Advanced Battery Charging Techniques: Pulse-Charging in Large-Scale Applications – Design of Divide and Conquer Technique for High-Capacity Batteries

Tho Nguyen, Linda Bushnell
Department of Electrical Engineering
University of Washington
Seattle, WA 98195-2500
tho@ee.washington.edu

1. Abstract

This paper analyzes the potential of intelligent pulse-charging for large-scale applications. A novel *divide and conquer* technique is developed to efficiently apply pulse-charging method in high-capacity battery pack applications. Experiments, which are conducted on a small-scale system, validate the effectiveness of the proposed charging method.

2. Introduction

Having a reliable battery is possibly the biggest issue facing the advancement of wireless technology today. As the demand for battery power grows, the size of the battery pack gets bigger and charging techniques become more complicated. The battery charging issue is ubiquitous in all electronics applications. It is clearly the limiting factor in the application area of autonomous mobile robotics. Like other areas of technology that work with autonomy and mobility of electronics, the challenge is to find a reliable battery package for the robots.

In an effort to investigate this problem, a study was launched to look into current literature, to examine currently available technology in intelligent battery charging, and to explore new solutions of battery charging systems for large-scale applications. This study encompasses two main parts. The first part covers an examination of three different intelligent charging methods through current literature and their current application. The second part of the study analyzes the principles and properties of intelligent pulse-charging. A conjecture is made that pulse charging can and should be applied in large-scale applications. The unique contribution of this paper is a new method for pulse-charging for large-scale applications. Real hardware experiments show the effectiveness of the proposed pulse-charging method.

This paper is organized as follows. In Section 3, three intelligent charging methods are presented and evaluated. Section 4 presents the new *divide and conquer* pulse-charging method. Section 5 concludes the paper.

3. Three Intelligent Charging Methods

In a basic battery, a chemical reaction takes place inside the battery and releases energy in the form of charge during usage. Once the chemical reaction is finished, the battery is "spent" or discharged. The idea behind charging is to put energy back into the battery to be stored and used again. As the most damage done to a battery is usually while it's being charged, intelligent control is necessary to properly charge a battery. There are several ways to do accomplish this task. The most common and recently developed methods are as described below:

Galvanostatic Charging: The most common and direct approach is to charge a battery is to force energy back into a battery by applying a higher potential across the terminals. As the name "Galvanostatic" implies, this technique involves driving a constant current into the battery. This method can be used to charge the battery quickly and is simple to implement.

Pulse-Charging: A second, and more recently developed, method of charging is called "pulse charging." This method also involves sending charge back into the battery; however, it is not done at constant current. Instead, pulse-charging cycles between a period of constant current into the battery and a brief moment of rest, as seen in Figure 1. The idea behind this technique is to allow time for the chemical reaction to settle, so the battery is charged more uniformly. This minimizes problems with the formation of the physical chemical make up of the battery – hence reducing long-term damage to the battery.

Burp-Charging: Along with the development of the pulse-charging method, another similar method was developed, called "Burp" charging. The name came from a very brief moment of discharge within the pulse-charge cycle (optimal discharge pulse relative to charge cycle can be calculated from algorithm discussed later). The idea behind the discharge pulse is to redirect the migration of oxide gas away from the reacting plates, preventing oxidization, allowing the battery to prolong its life and capacity.

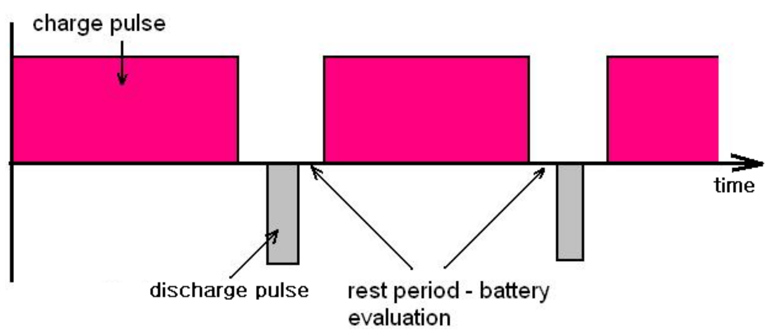

Figure 1. - Typical Pulse-Charge Cycle (only burp-charge has discharge pulse).

The development of the above three methods of intelligent charging led to studies to determine their effectiveness. One of the most thorough studies was done by NASA Johnson Space Center on battery life under these methods of charging [Darcy]. The NASA study examined battery capacity and life cycles through various charge methods. The data result from testing NiMH charge using pulse, burp, galvanostatic, and galvanostatic to 45^{o} C (constant charge current until battery temperature reaches 45^{o} C – note that once battery is full, extra energy is converted to heat). The test result indicate that galvanostatic to 45^{o} C produces the worst result, while the other three methods produce seemingly the same pattern as far as charge capacity, pulse-charge and burp-charge does extend battery life toward the end.

