A Battery Charging Smart System using a Power Management Algorithm and Adaptive Impedance

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***Abstract*—The paper proposes an original method experimented by the authors, in order to optimize the charging process for rechargeable batteries. The method involves: testing, adapting and implementing the on board charging function, depending on each type of battery used. First of all, the method proposes an algorithm for the identification of the battery internal resistance, which depends on the wear and tear of the battery. Also, the battery charging dynamics will be created according to its wear status. This is of particular importance in the maximum power transfer especially for batteries with high specific power. Secondly, each battery must be charged taking into account the type of chemical reaction used by the manufacturer in the battery construction process. For this, we will test the dynamics of the discharging in a short time interval and adapt the load to each type of battery differently. The entire process will be implemented and controlled by a microcontroller. The proposed solution is not a new approach, the subject being of great interest especially in the automotive industry, but two of distinct solutions will be implemented cumulatively during the same optimization process.**

Keywords-smart battery charging; power management; adaptive impedance; internal resistance; dynamic charging function; microcontroller based.

I. INTRODUCTION

In this paper, a type of battery charger is proposed that uses an initial battery test to determine the charging function for the charging battery, each time a battery is connected. Efficient charging and dynamic change of the resistance introduced by the power generator during the charging process is considered.

Although the subject was closely addressed by a multitude of researchers in the field, the topic being current and interesting in the field of industrial technology and home automation [1], [2] and [4]. This research consists of proposing the realization of a battery charger made in the original variant in which the maximum power transfer and the reduction of the losses to the load is taken into account.

The steps that have been implemented in carrying out the intelligent charging process are the following: connecting a new battery to the circuit terminals, testing the nominal voltage and its internal resistance by means of a controlled discharge for a short period of time, calculating an onboard current-voltage actuation function such that in small areas the generator's resistance should be adaptive and equal to the internal resistance of the battery, and the implementation of this function in real time during charging. The role of the initial testing of battery in efficient charging process was mentioned in [3], [5].

The entire process is implemented in 8-bit process microcontroller with analog read and writes hardware capabilities and precise time interval implementation. Additionally, two functional blocks have been created, the adaptive driver circuit and discharging and testing battery, electronic blocks that realize the interface of the process with the microcontroller. The two blocks play the role in implementation of the entire algorithm. The physical and mathematical aspects of the problem were taken into account, equations describing the maximum value of the power transfer theorem and the inversion with respect to the composition of the real variable functions.

In this paper, we have explained a general case of the proposed solution with details of the software model, experimental aspects of the solution including graphs of variations of the current, voltage and resistance. In section II the solution proposed by us was described, following that in section III some experimental and graphical results will be highlighted. In section IV the conclusions are presented.

II. PROPOSED SOLUTION

A schematic block of the proposed smart battery charger is presented in Fig. 1. The proposed solution consists of a power source generator providing power to an adaptive control circuit driver that charges the battery; the microcontroller applies control signals to the adaptive control driver circuit, based on the charge feedback and the results obtained from the discharging and testing battery circuit.

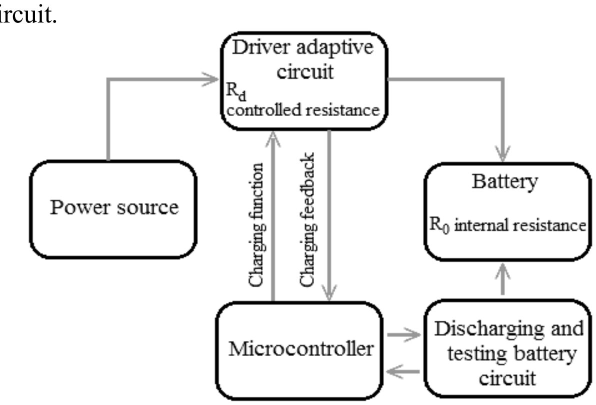

Figure 1. Block schematic of the proposed solution

From a theoretical point of view, we consider that a battery charger has to be energy efficient among other functions. We consider the case where we need to charge multiple battery elements with high energy density, like car batteries, where the energy transfer to the battery involves additional costs when the charging process has a low efficiency.

