BATTERY VOLTAGE RESPONSE TO PULSE CHARGING

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Abstract: Study of the voltage response of Ni-Cd, Ni-Mh, Lead-acid and Li-Ion accumulators to rising voltage, falling voltage, two load pulses and two pulse trains for specific purposes. The electrochemical system in the battery always oscillates around an equilibrium point. When this state is disturbed by the external environment (electric field), the system tends to return to its original state by amplifying the oscillations around this point. The four types of accumulators behave generally similar, but in particular there are small differences in their voltage response. The particle response to electric field change is manifested by producing an electromagnetic wave that is added to the battery charging or discharging pulses. This wave is completely attenuated after a few oscillations. If the loading pulse period coincides with the period of these oscillations, the oscillations are sustained. The energy of these oscillations can be captured and used. Based on the experimental results, a battery model is proposed that describes the transition periods.

***Keywords*,:** *pulse charging, Lead-acid, Ni-Cd, Ni-Mh, Li-Ion.*

I. INTRODUCTION

The charging of batteries with various pulses has been studied since more than half a century. With these methods we expect to achieve higher charging performances.

Since 1960, the negative pulse charging of batteries has been studied.[1]

Some researchers investigated the effects of charging period and frequency as well as the mechanisms that govern this process at the molecular level.[2]

The result of other researchers shows that charging using 8 minute pulse width current is the effective method for charging the lithium ion cell since it can reduce the charging time and decrease the capacity loss of the cell.[3]

Feasible and efficient charging of Li-ion batteries by a rotating triboelectric nanogenerator (TENG) with pulsed output current is demonstrated.[4]

The duty cycle of the pulse charge current played a major role in battery cycle life extension, followed by frequency at which the battery is charged.[5]

Introducing short periods of relaxation without current flow allows the concentration of Li+ ions to be replenished in front of the electrode surface promoting a uniform and efficient plating of Li metal.[6]

Other researcher uses the Taguchi orthogonal arrays to search for optimal pulse charging parameters that will maximize battery charge and energy efficiencies while decreasing charge time.[7]

By introducing stress control, a modified pulse charging (PC) method called the pulse charging constant current (PCCC) method, which starts with a PC operation followed by a constant current (CC) operation, is studied with good results.[8]

Disclosed is pulse charging of a battery that uses frequency modulation to vary the pulse periods of the charging pulses. Battery measurements can be made to determine the duty cycles of the charging pulses.[9]

A hybrid sinusoidal-pulse current (HSPC) charging method improves the charger efficiency related to the hardware and the battery energy transfer efficiency.[10]

Comparing with the standard constant-current and constant-voltage (CC-CV) charge strategy, the charge speed of the proposed duty-varied voltage pulse-charge strategy (DVVPCS) is improved by about 14%, while the proposed DVVPCS is improved by about 5% in comparison with the conventional duty-fixed voltage pulse-charge strategy (DFVPCS).[11]

The zero-current switching mechanism introduced ensures efficient power conversion from the renewable energy source to the battery bank.[12]

All-atom classical molecular dynamics simulations suggest that the different diffusion coefficients of Li ion in electrolyte under different applied voltage may be responsible for the different energy efficiencies.[13]

This article aims at presenting the results of the experimental research related to the complex event during the transition period[14], and the tries to create the electrochemical resonance phenomenon.[15]

The behavior of four types of accumulators: Ni-Cd, Ni-Mh, Lead-acid, Li-Ion, all in the 12V/4Ah configuration, was studied. We will present the response to increase and decrease of the charging voltage, to longer and shorter pulses, as well as to higher and lower frequency pulses.

II. EQUIPMENT

The used accumulators were Lead-acid 12V/4Ah DD12040, Li-Ion 12V/4Ah DC12400, Ni-Cd BD-D4000mAh 1.2VM, a series connected of 10 batteries resulting 12V/4Ah, ART NI-MH C 4000mAh 1.2V a series connected of 10 batteries resulting 12V/4Ah. The 220VAC/24VDC power supply and 24VDC/15VDC are linear adapter with a powerful filter for extra stabilization. The batteries have been switched using 24V relays of DRM570024LT type. The 0 and 5V logic level signals command a very fast power MOSFET

Manuscript received February 21, 2019; revised March 24, 2019

IXZ631DF12N100 driver module that provides battery charge current. For generating logic load signals as well as signal form monitoring, Analog Discovery2 complex apparatus and Digilent's Discovery BNC adapter, such as the WaveForms software, were used (figure 26). The results were saved in the personal computer in image and table format with all the data. There have been many repetitions of the signals obtained with a good precision, in order to formulate solid conclusions in each case.

