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Universal battery parameterization to yield a non-linear equivalent circuit valid for battery simulation at arbitrary load

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Abstract

A method of numerical representation for electrical storage cells based on measurement of wide frequency range impedance spectra at a number of different states of charge and measurement of the depth-of-discharge dependence of equilibrium voltage are developed. Applicability of this method to batteries with various chemistries and sizes are established by comparing numerical prediction to experiment. The model represents all tested batteries with accuracy (less than 1% in average deviation) in processes ranging from time constants of 1 ms to 10 h and from current densities of C/10 to 3C. The method includes the fitting of impedance spectra to physically relevant static linear transmission-line model and the use of parameters determined at different discharge levels to create a non-linear dynamic model. Formalization of the model as a non-linear equivalent circuit enables its direct application as a part of any electric device in digital circuit simulators like SPICE.

Keywords: Battery modeling; Battery parameterization; Diffusion hindrance; EIS model analysis; Equivalent circuit; Transmission line model; Non-linear model

1. Introduction

The increasing demand for portable electronic devices in last years resulted in considerable increase of number of battery types, models and manufacturers. One can choose a battery for a particular application from a wide spectrum of candidate batteries such as lead acid, Ni–Cd, Ni-metal-hydride (Ni-MH), Li-ion, and Li-polymer, etc. Batteries with similar chemistry produced by different manufacturers can also vary considerably in their properties, as shown by the authors of Ref. [1] for Li-ion batteries. So far the choice of a battery for particular application has been mostlydetermined based on discharge voltage, storage capacity (given for discharge method specified by manufacturer) as well as of the price of battery. These characteristics can give a rough impression of battery performance to the customer, but in many cases it would be misleading in regard to particular application, so large amount of additional information such as discharge curves at different currents, internal impedance and special features of discharge voltage profile are necessary. However, even in this case the evaluation of the battery for particular application remains only *qualitative* and *subjective*. A necessity to test an electrical device with real batteries made by each particular manufacturer still remains because all the standard features of battery has been obtained under steady state conditions. In certain cases this kind of test is impractical and costly so that a battery can be readily chosen after simply passing a test without performing further comparative tests. In particular, for instance, comparative tests for electric vehicle (EV) batteries are obviously not realistic due to heavy cost of manufacturing. The most time and cost efficient method to improve the confidence in the choice of the right battery substantially would be a digital simulation of the electrical device with a particular type of battery represented as an equivalent circuit. This approach will also improve the efficiency and stability of the device by matching impedance of its components with response of the chosen battery. This can be of large importance as shown in Ref. [2], and actually meaningful to simulate various situations arising from the failure of battery like the explosion of $1 billion Titan 4A rocket on August 4, 1998. All these can be done right in digital circuit simulator like SPICE, which has already become to an industrial

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standard and has been commonly used by electronics manufacturers for designing and testing their devices. A review on digital circuit simulators can be found in Ref. [3].

Unfortunately, the existing equivalent circuits for batteries are oversimplified and designed for the test of the electrical circuit itself rather than battery. Usually they comprise a constant voltage source in series with a resistor, which is valid only at DC conditions and in very short time because voltage change due to discharge of the battery is not considered. A more detailed approach which stores of battery discharge profiles at different discharge rates as a numerical table was proposed to use in a battery model for SPICE simulator in Ref. [4]. Although this method may correctly describe the constant current discharge of battery, it is not possible to treat charge/discharge processes of short time constants or transient conditions like pulse discharge.

A different approach to provide a representation for batteries including discharge voltage and internal resistance profile is disclosed in Ref. [5] for the purpose of using it in hardware simulator of thermal batteries. Similarly, Stoynov et al. [6] developed a step-by-step procedure obtaining parameters of a function which describes a simplified pulse current response at different states of charge, and used this parameters for stepwise prediction of the terminal voltage of battery. These models are valid in case of long time DC discharge but not in case of transient discharge conditions which occurs in many important application to portable devices like mobile phones, lap-top computers, power tools as well as in growing EV applications.