If we consider a simple circuit with generator, rechargeable battery and a measurement resistor (pull-down resistor), we can get the formula for the maximum power transfer while charging in the following form:

$$P_{Batt} = \frac{U_{R_0}^2}{R_0} = \frac{\left(U_d \dfrac{R_0}{R_0 + R_d}\right)^2}{R_0} \tag{1}$$

where:
-P_{Batt} is the power delivered to the battery,
-U_d is the voltage applied to the adaptive driver circuit
-U_g is the voltage applied to the battery
-R_0 is the internal resistance of the battery
-Rd is the variable resistance of adaptive driver

If we consider this function of a real variable (the internal resistance of the battery, R_0):

$$P_{Batt} = P_{Batt}(R_0) \tag{2}$$

We observe that this function has an extreme point (in this case a maximum) when the first derivative of the function is 0. After the first derivative is applied, we obtain:

$$\frac{dP_{Batt}(R_0)}{dR_0} = \frac{U_d^2\left(R_0^2 - R_d^2\right)}{\left(R_d + R_0\right)^4} \tag{3}$$

And this condition happens when:

$$\frac{dP_{Batt}(R_0)}{dR_0} = 0 \rightarrow (R_d = R_0) \tag{4}$$

In our proposed solution the internal resistance of the battery (R_0) is calculated onboard at the start of the charging process, after the tests performed by the microcontroller. The tests consist of fast discharge over very short time intervals, using the experimental circuit from Fig. 2.

The internal resistance of the battery has been calculated based on the numerical differentiation using following formula:

$$R_0 = \frac{du_{dis}}{di_{dis}} = \frac{u_n - u_{n-1}}{i_n - i_{n-1}}, \tag{5}$$

where u_{dis}, i_{dis} represents the values for the discharge voltage and discharge current during t internal resistance test of the battery.

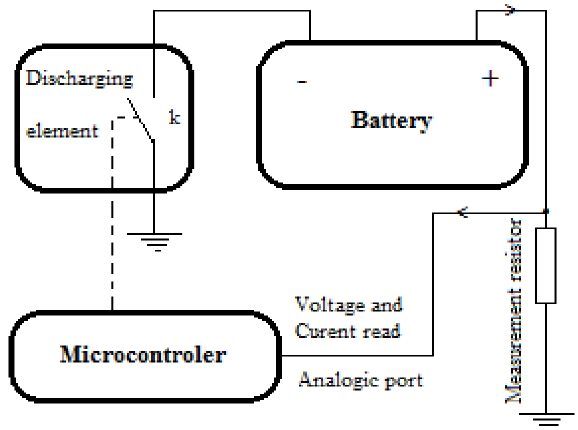

Figure 2. Discharging and testing circuit

The software used for this step was implemented in C and written on an Atmega 328p. A simplified excerpt is presented below:

```
float v1[m] = {1,2,3,…m};
float v2[n] = {1,2,3,…n};
float v3[p]= {1,2,3,…p};
void setup ()
{
float value = 0;
variable "value"
float value2 = 0;
for(int i=0; i< m; i++)
   {value=v1[i];
value2=v2[i];
value=value-(value-1)/value2-(value2-1);
v3[i]=value;
   }
```

A schematic of the section for the numerical differentiation is presented in Fig. 3.

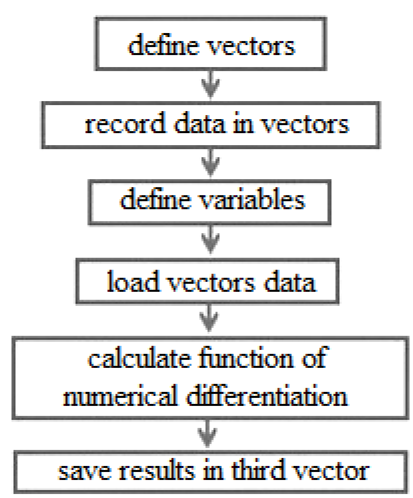

Figure 3. Schematic of the numerical differentiation section

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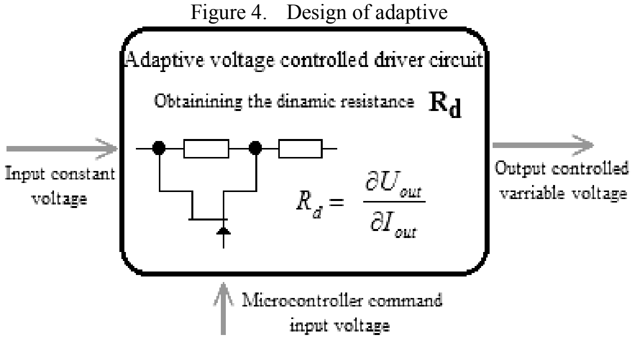
After the value of the internal resistance of the battery is determined, the dynamic charging function can be calculated. The implementation of the charging function is done using a dynamic adaptor with variable conductance. The configuration of the adaptive controlled driver circuit is presented in Fig. 4.

