that minimize the variability of the system with time, with interval since the previous charge and with depth of discharge, resulting in more uniform and predictable performance.

2. Batteries

2.1. *Conventional Li/$Ag_2V_4O_{11}$ batteries for implantable cardioverter-defibrillators*

The general construction of defibrillator batteries has been described at previous International Power Sources Symposia [5–7]. To meet power requirements of ICDs, batteries are typically designed with initial power capability of 10–15 W. The cathode-active material used in most ICD batteries is $Ag_2V_4O_{11}$, produced either by thermal decomposition of ammonium metavanadate with Ag_2O [8] (‘DSVO’) or combination of V_2O_5 with Ag_2O [9] (‘CSVO’). The cathode is typically a pressed powder mixture of $Ag_2V_4O_{11}$ and small amounts of carbon and polytetrafluoroethylene. The electrolyte used in most of these batteries is 1 M $LiAsF_6$ in a 50 vol.% mixture of dimethoxyethane and propylene carbonate [6].

Batteries for ICDs have traditionally been balanced with at least 6 equivalents of lithium per formula unit of $Ag_2V_4O_{11}$. The open-circuit voltage of the couple Li/CSVO is shown in Fig. 1 as a function degree of lithiation, measured as x in $Li_xAg_2V_4O_{11}$. Resistance, measured by voltage drop associated with a dc pulse that removes 0.6–0.7 J at current density 30–40 mA/cm^2 has been shown to vary significantly with depth of discharge as shown in Fig. 2. The increase in resistance in the composition range $x = 5$–6 causes extension of the time to charge the output capacitors as the device approaches end of service. In addition to this intrinsic increase in resistance with depth of discharge, the pulse resistance has been shown to undergo a time-dependent increase in the range $2.8 < x < 4$ [1].

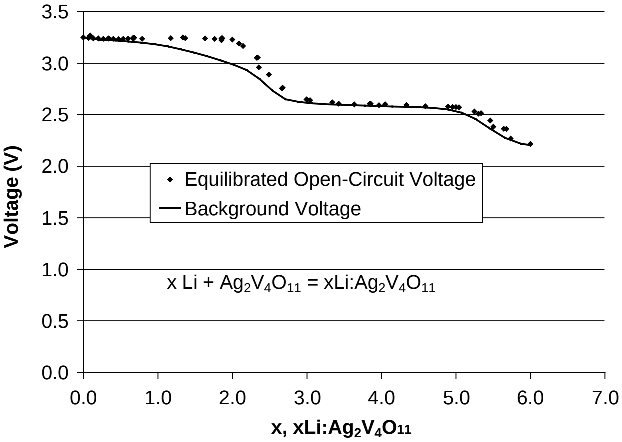

Fig. 1. Open-circuit voltage and load voltage at low current density (~0.1 μA/cm^2) of Li/$Li_xAg_2V_4O_{11}$ (Li/CSVO) as function of degree of lithiation, x.

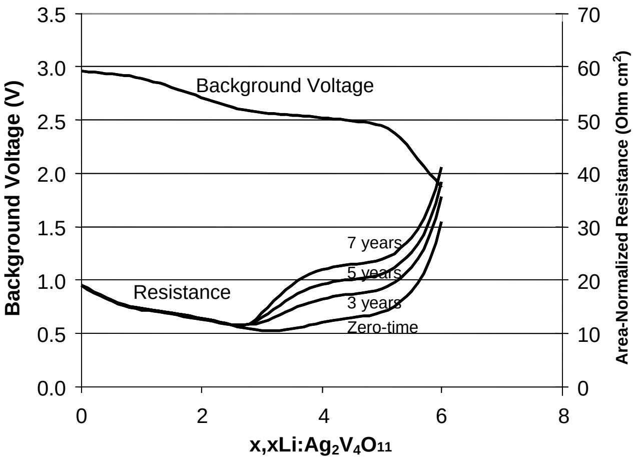

Fig. 2. Area normalized resistance for high-current pulses, as a function of degree of cathode lithiation, x in $Li_xAg_2V_4O_{11}$.

The time-dependent resistance increase appears to follow first-order kinetics in both cases, but the rate and magnitude differ significantly depending upon the type of silver vanadium oxide. With DSVO this time-dependent component of resistance can add significantly to charge time in the latter stages of discharge. With highly crystalline, phase-pure CSVO, the observed time-dependent increases are much smaller, but are nevertheless incremental to the significant intrinsic increase in resistance that occurs in the composition range ($5 < x < 6$).

Beyond $x \sim 6$, the cell potential drops to a point where lithium begins to reduce propylene carbonate from the electrolyte. Continued discharge of the cell then will produce propene gas, which can result in swelling of the hermetically-sealed battery case. In a device layout in which the battery is stacked upon the hybrid circuit, such swelling must be accommodated in the design.

To avoid the possibility of damage to the hybrid circuit from the swelling battery, when the ICD is not be explanted at the indicated end-of-service point, ICDs have been designed with a plate or standoff space between battery and hybrid circuit [3].