There has been a battery simulation method which partially considers the transient effects in order to predict open-circuit voltage of lead–acid batteries under dynamic discharge conditions [7]. This method includes measurements of charge and discharge voltage profiles at different currents and determination of five parameters for an equation which approximates the dependence of voltage upon total consumed/accumulated charge of lead–acid battery. The serial resistance is additionally determined to describe voltage behavior at charging or discharging conditions. Special equations have been used for different discharge modes, so the model can not be used directly under arbitrary load conditions. The applicability of the model is restricted to lead–acid batteries because it explicitly assumes a particular equation for voltage discharge profile. The simplification of diffusion hindrance to a serial resistance is also not sufficient in case of Li-ion batteries in which the transient time constants are comparable to total discharge time.

Obviously, there is a need for a model or an equivalent numerical representation of battery practically applicable and theoretically valid for digital simulation of all kind of batteries, in combination with arbitrary electrical load at wide range of electrical current densities and time-constants as well as for all depths of discharge. The model should be formalized in such a way that it can be directly used in electric circuit simulators. A standard automatic procedure to obtain all model parameters of a battery sample is also desired. In this work, we developed and tested a method corresponding to above requirements. Theoretical and experimental background of physically relevant impedance model used in this method is given in Refs. [8,9].

2. Formulation of universal battery model

2.1. Basic considerations

The process of energy storage in a battery, independent of particular chemistry, includes several common steps. The most important of these are (a) ionic charge conduction through electrolyte in pores of active layer and electronic charge conduction through conductive part of active layer, (b) electrochemical reaction on the interface of active material particles including electron transfer, and (c) diffusion of ions or neutral species into or out of electrochemical reaction zone. The combination of these steps usually makes the time-domain description of discharge process fairly complicated, because it requires a solution of non-linear differential equations in partial derivatives. Obviously it is not possible to fit experimental discharge curves to the solution of the system of non-linear differential equations, which requires iterative processes, with a view to obtaining desired parameters by using available computational resources.

However, in frequency domain at small-voltage approximation the effects of all steps can be easily accounted for by assigning to each of them an equivalent electrical element or circuit. The electrical elements of the circuit have explicit relationship to corresponding physical parameters, like diffusion coefficients, reaction rates, etc. All parameters of the circuit, which are valid for a fixed state of charge, can be determined from an experimental impedance spectrum by fitting it to the equation describing its frequency dependence of impedance. Once all parameters are known for a number of discharge states of a battery, and its steady-state emf-relation is known (voltage vs. state-of-charge relation), we have a total description of the system for a simulation at arbitrary load conditions. The more important is that the equivalent circuit used in frequency domain also remains valid, provided that all elements are set to be subject to state of charge and passive nature of the circuit is ensured. Numerical solution for a response of such a non-linear system with arbitrary load can be easily accomplished by using standard methods frequently used in theoretical electronics or even can be solved automatically in an electronic circuit simulator.

2.2. Formulation of linear static battery model

The equivalent circuit shown in Fig. 1 is based on a physical model representing an insertion electrode as macroscopically homogenous two-phase system and consisting of solid particles of active material (electrically conducting due to its own conductivity or conductive additives like carbon black) and pores filled with electrolyte. It has been shown by Paasch et al. [10] that small-voltage behavior of such a system is analogous to one of short-circuit terminated transmission line. This model gives a physically meaningful description of thickness and potential dependence of impedance spectra measured on different kinds of Li-insertion electrodes [9] and is therefore suitable for the purpose of battery modeling. The equation for impedance on frequency dependence of such a transmission line is given by,

$$Z = \sqrt{\rho Z_i}\,\coth\left(d\sqrt{\frac{\rho}{Z_i}}\right) + R_{ser} \quad (1)$$

where ρ is the specific resistance of active mass in unit of Ω m), Z_i is the parallel impedance of an unit volume of active particles constituting the active mass in unit of Ω m^3, and R_{ser} is the serial resistance accounting for the resistance of separator and current collector. The parameters for cathode and anode can usually not be separately determined from the total impedance spectrum of a battery. However, it has been recently shown [11] that electrochemical kinetics of many known insertion cathodes and anodes are very similar and can be described by the same equivalent circuit. Taking it into account that the equation for impedance of two serially connected transmission lines can be expressed as an equation for one transmission line with modified parameters, we can use only one transmission line to describe the total impedance of the battery. Considering that neither the geometric surface area nor the thickness of active layer is known for a battery, it is desirable to formulate the equation in normalized form as,