Due to the fact that the used MOSFET has a switching speed of few nanoseconds and the maximum applied frequency was around 2MHz, we can consider it sufficiently fast for these experiments. With additional filtering and shielded cables for high-speed data transmission, the effect of external noise or power is minimized. The two-channel oscilloscope has a bandwidth of 30MHz, with 14-bit and 100MS/s ADCs. The signal generator supports up to 12MHz with 14-bit and 100MS/s DACs performance.

III. THEORETICAL GROUNDS

Inside the battery, reversible electrochemical reactions occur permanently. The percentage of the component elements oscillates around an equilibrium point according to the level of charge, between the fully loaded and fully unloaded state. Under an external influence on the system (charging/discharging) this balance is lost and electrochemical reactions occur according to these influences. Any system in equilibrium will try to restore it by opposing the external action, due to its inertia. As a result, when applying a voltage to the battery, its voltage will decrease in the first phase as the system opposes the change and attempts to maintain its original equilibrium state. By keeping the external action on the system, the system will conform to this action. The new state of equilibrium is not reached instantly, due to the inertia of the system. At first the equilibrium is exceeded.. These consecutive passes around the new state of equilibrium are seen as attenuated oscillations over time.

IV. EXPERIMENTAL RESULTS

I will present each experimental result separately for 6 types of actions on the battery. All experiments were produced under the same external environmental conditions. All generator and oscilloscope settings have been preserved in the same type of experiment, with the exception of vertically centering the voltage level to view the full shape of the signal at full resolution due to the differences in charging of the four accumulators at that time. The results on the same battery were very similar in several attempts, so these graphs can be considered conclusive. After the command signal is applied, there is a short delay due to the propagation of the signal through the MOSFET, after which the voltage response of the batteries is observed.

IV.1. Rising slope

A 1kHz rectangular pulse was generated with 50% duty cicle, for 1ms and the effect was monitorized around the signal slope. The horizontal resolution on the time axis was 200ns/div and vertically on the voltage axis was 70mV/div. (The signals are shown in figures 1-4.)