2.2. *The charge–time optimized battery stabilizing battery resistance and dimensions through cell balance*

Balancing the system Li/$Ag_2V_4O_{11}$ with more than 6 equivalents of lithium per formula unit $Ag_2V_4O_{11}$ maximizes the energy density of the battery, but allows significant increases in battery resistance and in time to charge the output capacitors over the normal service life of the ICD. An approach to cell design that minimizes the increase in battery resistance and in device charge time is to identify the elective-replacement point of the device near $x = 3$. At the elective replacement indicator (ERI) point, the device signals that it needs to be replaced within a specified period.

If the total lithium in the cell is <6 equivalents per formula unit $Ag_2V_4O_{11},$ then propylene carbonate will not be reduced to form propene, and the battery will have stable dimensions. Thus, a rebalanced $Li/Ag_2V_4O_{11}$ battery with more than ~3 but less than 6 equivalents of lithium per $Ag_2V_4O_{11}$ formula unit would be optimized for uniform resistance throughout the service life and for stable dimensions. This battery provides uniform, short, predictable charge times for the patient independent of depth of discharge and independent of service life. The battery has somewhat lower energy density than a conventionally balanced battery. However, this size penalty is offset in the device by elimination of the need to accommodate dimensional changes, because the cell would not generate internal gas pressure at any depth of discharge.

3. Capacitors

The other component of an ICD that normally contributes to systematic variation in charge time is the output capacitor. Traditionally, cylindrical aluminum electrolytic capacitors similar to those used in electronic photoflash units have been used for the high-voltage output. To achieve voltages in the range 750–800 V, two capacitors with voltage rating about 400 V are charged in parallel and then discharged in series.

In recent years, demand for smaller ICDs with a more rounded shape has led to development of special stacked-plate aluminum electrolytic capacitors for this application [10,11]. In these capacitors, etched foil materials similar to those used in cylindrical aluminum capacitors are cut into plates that are then stacked to form alternating layers of anode and cathode and appropriately joined.

For maximum volumetric energy density, electrolytic capacitors are designed as non-symmetrical, polar devices. Both anode and cathode are designed to have high capacitance. However, the cathode is designed with significantly higher capacitance than the anode, resulting in significantly higher voltage on the anode and most of the stored energy associated with the anode. To sustain the high voltage, a dielectric oxide is formed electrochemically over the surface of the anode at a potential greater than the desired operating potential. If a capacitor remains uncharged for some time, the capacitor may need to be cycled to restore the original charging efficiency of the capacitor. The loss of efficiency depends on the interval since the previous charge. The process of restoring the charging efficiency requires additional energy beyond the normal energy to charge the capacitor [4]. This manifests itself both as extended charge time and extra energy drawn from the battery.

Several physical processes have been identified in the charge-interval dependency of cycling efficiency of aluminum capacitors [4]. The most significant of these is thought to be oxide reformation or repairing imperfections in the aluminum oxide dielectric that grow with the interval between high-voltage charges. Partial hydration of the aluminum oxide at the interface with electrolyte is thought to promote deformation by stressing the dielectric layer resulting in cracks that breach the dielectric layer.

Electrolytes are typically complex mixtures of glycol, water, and other solvents together with dissolved salts, typically salts of mono- and dicarboxylic acids and salts of inorganic oxyacids. Moisture contents of commercially available electrolytes for aluminum capacitors can range above 5 wt.%. Use of electrolyte formulations that achieve good electrical performance with lower water content in conjunction with assembly and processing conditions that minimize water content and use of optimized electrical conditioning of the capacitor can significantly reduce the rate

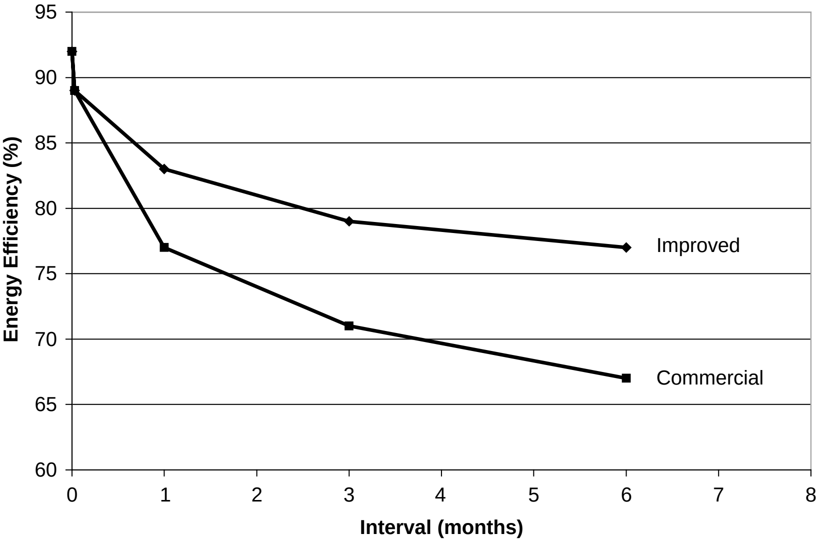

Fig. 3. Cycling efficiency of commercial cylindrical and improved stacked-plate aluminum electrolytic capacitors as a function of interval between charges.

of deformation in aluminum capacitors. Two examples of overall energy efficiency, defined as (energy output/energy input) are shown in Fig. 3. Energy efficiency contains resistive losses, deformation and other dielectric losses that occur on the time scale of a typical charge–discharge cycle. The ‘improved’ stacked-plate capacitor shows a marked reduction in such losses relative to typical cylindrical photoflash capacitor technology. The details of these improvements are beyond the scope of this paper.