$$Z = \sqrt{\rho_t Z_t A^2}\,\coth\left(d\sqrt{\frac{\rho_t}{Z_t d^2}}\right) \quad (2)$$

where ρ_t is a total distributed resistance of a cubic meter of active material defined as $\rho d/A$, A is the geometric surface area of electrode, d is the thickness of active mass, and Z_t is the total distributed parallel impedance given as $Z_t = Z_i dA^2$ where $d = 1$ m and $A = 1$ m^2. Advantage of this representation is that actual values of ρ and Z_i can always be recalculated from the fit values of ρ_t and Z_t once actual A and d are known, while actual values of A and d are necessary neither for the fit itself nor for the simulation of the battery behavior.

The distributed parallel impedance of this transmission line corresponds to the kinetics of electrochemical reaction inside solid particles. This is defined by solid-state diffusion and charge transfer reaction. Usually the insertion of ions into a solid state film is described as an open-circuit terminated transmission line, as first proposed by Ho et al. [12]. However, we have shown in Ref. [9] that this approach does not give satisfactory description of the low-frequency impedance behavior of Li-intercalation electrodes, which results in deviations from experiment in case of long time transient calculations. In case when the charge storage involves building of a new phase, a model of finite length diffusion with transmissive boundary described in Ref. [13] would be more appropriate. This corresponds to finite length transmissive Warburg impedance in series with charge storage capacitance C_s. The charge transfer resistance R_{ct} in parallel with double layer capacitance C_{dl} is a usual representation for interfacial electrochemical

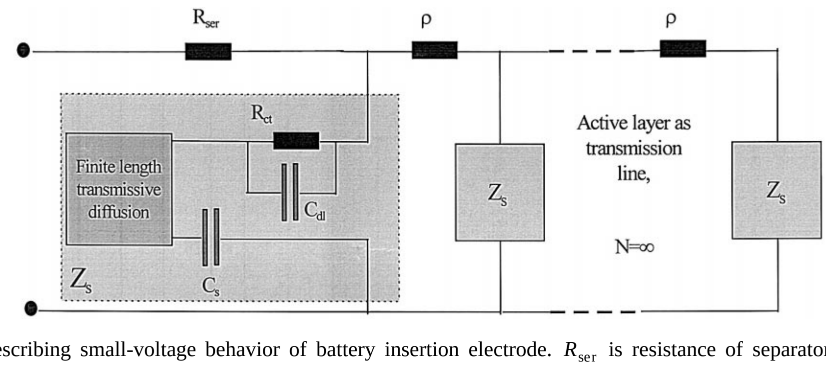

Fig. 1. Equivalent circuit describing small-voltage behavior of battery insertion electrode. R_{ser} is resistance of separator and current collectors; ρ is distributed resistance of transmission line representing electronic and ionic resistance of the layer of active material; Z_s is impedance of infinite-thin layer of active material including: charge transfer resistance and passivation layer resistance on particle interface R_{ct}, double layer capacitance C_{dl}, diffusion and charge storage inside particles represented as transmission line with variable termination (generalized Warburg impedance) and C_s representing additional charge storage processes.

impedance. The total impedance of unit volume of particles in this case is given by,

$$Z_i = \frac{1}{\frac{1}{R_{ct}} + sC_{dl}} + \frac{1}{C_t}\frac{\tanh\left(\sqrt{\frac{s}{D_t}}\right)}{\sqrt{sD_t}} + \frac{1}{sC_s}. \qquad (3)$$

Here, s is complex angular frequency ω. Because the size of the particles is unknown in general case, a normalized chemical diffusion coefficient $D_t = D/l^2$ is used where l is radius of particles, assumed to be of 1 m to normalize value of D_t. The C_t is a capacitance characterizing the charge stored in particles due to the concentration polarization during intercalation process and lost during the relaxation. It has a physical meaning as $C_t = zF/(\mathrm{d}E/\mathrm{d}c)$.

