BATTERY CHARGING:

New Technologies for New Designs

Advanced Charger Technology, Inc. (ACT)

A. INTRODUCTION

Since the 1990s, the number of battery-powered devices in the marketplace continues to exponentially increase. Dependence on these portable devices has transformed every aspect of our lives. Nowhere is this more evident than with portable communication devices. The increase has fueled remarkable improvements that differentiate products in vertical markets – and consume even more power than ever. This paradigm shift, which has taken portability from a novelty to a necessity, has led us to expect our tools to perform reliably and consistently. But even the best-designed portable products have an Achilles' Heel that hasn't been addressed. Batteries do not deliver the consistent reliability and performance the products require. They lose capacity, they deteriorate, and they allow our critical tools to fail us.

Rechargeable batteries have improved over the years as product designers have moved from Nickel Cadmium (NiCd) to Nickel Metal Hydride (NiMH) to Lithium Ion (Li Ion) to meet the increasing power demands. In spite of these changes, battery power problems are still a top customer complaint throughout the portable industry. Newer, better batteries cannot solve power problems when old charging routines are used. With all the effort spent developing new battery chemistries and improving old ones, little effort has focused on the charging system. Without the charging system, *any* battery is useless. With a standard charging system, a battery powers the device, but lengthy charge times, capacity loss and poor product performance are the norm. As long as batteries are a consumable product, and business projections depend on their obsolescence, battery manufacturers will not build a better charger.

B. General Overview of Battery Chemistries

Unlike mass-market, single-use batteries, rechargeable batteries vary in chemistry, construction and size. Designs vary according to the usage requirements, such as power draw, form factor and operating temperatures, of the device for which they are designed. Some battery designs accommodate fast charging better than others, but charging speed can be limited by the size of the power supply available to provide sufficient current for a faster charging rate.

Nickel Cadmium Batteries

For decades, NiCd batteries have been the "workhorse" of the portable industry. Compared to other battery types, NiCd costs the least per cycle to operate, and can last more cycles – from 300-600 under normal conditions. The drawbacks to NiCd batteries is their heavier weight, their susceptibility to the memory effect, which decreases capacity, and their cadmium content, which means they must be disposed as hazardous chemicals. NiCd batteries can be charged in as little as 1-2 hours, but most NiCd chargers take three to 16 hours to deliver a full charge. The factor limiting charge time for every battery is the amount of polarization that develops. The polarization results from different mechanisms, including mass transport and diffusion limitations. **DEW™** technology has successfully increased charging speed to meet the electrochemical state of the battery, and achieved more than 2000 cycles on average with NiCd batteries.

Nickel-Metal-Hydride (NiMH) Batteries

NiMH batteries have replaced NiCd's in many applications where weight and capacity impact the marketability of the portable device. NiMH use is increasing in countries with strict environmental codes, as NiMH is believed to have fewer toxic disposal limitations than NiCd. NiMH can cost about twice as much as a NiCd battery, and has somewhat better weight and volume energy density than NiCd. However, NiMH evolves more heat than NiCd during charging, has a high rate of self-discharge and is more difficult to terminate at full capacity during charging. A NiMH battery can be charged at 1.5-2C rate with the correct algorithm.

Lithium Ion (Li-Ion) Batteries

The Li-Ion battery is fast becoming the portable battery of choice on the market today. High energy density and higher voltage per cell make Li-Ion the premier battery for the next century. However, relatively higher costs and fewer charge/discharge cycles have limited its application. Since lithium is a highly reactive metal, extra precautions must be taken to ensure the batteries are fully charged without being overcharged. Although standards of Li Ion batteries have improved, safe handling is a priority. Overcharging and overheating can result in damage to the battery and its associated device. With standard chargers, Li Ion batteries are charged in 3-6 hours and last about 300 cycles. **DEW™** technology charges Li on batteries in less than 90 minutes and averages 1800 cycles.

C. COMMON BATTERY CHARGING METHODS

The standard battery charger has always been a trickle charger, which delivers a steady, low-level 100-200 mAh, positive current. It takes 10 or more hours to charge a battery and doesn't terminate at maximum capacity; increasing the likelihood of overcharging, heat generation, inadequate charged capacity, and a shorter life for the battery. The extended low charge rate also enables chemical reactions to localize on the electrode surface, leading to dendrite growth and oxidation.