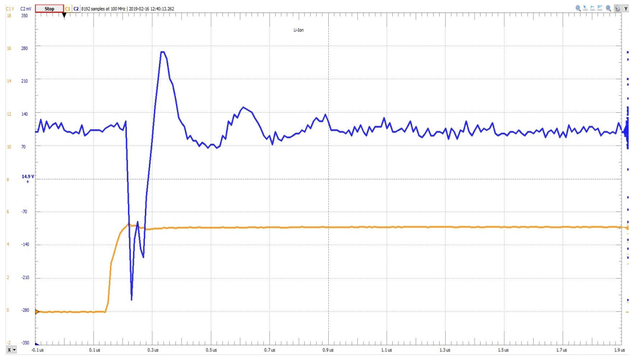

Figure 1. The rising slope of the Li-Ion battery

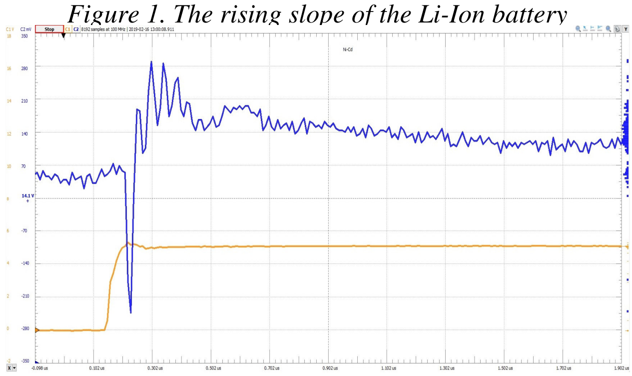

Figure 2. The rising slope of the Ni-Cd battery

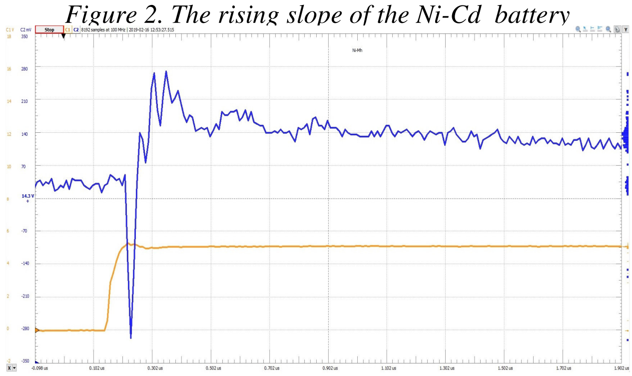

Figure 3. The rising slope of the Ni-Mh battery

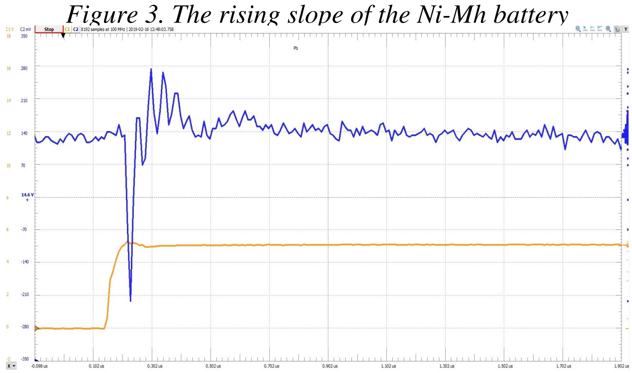

Figure 4. The rising slope of the Lead-acid battery

In all four cases, we notice a decreasing abrupt voltage slope at the battery. This is due both to the system's opposition to external influence and to the mobilization of free ions from electrolyte under the influence of the electric field. After a few oscillations around the new equilibrium point, the system stabilizes under load. The oscillation period is very similar for the four types of accumulators, it is around 210ns. Unlike the others, for the Li-Ion battery, we have the higher amplitude of the first single-peak oscillation, indicating a more focused reaction of the system. In the other cases there are 5 small peaks up and down showing a higher system agitation.

IV.2. Decreasing slope

A rectangular pulse with 100kHz frequency and 50% duty cicle, was generated for 20us, after which the effect was observed around the signal slope. The horizontal resolution on the time axis was 300ns/div and vertically on the voltage axis was 600mV/div. (The signals are shown in figures 5-8.)