It is known in electrochemical impedance spectroscopy (EIS) analysis that an impedance spectrum in certain frequency range can be described by many different kinds of equivalent circuit with completely unrelated internal structure. Here we have a naturally arising question: why should we use rather a complicated physically-relevant frequency domain model as a backbone of our battery representation instead of using a very simple model like a series of serially connected RC-couples which can reproduce the experimental impedance spectrum with the same precision? In case of usual EIS analysis the parameters are obtained mainly for the purpose of analysis,understanding of different processes in electrochemical system, but in our case they could be only just internal parameters of numerical simulation. However, there are several reasons why we still need physically relevant model. First, the model should give a correct extrapolation of impedance value to frequencies where we do not have experimental data. For example, provided that a 'real' system is given by a transmission line with an open termination, the generated impedance spectrum in frequency region from 20 mHz to 1 KHz can be correctly fitted by a model comprising a series of 10 RC circuits. However, the deviation from 'experimental' data immediately becomes significant outside of this range as shown in Fig. 2a. This also means in time domain that the series RC-equivalent circuit will be completely discharged some time after switching off the current, whereas 'real' system remains at constant voltage after reaching an equilibrium conditions as shown in Fig. 2b. Secondly, the important reason to use physically relevant model is due to the non-linear behavior of parameters subject to the state of charge. The change of parameter values can have drastically different effects on terminal voltage of equivalent circuits with different internal structure, even if they have the same impedance in measured frequency range under constant parameter approximation. For example, increase of a resistor value can effectively disconnect all capacitors in a network of serially connected RC circuits and have almost no influence on network of RC circuits connected in parallel. Obviously, the correct prediction of non-linear behavior can be expected only in case if the internal structure of circuits maximally match the one of the modeled physical system.

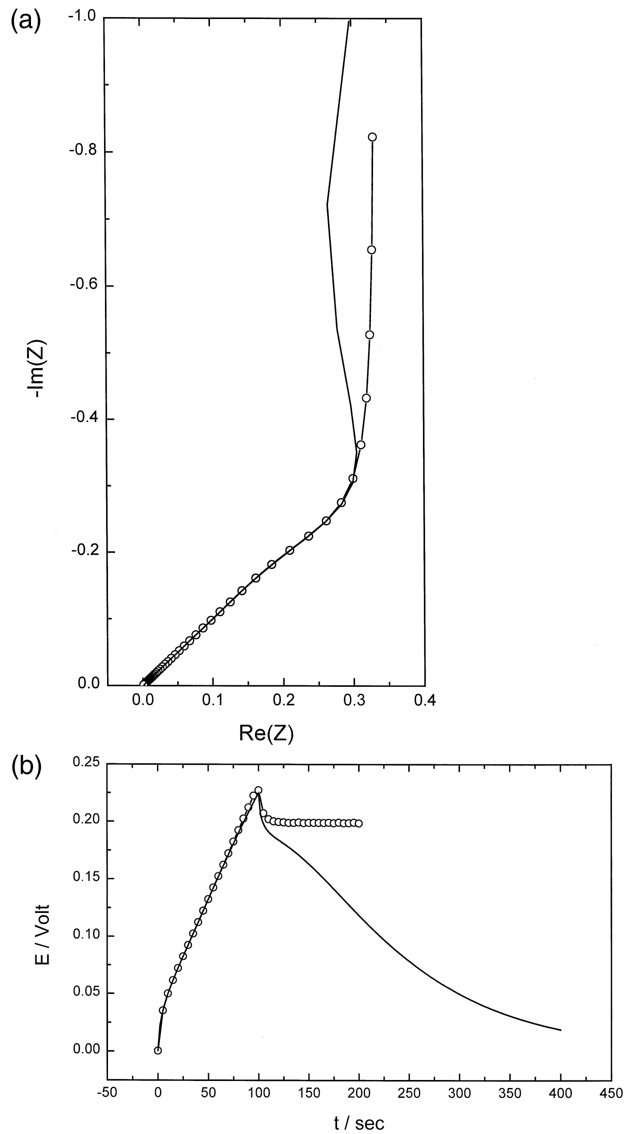

Fig. 2. (a) Impedance spectrum of an open-circuit terminated transmission line with 50 F limiting capacitance, 1 Ω distributed resistance and 1-m length (markers), compared with impedance spectrum of 15 serially connected RC-circuits, fitted to the spectrum of transmission line in region between 1 kHz and 20 mHz (line). (b) Response to a pulse waveform consisting of a current pulse of 0.1 A for 100 s and 0 current for more 300 s of example transmission line (markers) and same RC-model, fitted to the spectrum in above frequency region (line).