The NASA study also looked at the heat and gas generation by various charge methods. In respect to gas generation, pulse-charge and burp-charge consistently produces less gas than galvanostatic method. As for heat generation, pulse-charge and burp-charge produces less heat than the conventional galvanostatic method again – with significant improvement from the burp-charge method. Note that excess heat is very damaging to a battery.

From available literature and data, a conclusion can be drawn that pulse-charging methods – inclusive of both pulse-charge and burp-charge – are superior to the conventional galvanostatic method. It can prolong the battery life, reduces gas and heat generation while charging (which also decreases battery hazard to the outside environment). Though the overall results of both charge methods are almost comparable, however, burp-charge has a slight superiority over pulse-charge.

4. The *Divide and Conquer* Pulse-Charging Method

Even though the advantages of pulse-charging can easily be seen and explained, this relatively new idea has been slow to integrate into various industries. There are a handful companies in the world who are pursuing the design and manufacture of chargers using these new ideas. One can attribute industry's resistance to these new pulse-charging methods to the lucrative business of battery and replacement parts manufacturing.

Despite being largely ignored by the industry for the most part, pulse-charging is slowly expanding into the consumer market. For now applications of pulse-charging remain at the small-scale. Pulse-charging applications include portable electronic devices in government agencies such as police and firefighter walkie-talkie radios, specialty tools, and limited use in consumer electronics such as power tool and remote control toys. The technology is currently expanding and undoubtedly will be available to the average consumer in the future but for now the option remains very limited.

As current literature indicates, pulse-charging has been tested and verified to be superior to conventional galvanostatic method. However, testing was largely conducted on low-capacity battery cells – capacity ranges at average consumer electronics level. The authors of this paper hypothesize that pulse-charging can be equally beneficial in large-scale application (i.e., charging Hybrid-Electric Vehicle batteries where operating voltage and current are very high) if implemented correctly. Due to the dangerous nature of high-capacity batteries (fatalities have resulted from certified technician working on HEV batteries), specific tests with high-capacity batteries were not conducted; instead, the proposed *divide and conquer* charge method is verified in a low-capacity battery with the same characteristics. Detailed feasibility analysis below shows that integration of pulse-charging into large scale applications has high potential and should yield the same benefits.

Charging of a high-voltage battery pack can be done in two ways. The first is to apply charge to the entire battery pack by one charger. However, most high capacity batteries are usually broken into smaller sections to output desired voltage (i.e., an HEV may want to draw a small voltage for its electronics along with another higher voltage for the electric motor). This characteristic leads to the ability to partition the battery into smaller capacity sections. Therefore, a second way to charge a high capacity battery is to have a series of smaller chargers working on charging small sections at the same time – this is the basic idea behind the proposed charging method.

High Capacity Battery Charged as Single Pack

A high capacity battery pack consists of either many small battery cells, or larger cells (but fewer in number). As mentioned earlier, pulse-charge's advantage lies in its ability to allow the battery to rest between pulse cycles to achieve a uniform charge (chemical reaction has time to take place uniformly). In case of a larger battery cell, it is only intuitive that the battery charge cycle must be **extended** in order to achieve the same effect. An equation for calculating the optimal charge cycle of a battery can then be determined by:

$$T = \tau_{charge} + \tau_{initial\_rest} + \tau_{discharge} + \tau_{secondary\_rest}$$

Where **T** is the total charge cycle time, τ_{charge} is charge pulse duration, $\tau_{initial\_rest}$ is the initial rest duration, $\tau_{discharge}$ is the discharge pulse duration, and $\tau_{secondary\_rest}$ is the rest time after discharge. Battery evaluation is also performed during the rest time after the discharge.

The relationship between the battery capacity and charge time is proposed to have a logarithmic correlation. This relationship is shown below in Figure 2.

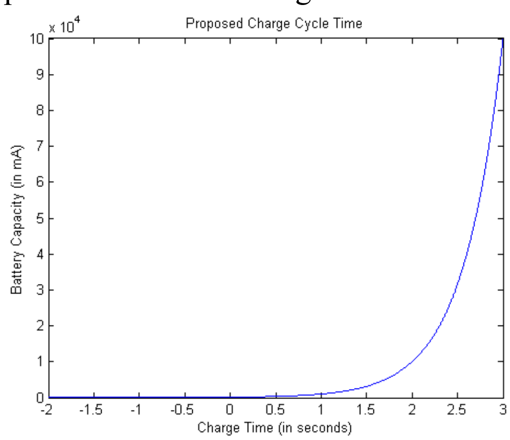

Figure 2. Charge Cycle Time and Battery Capacity Relationship

Charge cycle time can then be calculated as follows:

$$C_T = \log_{10}(Battery\_Capacity_{in\_mA}) - 2$$

Where C_T = charge-cycle time. Individual time slices within the charge cycle can be calculated using:

$$\tau_{charge} = \alpha_1 C_s \qquad \tau_{initial\_rest} = \alpha_2 C_s$$
$$\tau_{discharge} = \alpha_3 C_s \qquad \tau_{secondary\_rest} = \alpha_4 C_s$$

Where $\propto_1 = 0.98$, $\propto_2 = 0.005$, $\propto_3 = 0.005$, $\propto_4 = 0.01$

Therefore, a 1000 mA capacity battery has cycle time of 1 second, τ_{charge}= 980µs, $\tau_{initial\ rest}$= 5µs, $\tau_{discharge}$= 5µs, $\tau_{secondary\ rest}$= 10µs. A 10,000 mA battery will have twice as long charge cycle time and time slices.