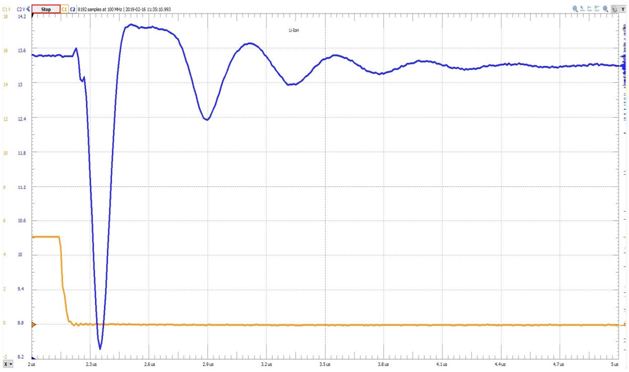

Figure 5. Decreasing slope of the Li-Ion battery

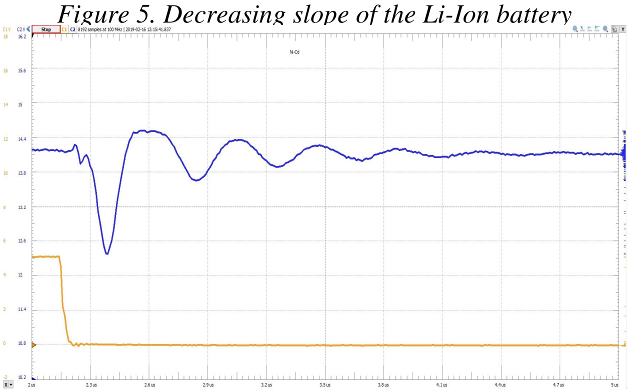

Figure 6. Decreasing slope of the Ni-Cd battery

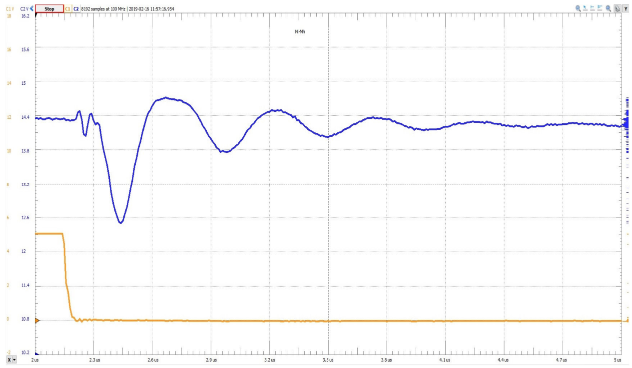

Figure 7. Decreasing slope of the Ni-Mh battery

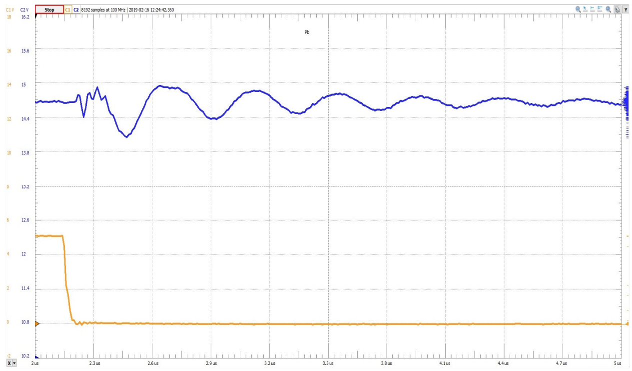

Figure 8. Decreasing slope of the Lead-acid battery

In all four cases, a Z-form appears vertically, then attenuated according to the type of battery. After that, there is a significant decreasing slope in voltage at the battery. The biggest one is in the Li-Ion battery and the smallest is in the Lead-acid battery. This voltage slope occurs as the system is released from the external influence of the charging electric field. Of course, it continues with the oscillations until the final equilibrium is reached. The oscillation period is very similar for the four types of accumulators, its duration is around 450ns.

IV.3. Pulse with both rising and decreasing slopes

A pulse of 700ns was generated. The horizontal resolution on time axis was 400ns/div and vertically on the voltage axis was 350mV/div. Both slopes are shown together, to help visually compare them. The settings of the four figures are identical (see in Figures 9-12).