2.3. Formulation of non-linear equivalent circuit for battery

Eqs. (1)–(3) described in Section 2.2 are not valid in the case when parameters of the circuit depends upon voltage. Generally the terminal voltage of a circuit with non-linear elements can not be described by such equations but can be obtained from a solution of the system of

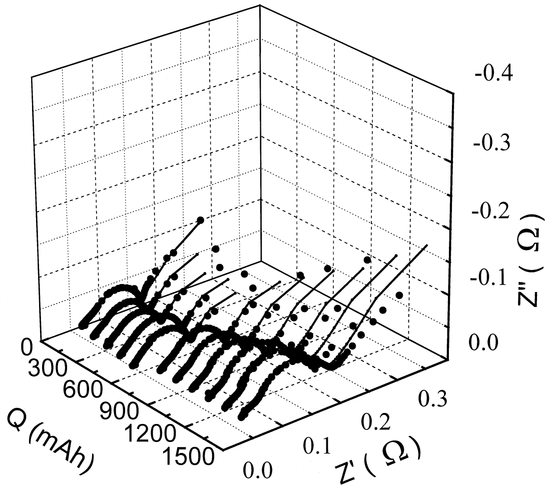

Fig. 3. Experimental impedance spectra measured at various discharge levels on Sony Li-ion battery (markers) and non-linear fit results (lines, markers).

non-linear differential equations. The non-linear circuit used in this work is created by modification of the linear circuit described above in order to extend beyond the restrictions of small-voltage approximation. This can be reached by the following steps.

(a) Electric elements (resistors, capacitors and transmission lines) are replaced by non-linear elements depending on the state of charge. First, the value of C_s is determined from discharge curve measured with discharge rate C/10. This discharge rate is found to be good enough approximation to the steady state conditions, since further decrease of discharge current does not make noticeable change in obtained $C_s(Q)$ curve. All parameters for linear static model (except C_s) at a series of different states of charge are obtained by performing a series of impedance measurements for different states of charge and then by performing non-linear least square fit using parameters of Eqs. (2) and (3).

(b) At high currents the R_{ct} additionally depends on the polarization as described by Butler–Folmer equation defined as,

$$R_{ct}(\upsilon C_s, \upsilon R_{ct}) = \frac{\upsilon R_{ct} R_{ct}(\upsilon C_s)}{K\left[e^{\frac{\beta \upsilon R_{ct}}{K}} - e^{-(1-\beta)\frac{\upsilon R_{ct}}{K}} \right]} \quad (4)$$

where νR_{ct} is the voltage across the resistor R_{ct}, β the transfer coefficient assumed here to be 0.5 and $K = RT/F = 0.0253$ V.

(c) The capacitors should be replaced by electric circuit elements designed to provide passivity. This means that only electrical energy can be supplied to the circuit from outside. Non-linear capacitors are generally not passive elements. Variation of capacitance for a charged capacitor requires external force, which is not physically feasible. The energy stored in the capacitor, ε, is changing with its capacitance as,

$$\frac{d\varepsilon}{dC} = -\frac{1}{2}\frac{Q^2}{C^2} \quad (5)$$

This change should be compensated by additional electric elements.

If the described changes are made in the linear static circuit, it represents an exact electrical equivalent of a battery and will reproduce battery behavior at any kind of electrical load applied to its terminals. However, the calculation of non-linear circuits including distributed elements such as Warburg diffusion impedance is difficult and requires special approach in each particular case. One possible method enabling automatic procedure includes formalization of Warburg impedance as transmission lines and replacement of ideal transmission lines by a network with finite number of chain connected two-ports. For this purpose transmissive finite length Warburg impedance in Eq. (3) should be formalized first as short-circuit termi-

Table 1
Set of parameters representing a numerical image of Sony 18650 size battery