In the case of NiCd and NiMH, if the battery isn't discharged prior to a trickle charge, voltage depression or "memory effect," which often causes the early demise of batteries, begins to occur even sooner. When NiCd batteries and, to a lesser degree, NiMH batteries are recharged before they are fully discharged, electrodes oxidate, dendrite growth is accelerated and other reactions occur which reduce the batteries capacity.

Most fast charging systems use Constant Current/Constant Voltage (CC/CV) techniques and charge the battery in two to six hours. They usually maintain the high current rate until a specified voltage is reached and then decrease current to hold that voltage. Over time, charging at a high constant current rate causes significant deterioration, similar to, or worse than the trickle charger. This will result in reduced capacity with each charge, rapid wear-down and fewer charge/discharge cycles for the battery.

Pulse charging, first introduced to charge Lead Acid batteries in 1918, helped extend battery life and speed up charge times, but has not been the breakthrough that it was hyped to be. Most pulse chargers insert one positive and one negative pulse of fixed size and then follow the trickle charge or the CC/CV routine. Since the battery exhibits properties of a capacitor and a resistor, these pulses affect little change, as they do not deliver significant current to alter the battery.

D. CHANGING THE PARADIGM: DEW™ TECHNOLOGY

In 1989, Chief Research Scientist Yury Podrazhansky found that approaching the battery from the atomic perspective allowed him to create a process that controls the atoms, ions, molecules and compounds in a battery, battery charging entered a new phase. His discovery resulted in a process that charges batteries up to 10 times faster and more than triples battery life in NICD chemistries. The breakthrough in battery charging introduced with **ACT**'s first patent has improved over a decade of dedicated research, developing into a comprehensive *battery operating system* called Dynamic Electrochemical Waveform (**DEW™**) technology, which is embedded as software onto a microcontroller.

DEW™ technology offers the first significant opportunity to impact design and functionally in battery-powered devices. Continuous research has yielded remarkable results in the three major rechargeable battery chemistries – Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH), and Lithium Ion (Li Ion). **DEW™** technology reduces charging times by as much as 90%, dramatically extends the life of the battery, minimizes battery heating while charging, delivers maximum capacity consistently and reduces formation time both in the manufacture and initializing of batteries.

Podrazhansky discovered a method that generates a response from the battery that is analyzed by a microcontroller to determine what was happening inside. He found that by using an intelligent fuzzy logic software process he was able to control the electrochemical process inside the battery. The fuzzy logic controller uses positive and negative current pulses of many shapes and sizes that may change in response to the battery on a millisecond basis. Some batteries may need very short, multiple negative pulses with a very high magnitude to increase their ability to accept a charge. These larger magnitude discharge pulses are inherently focused in the area of dendrites that form on a battery's cell plates. When allowed to build up, dendrites can short-circuit a battery's electrodes. The brief, high currents rapidly balance the ion concentration and improve the crystalline structure of the electrodes and remove dendrite formations. In NiCd batteries, they momentarily pull the battery voltage down, resulting in the *reversal of voltage depression*. The improved balancing of ion concentration and removal of the inner and outer Helmholtz plane leads to a highly efficient charge process that enables a much higher charge current, yielding the shortest charge times possible and uniquely conditioning batteries as they are charged, eliminating the need to discharge first.

DEW™ software provides real-time control of the atomic level electrochemical reactions during the charge process. This real-time control, along with the ability to monitor the electrochemical reactions and provide instantaneous feedback, allows **DEW™** technology to efficiently charge any battery while increasing its cycle life. Since each battery is composed of different materials (NiCd, NiMH, Li-ion), the **DEW™** software has a set of tuned algorithms for each type of battery. The algorithms in this unique battery operating system create varying current waveforms that dynamically change shape, amplitude, direction and duration in the millisecond range in response to feedback from the battery. This allows the control of ion creation, transport, consumption, concentration gradients, diffusion rates and intercalation speeds. At the same time, the side reactions frequently caused by standard chargers, which are the main cause of battery failure, are inhibited and often reversed, restoring the capacity of the battery.

To demonstrate the **DEW™** technology, the company developed prototype chargers which fully charge a 6V NiCd battery pack to 100% in five minutes with less than 3 degrees of heat rise, and a Li-on battery pack from dead to full in 45-70 minutes with more than 1800 full charge-discharge cycles. The implications for such speedy delivery of charge can significantly impact the design and usage of many portable products, as well as reduce the cost of ownership. An illustration of a few of the **DEW™** waveforms is shown in Figures 4a, 4b, 4c, 4d and 4e.