Figure 4. Design of adaptive



voltage controlled driver circuit

The electric circuit contains an active element whose transconductance and dynamic resistance introduced in the circuit can be controlled by a command voltage applied to the command pin of the active element in order to achieve dynamic charging. The input of the circuit is connected to the constant voltage generator and the output provides control of the output resistance, by controlling the output voltage and current.

The formula for the adaptive impedance implementation of the battery with the power circuit is depending on forms:

$$R_d = \frac{\partial U_{out}}{\partial I_{out}} \tag{6}$$

And the differential form in the discrete case to implement is:

$$R_d = \frac{du_{out}}{di_{out}} = \frac{u_{n+1} - u_n}{i_{n+1} - i_n} \tag{7}$$

Both the resistance of battery and of the generator must be equal. For this to happen we propose the next form of charging function:

$$R_d = \frac{\partial U_{out}}{\partial I_{out}} \cong R_0 \rightarrow F_{charge} = inv[u_{dis}(i_{dis})], \tag{8}$$

where $inv[u_{dis}(i_{dis})]$ is the mathematical invert of the short-circuit resistance curve, obtained by recording the data during the controlled discharge tests.

The software used for this step was implemented in C and programmed on an Atmega 328. A simplified excerpt is presented below:

```
float v1[m] = {0,1,2,3,…m};
float v2[n];

void setup ()
{
float
value = 0;
for(int i=0; i< m; i++)
   {value=v1[i];
value=sqrt(value*value-2*value+6);
v2[i]=value;
      }
```

The schematic for the charging function is presented in Fig. 5:

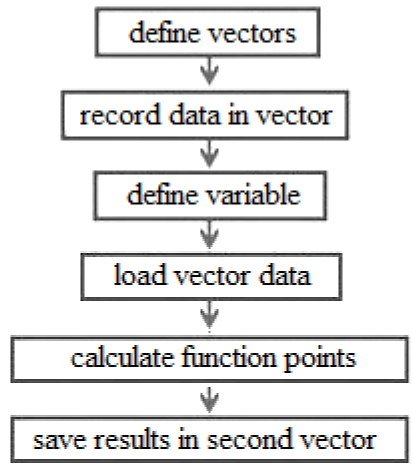


Figure 5. Schematic of the charging function

III. EXPERIMENTAL DATA AND RESULTS

In this section, experimental data and graphs are presented and the implementation of the proposed method. Using the discharging and testing block, controlled by the microcontroller, several short experiments (200-500 ms) have been performed and the values of the short-circuit voltage and current have been recorded. The Li-Ion battery of 3.7V, type 18650 was considered and experimental data obtained are presented in Table I.

Using the data from Table 1, recorded in a 300 ms long test, the graph from Fig. 6 has been generated. The graph contains three variations represented in red, green and blue. The line with a negative slope represented in blue is the current-voltage variation during the discharge and was generated using data from Table 1, consisting of 48 distinct values. It is noted that both the voltage and current drop during the discharge. The red line with zero slope represents the internal resistance of the battery and was obtained using numerical differentiation of the voltage and current.