4. Reducing systematic variation in charge time

Interval-dependent decreases in capacitor efficiency and time-dependent increases in battery resistance can each contribute to lengthening the interval between detection of fibrillation and delivery of therapy. Interval-dependent variation in efficiency of aluminum electrolytic capacitors can be minimized by minimizing water content of the capacitor and by optimized electrical conditioning. Time-dependent increases in battery resistance can be reduced by conditions used to synthesize the silver vanadium oxide battery cathode material.

Overall increases in battery resistance can be minimized by balancing the cell for ∼3-electron reduction of $Ag_2V_4O_{11}$ instead of the traditional >6-electron balance.

Empirical models have been developed that describe battery power capability as a function of time and depth-of-discharge and of capacitor cycling efficiency as a function of charge interval [1,3]. The battery model was developed with data over a range of discharge rates up to 7 years for conventionally balanced batteries and has been extended to batteries balanced for ∼3-electron reduction. Using these models, the total systematic variation in charge time can be simulated over the field of device longevity and charge interval, assuming uniform discharge rate and charge interval.

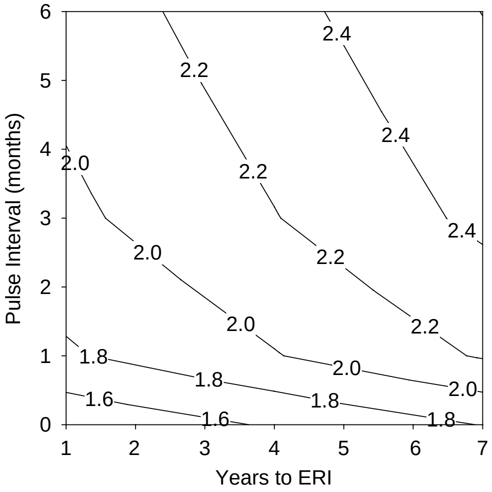

Fig. 4. Charge–time ratio for conventionally balanced Li/CSVO battery paired with conventional cylindrical photoflash capacitors. Charge–time ratio is the time to charge the output capacitors the first time after discharging a given number of years to the elective replacement indicator (ERI) point and for a given interval since the previous charge of the capacitor, normalized by the corresponding charge time for a fresh battery charging a fully formed capacitor.

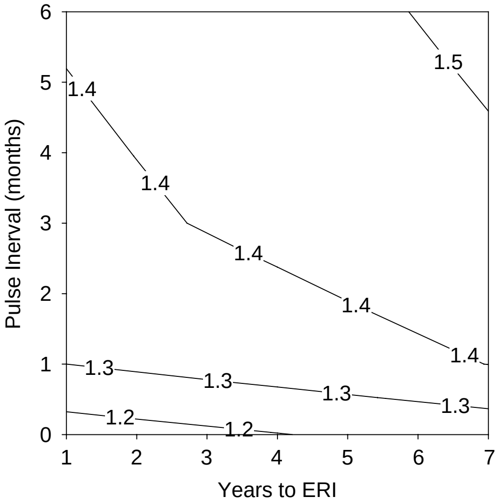

Fig. 5. Charge–time ratio for battery balanced for ∼3-electron reduction of $Ag_2V_4O_{11}$, paired with optimized stacked-plate aluminum electrolytic capacitors.

Two cases are shown, plotted as ratio of first-cycle charge time at the elective replacement point, near end of the device service life, to the charge time for a fresh battery charging a fully formed capacitor. This ratio is displayed over the field of time to reach elective replacement and charge interval. Contours of equal charge time are indicated. The first pairing, shown in Fig. 4, employs a conventionally balanced ICD battery based on CSVO with a typical commercially available photoflash capacitor. The second example, shown in Fig. 5, shows the same ratio for a battery balanced for ∼3-electron reduction of $Ag_2V_4O_{11}$ charging a stacked-plate aluminum electrolytic capacitor that has been manufactured with materials and processes designed to minimize interval-dependent losses of cycling efficiency. The two capacitors are sized to deliver the same energy when discharged in an ICD circuit.

In the first instance, it may take as much as 2.4 times as long to charge the capacitor after a 7-year discharge and a 6-month interval since the previous charge as when the battery was fresh and the capacitor fully formed. In the second instance the same ratio has been reduced to a maximum of about 1.5.

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