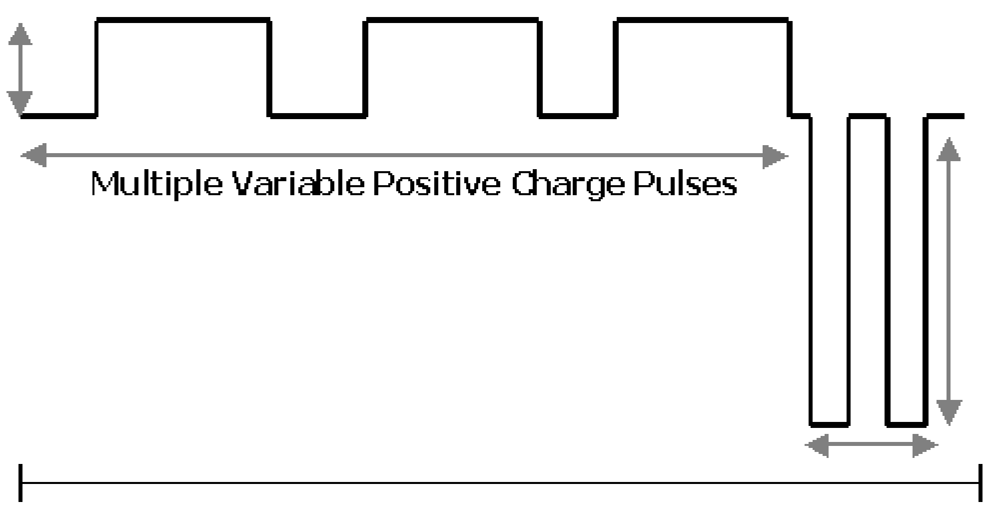

Figure 4a

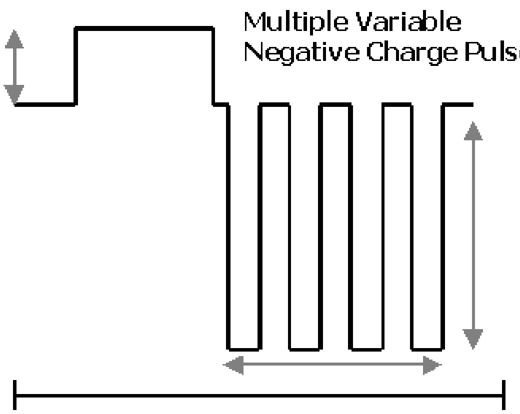

Figure 4b

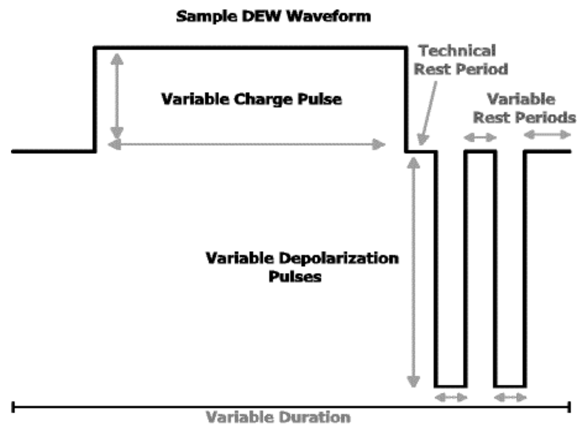

Figure 4c

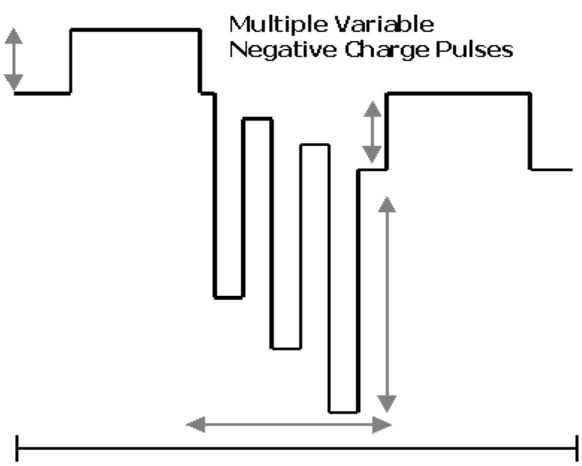

Figure 4d

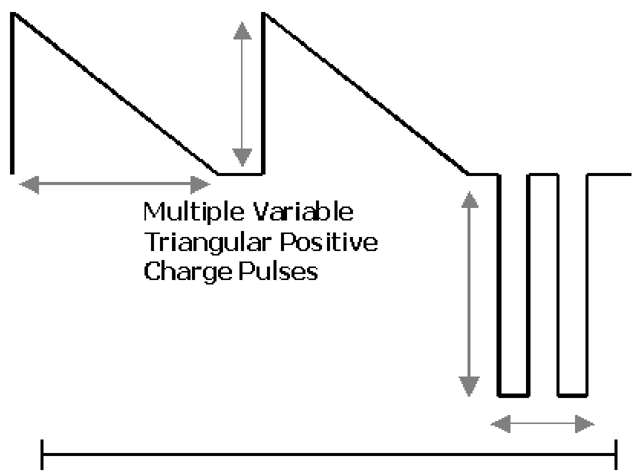

Figure 4e

Termination

Podrazhansky's research into intelligent charging techniques resulted in the discovery that the common methods of termination lacked the level of sophistication necessary to prevent battery degradation. For instance, he found that methods that relied on the sensing of battery voltage and its negative change did not provide a reliable indicator of the completion of a charging cycle. The reason for this is that the battery voltage is not a stable indicator as it varies as a function of temperature and charge cycle history. Another technique that is commonly used is a temperature sensing method. In practice, this method fails because the temperature warning is sensed too late to prevent the battery from becoming overheated. A final technique used for termination is based on the passage of a particular length of time. This approach depends upon the assumption of the battery's particular state of charge at the beginning of the charge cycle. Because this is not commonly known, this method typically either undercharges or overcharges the battery.