TABLE I. EXPERIMENTAL DISCHARGING DATA

I[A]	U[V]	I[A]	U[V]	I[A]	U[V]
0.84	3.87	0.712	3.772	0.584	3.675
0.832	3.864	0.704	3.766	0.576	3.669
0.824	3.858	0.696	3.76	0.568	3.663
0.816	3.852	0.688	3.754	0.56	3.657
0.808	3.846	0.68	3.748	0.552	3.65
0.8	3.84	0.672	3.742	0.544	3.644
0.792	3.833	0.664	3.736	0.536	3.638
0.784	3.827	0.656	3.73	0.528	3.632
0.776	3.821	0.648	3.724	0.52	3.626
0.768	3.815	0.64	3.718	0.512	3.62
0.76	3.809	0.632	3.711	0.504	3.614
0.752	3.803	0.624	3.705	0.496	3.608
0.744	3.797	0.616	3.699	0.488	3.602
0.736	3.791	0.608	3.693	0.48	3.596
0.728	3.785	0.6	3.687	0.472	3.589
0.72	3.779	0.592	3.681	0.47	3.583

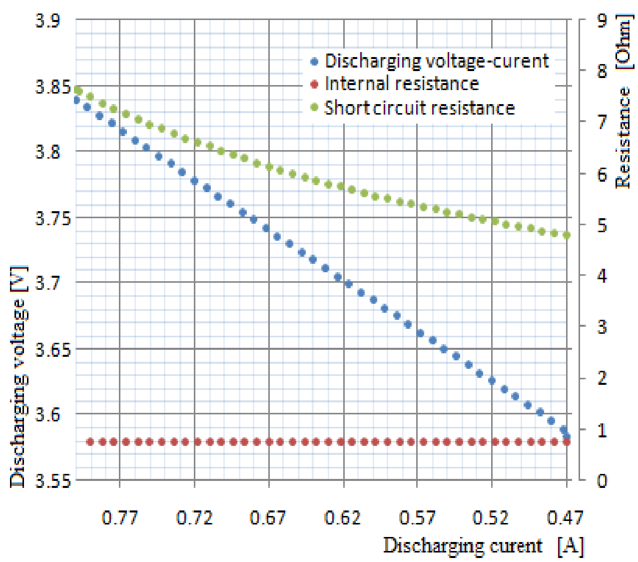


Figure 6. Discharge voltage and current

Numerical differentiation of the experimental data has led to the determination of the value of the internal resistance $R_0 \cong 0.76\Omega$

The green curve with a hyperbolic variation represents the implicit variation of the current and the voltage measured at the terminals of the battery determined in short-circuits conditions and influenced by the internal resistance of the battery.

During this short test the internal resistance was constant. It implies that during the invers process, the charging process, the charging voltage and current has to follow a similar curve but with inverted variation.

The curvature and type of variation will determine the charging function. The shape of the variation of the specified mathematical function, of the current and voltage during the discharge was obtained using a second order polynomial interpolation, in this case.

$$u_{dis}(i_{dis}) = 12.47 i_{dis}^2 - 24.28 i_{dis} + 16.24 \tag{9}$$

Assigning to function the mathematical invert along the first bisector we can calculate analytical the inverse function. In this example it has the next form.

$$i_{charge}(u_{charge}) = 0.973 - 2\sqrt{0.02 u_{charge} - 0.088} \tag{10}$$

During our experiment after the completion of the test to determine the internal resistance of the battery, we will not perform onboard implementation of the analytical calculated function from (10) because it involves floating point operations and extra calculations, instead we will use the numerical invert of function, and for the experimental curve by simply inversing the experimental data obtained during the discharge process, controlled using the equation:

$$Inv[Y(X)] = X(Y), \tag{11}$$

which becomes:

$$F_{charge} = inv[u_{dis}(i_{dis})] = i_{charge}(u_{charge}) \tag{12}$$

The algorithm involves the determination of the internal resistance of the battery by performing a fast discharge test, before the start of the charging process, and the determination of the voltage-current variation curve for which the internal resistance of the battery stays constant and it is the basis for functional inversion of the charging voltage and current of the battery that does not change the internal resistance.

The difference is that the charging process will last longer than the discharge process. The time variable described in the discharge experiment is implemented using an optimized process controlled by the microcontroller.

In the following, several experimental results are presented for repeated charging of the same battery. We are presenting in Table II the experimental data of approximate 600 seconds of battery charging, in voltage and current variations. We used the same Li-Ion battery of 3.7V, 18650 types.

Fig. 7 presents the results of the voltage charging solution. Using the microcontroller controlled charging the voltage was rising with values in the [3.971-4.031V] interval. The function for the implementation of adaptive impedance was represented in red, and it represents the correction applied to the adaptive driver circuit by the microcontroller.

The current variation between (0.083 - 0.108) Amps, are presented in Fig. 8, during the charging process and the variation of the adaptive driver.