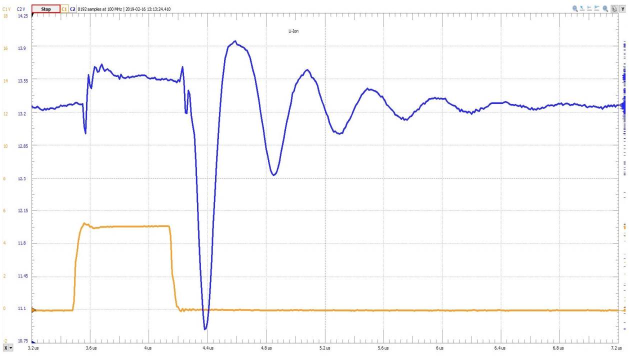

Figure 9. The pulse of the Li-Ion battery

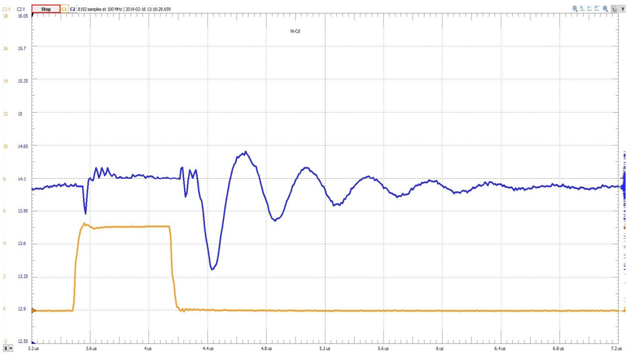

Figure 10. The pulse of the Ni-Cd battery

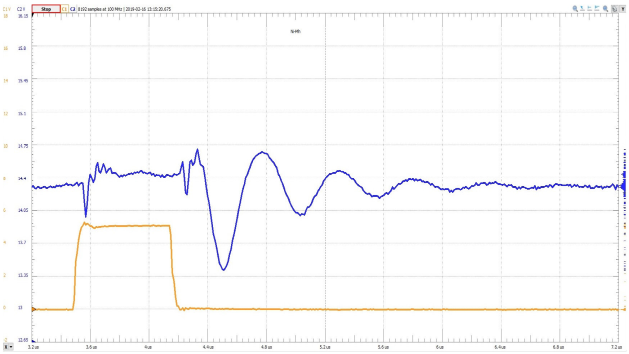

Figure 11. The pulse of the Ni-Mh battery

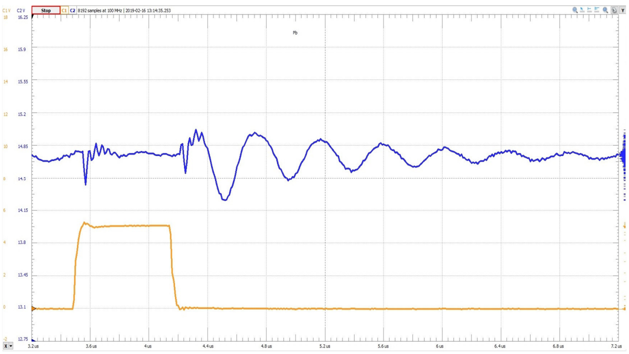

Figure 12. The pulse of the Lead-acid battery

It is possible to observe the vertical Z forms in opposition to each other on the two slopes. The shape of the signal at the rising slope is similar to the first part of the shape of the falling slope. After that we have a long oscillation that stabilizes at about 4us. Note that the attenuation of the oscillations is more pronounced in case of the Li-Ion battery and it is less pronounced in case of the battery with Lead-acid, even though it started with the smaller amplitude.

IV.4. Needle pulse

A pulse of 50ns width was generated. This is the shortest pulse applicable to this device, which can command the opening of the MOSFET driver module and the application of an electric charging field. The horizontal resolution on the time axis was 400ns/div and vertically on the voltage axis was 170mV/div. Forms of the signals of the four accumulators are shown (in figures 13-16).

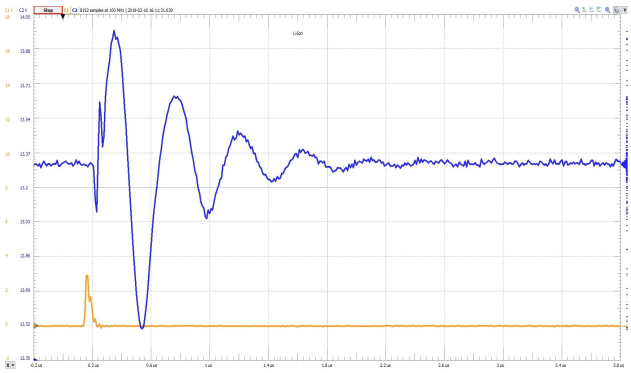

Figure 13. The needle pulse of the Li-Ion battery

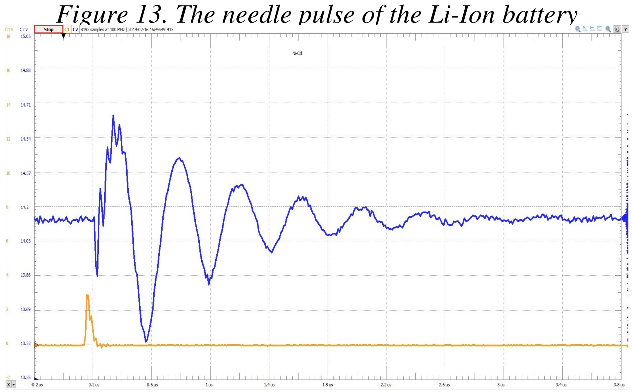

Figure 14. The needle pulse of the Ni-Cd battery

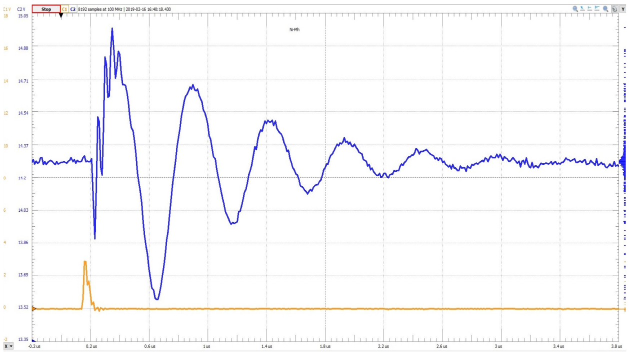

Figure 15. The needle pulse of the Ni-Mh battery

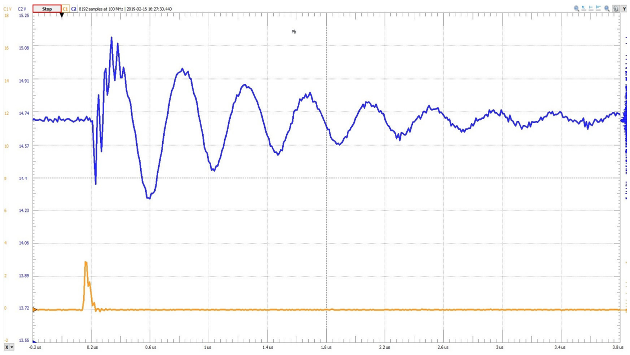

Figure 16. I The needle pulse of the Lead-acid battery

It is interesting that a very short duration impulse that corresponds to a small amount of invested energy, generates an oscillation of the system with a high amplitude..