Optimum detection of full capacity requires increasingly sophisticated algorithms and sensing circuitry so ***ACT*** technology utilizes several patented termination techniques. The foundation of the ***ACT*** process stems from the extension of real-time feedback and control. Because the **DEW™** software is constantly monitoring the battery's condition, the intelligent waveform adjusts as the battery approaches full capacity. Numerous measurements of the battery's active components are acquired during the application of the charge algorithm, which are analyzed by the **DEW™** software programmed into the microprocessor to calculate the battery's exact state of charge. Because this method is not based on assumptions or estimates, the charging process can be stopped at full capacity without overcharging. This avoids the necessity of a "topping" charge, which can triple the charge time, to ensure a complete charge. Figure 5 depicts the process of continuous monitoring during a charge cycle.

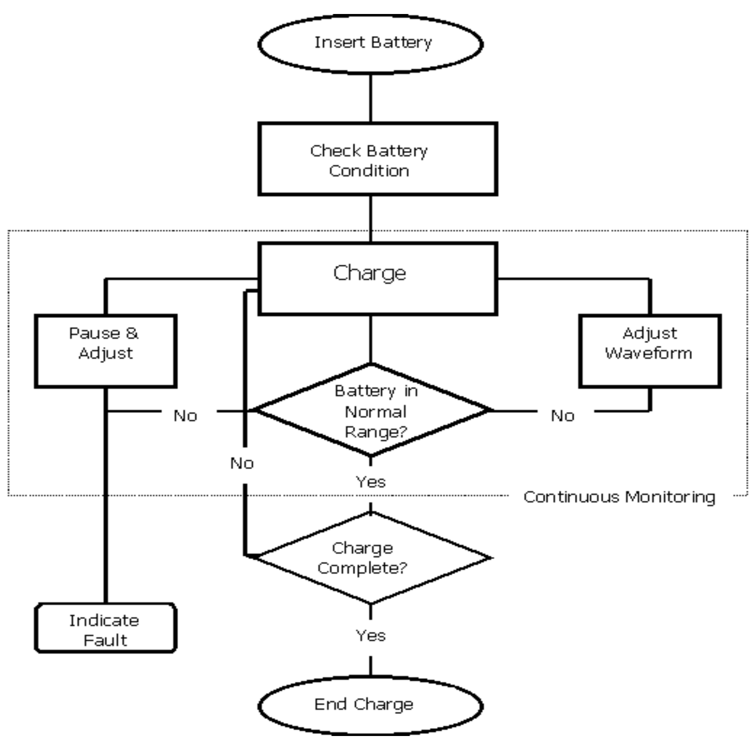

Figure 5

E. Summary

The benefits of using a lighter, smaller, longer-life battery will result in user-friendly devices that deliver peak performance as dependably on the 1500th day of use as on the first. Highly sensitive, power-dependent products such as medical and military devices can be designed for portability with confidence. Battery failure will no longer hinder our work or undermine product performance.