TABLE II. EXPERIMENTAL CHARGING DATA

U[V]	I[A]	U[V]	I[A]	U[V]	I[A]
3.971	0.108	4.000	0.098	4.016	0.090
3.974	0.106	4.001	0.097	4.017	0.090
3.977	0.105	4.002	0.097	4.018	0.090
3.979	0.104	4.003	0.096	4.019	0.090
3.981	0.103	4.004	0.096	4.020	0.089
3.983	0.103	4.005	0.095	4.021	0.089
3.985	0.102	4.005	0.095	4.022	0.089
3.987	0.102	4.006	0.094	4.023	0.088
3.988	0.101	4.007	0.094	4.024	0.088
3.990	0.101	4.008	0.093	4.025	0.087
3.991	0.101	4.009	0.093	4.025	0.087
3.992	0.100	4.010	0.092	4.026	0.086
3.993	0.100	4.011	0.092	4.026	0.086
3.994	0.100	4.012	0.091	4.027	0.085
3.995	0.099	4.013	0.091	4.028	0.085
3.996	0.099	4.014	0.091	4.029	0.084
3.998	0.099	4.015	0.091	4.030	0.084
3.999	0.098	4.015	0.090	4.031	0.083

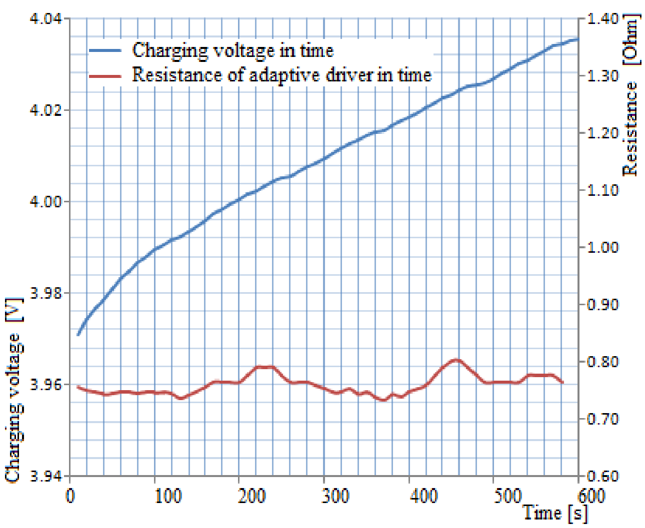


Figure 7. Charging graph of voltage in time

In Fig. 8 we are also highlighting the variation of adaptive resistance in time obtained in adaptive driver circuit. The variations of resistance of the adapter block are the answer due to the variations of internal resistance during the charging in time of the chemical element (battery).

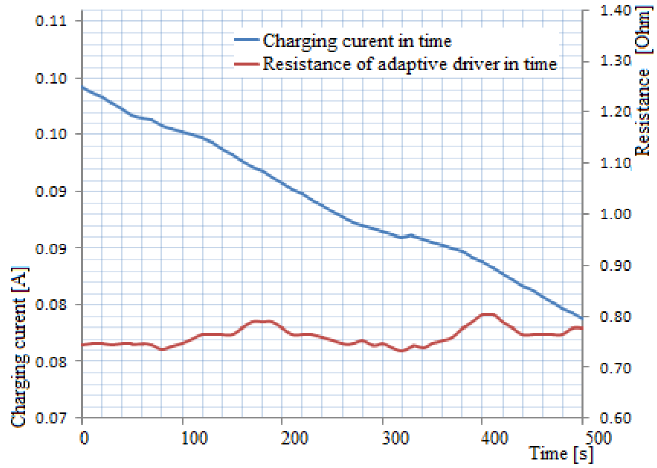


Figure 8. Charging graph of curent in time

IV. CONCLUSION AND FUTURE WORK

In this paper the possibility of using a microcontroller controlled battery charger is discussed. The method is based on theoretical considerations and numerical calculation and implementation. The experimental results show that the process can be carried out with high efficiency by controlling the conductance during the charging period using the adaptive circuit and an initial battery resistance test. Only one type of battery was tested, but the authors want to test and implement the method on several types of batteries and at various stages of wear. With the results obtained we will develop in a future project a model of functional charging in minimum time and maximum efficiency.

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