IV.5. Long pulse train

The period of a long pulse consists of a few oscillations of the system. Before the system oscillations disappear completely, the next pulse is applied, forming a load pulse train. A rectangular signal with a 500 kHz frequency and 1% duty cicle was generated.

Horizontal resolution on the time axis was 1us/div and vertically on the voltage axis was 170mV/div. Forms of signals of the four accumulators are shown (in figures 17-20).

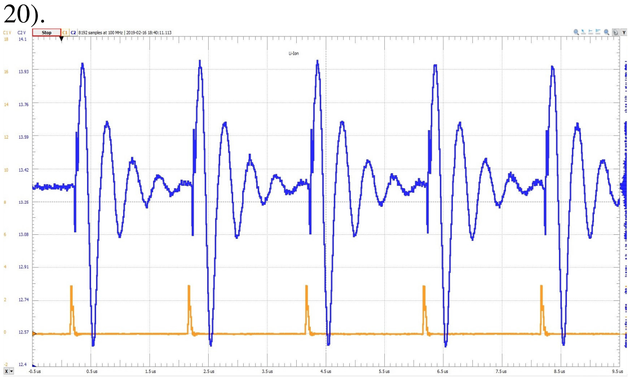

Figure 17. 500KHz pulses on the Li-Ion battery

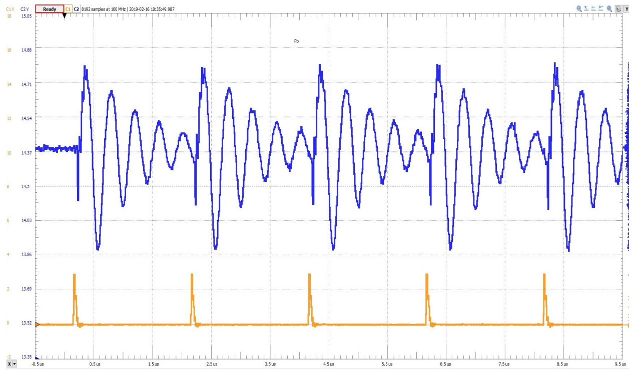

Figure 18. 500KHz pulses on the Ni-Cd battery

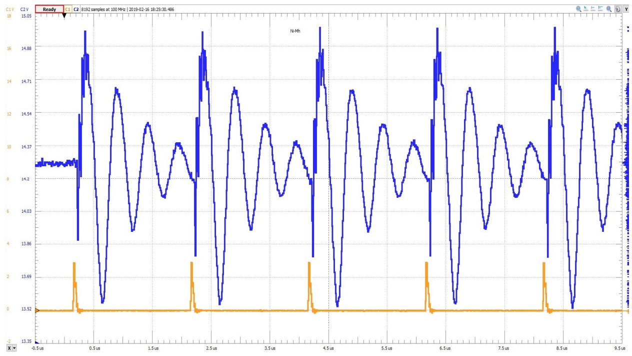

Figure 19. 500KHz pulses on the Ni-Mh battery

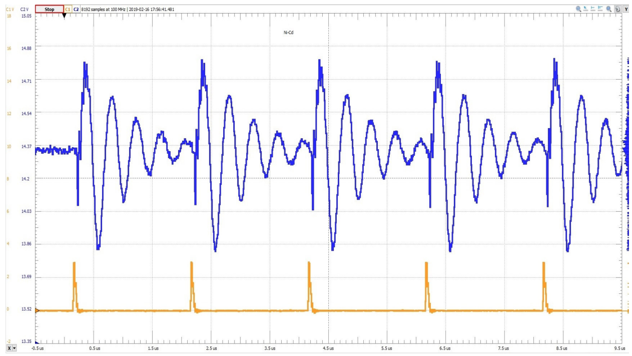

Figure 20. 500KHz pulses on the Lead-acid battery

The energy of the oscillations can be extracted and used. Extracting the energy of system oscillations will increase the attenuation, and the frequency of the control pulse will have to be increased.