The Divide and Conquer Approach to Charging a High-Capacity Battery Pack

Our proposed method for implementing pulse-charge in high-capacity batteries is to partition the battery pack into smaller sections (possibly already done to accommodate by the electronic requirement variations). This is shown in Figure 3.

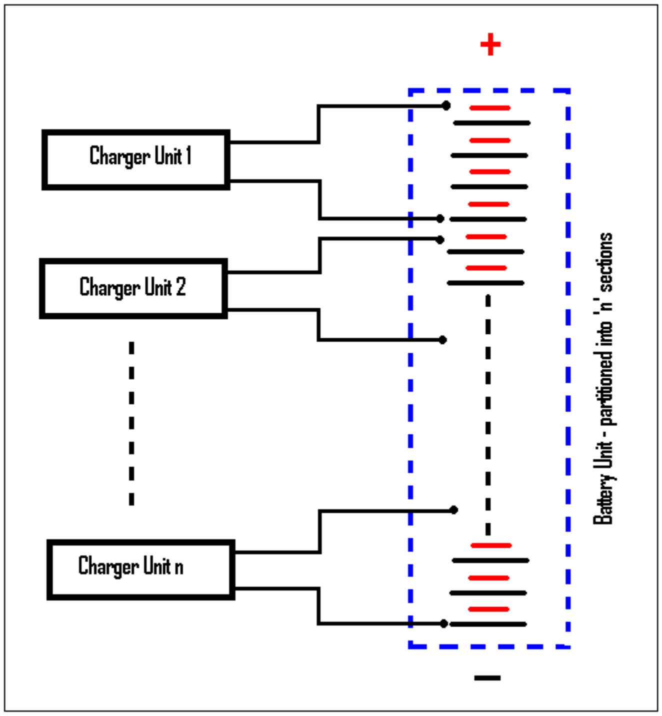

Figure 3. The Divide and Conquer Method to Charge a High-Capacity Battery Pack.

A series of pulse-chargers is then applied to charge these sections individually. The reasoning behind this method is that if a battery pack is comprised of individual cells, the cells' characteristics are not identical hence may not charge/discharge at a uniform rate as the pack is in used. Therefore, breaking the pack into smaller sections and charged individually with an intelligent charger allows them to be conditioned correctly and more uniformly.

Charging individual sections as shown above is proposed as the better method to charge a high capacity battery pack. However, implementation of this method is more complicated and expensive than charging the pack as a whole. Additional control logic needs to be implemented to keep the chargers' inputs and multiple load outputs to maintain efficiency.

5. Conclusion

Advances in advanced battery charging technology have been numerous, including the development of the battery conditioning concepts, intelligent fast charging, and pulse charging. Pulse charging combined with intelligent control yields many advantages over conventional methods in maintaining battery capacity as well as extending battery life. This paper proposes a new *divide and conquer* method to charge small sections of high-capacity battery pack, which was experimentally shown to be more efficient than charging the whole battery pack simultaneously.

Applications of this new battery charging method are currently being explored. Future work includes testing out the proposed methods on real high-capacity batteries such as the hybrid-electric motor used in automobiles.

Acknowledgements

The authors would like to thank George Sage P.E. (Pulse Power Inc.), Dave Whitmer (Galaxy Power Inc) and Andy Crick (ARCS lab mentor) for their insight and comments on this work.

References

[Darcy] – Eric C. Darcy, "Investigation of the Response of NiMH Cells to Burp Charging," A Dissertation Presented to the Faculty of the Chemical Engineering – University of Houston, December 1998.

Eric C. Darcy, "Burp Charging Nickel Metal Hydride Cells," NASA – Johnson Space Center, October 1995.

T. J. Liang, T. Wen, K. C. Tseng, J. F. Chen, "Implementation of Regenerative Pulse Charger Using hybrid Buck-Boost Converter," Proceedings of IEEE 4th International Conference on Power Electronics and Drive Systems, Oct. 2001

K. C. Tseng, T. J. Liang, J. F. Chen, M. T. Chang, "High Frequency Positive/Negative Pulse Charger with Power Factor Correction," Power Electronics Specialists Conference, IEEE, June 2002.

David Whitmer, "Makita Cycling NiMH – 14.4V/2.2A NiMH Power Tool Battery Life Cycle Comparison Using Makita DC1411 Charger," Galaxy Power Inc., 2003.