DEW™™ technology has been widely accepted and is in use throughout the world by all branches of the US Military, US Federal, State, and Local agencies as well use among the International First Responder community.

The ACT iCHARGE™ products are the only chargers capable of monitoring the internal condition of the battery and changing the waveform accordingly. The charge can alter the electrochemical structure of the battery cells and keep batteries in a constant charge-receptive state, which allows the ACT charger to improve the battery cell structure and performance. No other charger can provide the unique, individual response to optimize batteries that **DEW™** technology delivers. Battery failure will no longer hinder our work or undermine product performance. There will be no more Achilles' Heel for batteries.

Addendum

Products

The ACT iCharge™ line of intelligent chargers provide all the benefits of a conditioner. A micro-controller manages the charging process, and begins operating automatically when the user inserts the battery. The micro-controller immediately assesses the condition of the battery, and, based on this condition, determines which processes to implement.

If the battery is in nominal condition -- used and discharged but otherwise fine, the charger will switch directly into charge mode, conditioning the battery as it charges. The DEW™ micro-controller monitors voltage and current levels as the battery is being charged, adjusting the charging algorithm to achieve maximum charging receptivity. When charging is complete, a *charge complete* indicator illuminates for the user and the ACT charger halts automatically, delivering the battery in peak condition without overcharging. The battery can be left on the ACT charger indefinitely without damage.

As a result, current density can be increased during a charge pulse while dramatically decreasing the possibility of dendrite growth. These factors and the absence of heat combine to create optimal charging parameters for the battery. The result is a maximum-capacity charge, which extends battery life and can be performed at remarkably high speeds – up to 10 times faster than other charging methods.

Comparison

The first patent on pulse charging was issued in 1918. Beginning in the early 1970s, pulse charging with a discharge pulse was incorporated into battery chargers. The pulse charge was a small improvement over constant current charging, but batteries still heated up, and maximum battery cycle life was not achieved. The single, high-magnitude negative pulses used in these methods cause ion transportation problems in the reverse direction, as well as excessive discharge of the battery, which increases potential charge time.

Other problems found in battery chargers using this dated method are those caused by the application of “topping” charges and “maintenance” charges. For example, the charger will switch from the fast charging mode to the topping mode when it has sensed that the battery has reached full capacity. If a battery has a 1000 mAh (1 Amp Hour) capacity, the termination method found in the fast charge mode will theoretically stop the fast charge stage when the battery has reached 1000mAh. At this point, the topping stage will begin to apply current at a C/10 rate or 100 mAh per hour (1000mAh/10 = 100mAh). The topping charge stage lasts for 2 hours, meaning that an additional 200mAh of energy is pumped into the battery. If the battery was in fact charged to 1000mAh during the fast charge stage, the topping charge stage will have over-charged it by 20%.

Next, the maintenance mode will continue to apply 25mAh per hour as long as the battery is left on the charger. The purpose of the maintenance charge is to counteract a battery’s natural self-discharge rate. Rechargeable batteries have some degree of self-discharge, meaning that if left alone, capacity will diminish over time. The self-discharge rate of NiCd batteries is approximately 1 percent per day and NiMH batteries have been known to self- discharge at roughly 3 percent per day at room temperature. The application of the maintenance mode, continuing with our 1000mAh battery example, will apply an additional 600mAh of energy every day, 4,200mAh of energy every week and 16,800mAh per month! Clearly, the application of the maintenance stage is far greater than what is required to maintain a battery at full capacity. Further, overcharging batteries produces an abundance of oxygen and hydrogen to develop which cannot be recombined into the battery's electrolyte. This occurrence leads to a rapid degradation of the battery's active chemical materials.

The DEW™ technology differs from other technologies in that it actually varies according to the specific electrochemical state of the battery being charged. The battery is charged in a high current mode until diffusion limitation occurs. From this point of charge, the microprocessor reduces the amplitude of the charging current, maintaining the charging process at maximum possible speed. The *ACT* charging innovations, which enable batteries to be charged at very high currents without detrimental temperature rise, actually condition batteries as they are charged and eliminate the need to discharge first. Proper sensing of the battery condition during the charging process and the ability to alter the electrochemical structure of the battery cells by controlling the kinetics of the chemical reaction during charge for maximum efficiency are two major gains achieved with the ACT charging technology.

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