IV.6. Short pulse train

The period of a short pulse is smaller than or equal to the oscillation period of the system. The charging pulses are repeated to form a pulse train. A rectangular signal with a frequency of 2.05MHz and duty cycle of 4% was generated. Horizontal resolution on time axis was 300ns/div and vertically on the voltage axis was 170mV/div. Forms of signals of the four accumulators are shown (in figures 21-24.)

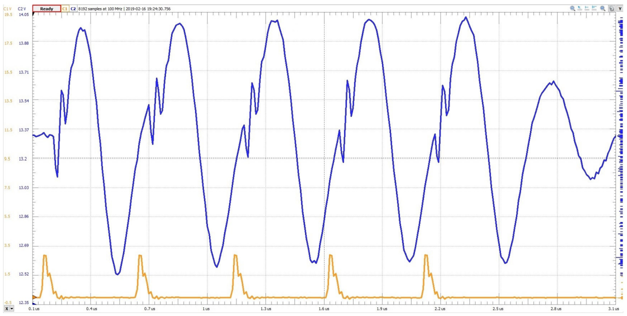

Figure 21. Pulse train of 2.05MHz on Li-Ion battery

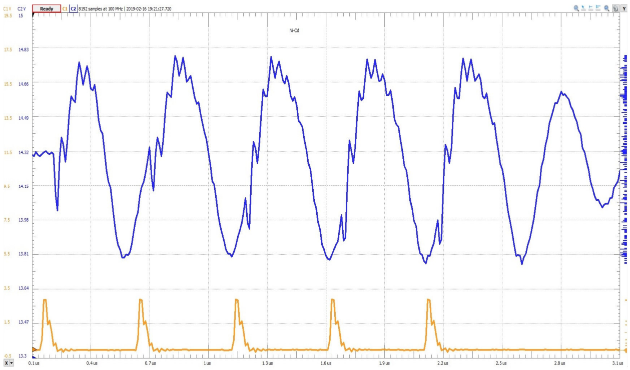

Figure 22. Pulse train of 2.05MHz on Ni-Cd battery

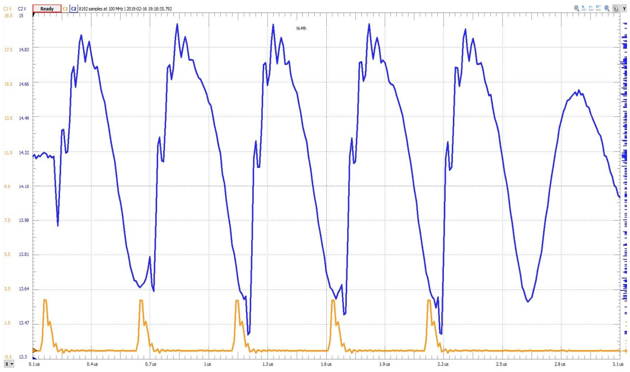

Figure 23. Pulse train of 2.05MHz on Ni-Mh battery

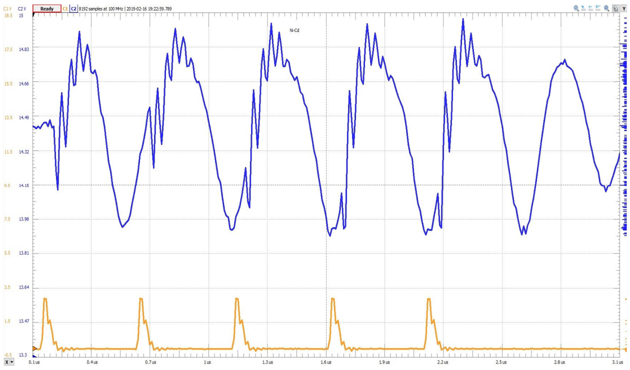

Figure 24. Pulse train of 2.05MHz on Lead-acid battery

If the load signal pulse is synchronized with the system response, less energy has to be invested for charging, because the charging process is assisted by the system. In this case, the electrochemical resonance phenomenon occurs.

V. THE PROPOSED MODEL

Taking into account experimental results, it is proposed to modeling the battery transition period (Figure 25).

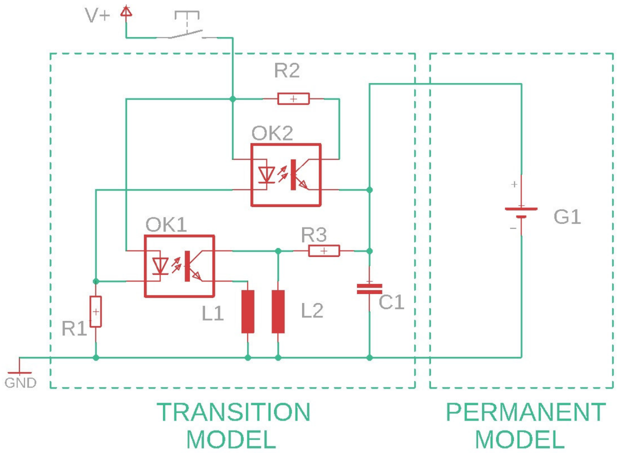

Figure 25. The proposed model for transition period

When charging voltage is applied, the R1 resistor closes the OK1 and OK2 optocouplers. The optocoupler OK1 will connect the L1 and L2 inductors in parallel resulting in an equivalent inductance much lower than L2. Battery G1 is charged through optocoupler OK2 and resistor R2. When charging voltage is applied, the R3, L1, L2 and C1 groups will produce a waveform similar to those obtained. When the charging voltage is interrupted, R3, L2 and C1 will produce oscillations with a much lower frequency but longer. The permanent model can be any known battery model so far.

VI. CONCLUSION

In the transition period, due to the increasing and decreasing slope of the charging pulse, the system enters into an amplified oscillation until reaching the charging equilibrium state or final rest. Of these two types of oscillations, it is worth noting the high amplitude and long duration of oscillations at decreasing slope, i.e. when the battery charge signal is interrupted. In comparison, the Li-Ion battery has a higher amplitude oscillation and a shorter stabilisation time. The Lead-acid battery has a lower amplitude oscillation, but a longer stabilization time than the others batteries. Ni-Cd and Ni-Mh batteries are in the middle area.

From the point of view of power management, when charging the batteries we have two directions to explore further. The first concerns the capture of electrical energy from the oscillations of the system after the charging pulses. The other is to find the exact charging pulse frequency and duty cycle that will generate the resonance phenomenon, which will lead to more efficient charging. Of course, in an advanced phase the two directions can be combined. In both cases, it is necessary to have equipment with higher performance as well as a special circuit to capture this energy at high speed. Although the multiple phenomenons that happen inside the battery require a complex theoretical support coming from many different research domains, over time it will be possible to explain and even simulate or model these phenomenons.

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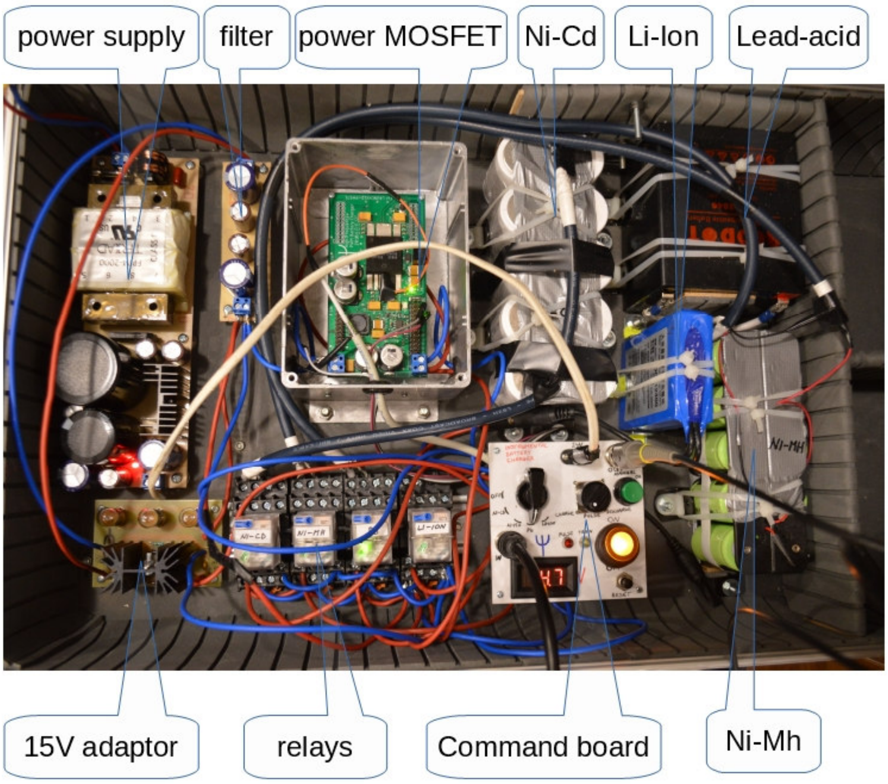

Figure 26. Hardware used in the experiments