Q (mA h)	R_{ct} (Ω)	C_{dl} (F)	C_{ps} (F)	ρ (Ω)	R_{ser} (Ω)	D (m^2 s^{-1})	E (V)	C_s (F)
0	0.0687	1.361	4142	0.0834	0.0701	0.00095	4.106	4646
130	0.0610	1.457	1940	0.0798	0.0644	0.00321	4.014	5318
260	0.0613	1.463	2273	0.0838	0.0598	0.00319	3.944	7736
390	0.0701	1.504	2133	0.0955	0.0567	0.00342	3.886	8661
520	0.0651	1.415	2151	0.0927	0.0509	0.00360	3.837	9675
650	0.0730	1.417	1752	0.0858	0.0743	0.00347	3.777	7039
780	0.0789	1.408	1611	0.0848	0.0747	0.00316	3.677	3631
910	0.0864	1.422	1333	0.0849	0.0747	0.00326	3.523	2674
1040	0.0988	1.485	1101	0.0894	0.0746	0.00331	3.313	1977
1170	0.1001	1.649	847	0.0834	0.0755	0.00374	3.042	1604
1300	0.0945	1.645	710	0.1093	0.0745	0.00329	2.717	1356

nated transmission line with total distributed resistance is given by,

$$R_d = \frac{1}{C_t D_t S} \tag{6}$$

where S is surface area equal to 1 m^2, and C_t and D_t are normalized quantities. This transmission can be represented approximately as a network of chain-connected two-port line in both linear (small-voltage) and non-linear cases. The resulting network can be numerically solved as a part of any device or separately at arbitrary load using common standard methods in electronics, for example, by employing SPICE simulator using finite difference method. Here we employed a method obtaining direct solution of non-linear differential state equations [14] using Livermore stiff ODE solver.

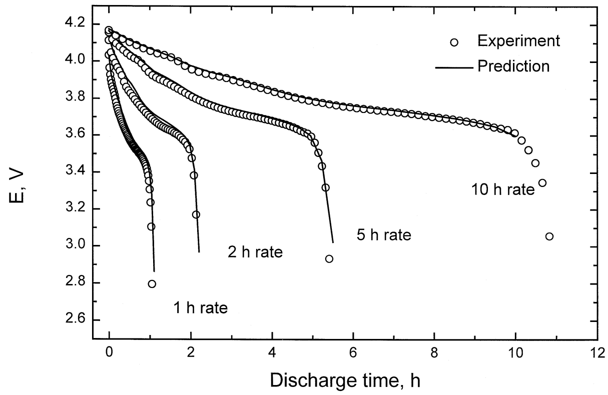

Fig. 5. Dependence of battery terminal voltage on the state of charge during discharge at various discharge rates, calculated on the basis of non-linear model derived from circuit in Fig. 1 and experimentally obtained numerical image of Matsushita 18650 Li-ion battery.

3. Experimental

The 18650 size Li-ion battery samples manufactured by Sony, Sanyo and Matsushita were obtained from commercially available cellular phone battery packs. All batteries had the capacity of 1350 mA h at the maximal charging voltage of 4.2 V and discharge rate of C/5. The AA-size Hitachi Ni-MH batteries had the rated capacity 1100 mA h at maximal voltage 1.2 V and discharge rate of C/5. Fresh batteries were 10 times cycled to reach relatively non-varying impedance and charge capacity before parameterization procedure. If not specified otherwise batteries were charged prior to all measurements at 1C rate until voltage reached 4.2 V and then kept under potentiostatic control at this potential for 2.5 h to reach a full-charged state.

The charging and galvanostatic discharging of battery was performed using a TOSCAT 3000U computer-controlled battery cycler. The current pulse measurements was made using EG&G model 273 potentiostat controlled by home-made software.

Impedance measurements were performed under galvanostatic conditions using multi-wave FFT impedance measurement system based on EG&G model 273 potentiostat. Detailed description of the measurement system can be found in Ref. [15], and special considerations related to galvanostatic measurement in Ref. [16]. The perturbation current can be chosen in such a way that a response voltage do not exceed 20 mV to provide validity of small-voltage approximation and linearity of the system. Used measurement method enabled independent check of the system linearity by analysis of response power spectrum. All the impedance spectra were acquired at frequency region of 1 mHz–1 KHz. Experimental impedance spectra measured at different discharge states were fitted to Eq. (2) using LEVM non-linear complex least square fitting program described in Ref. [17] to obtain parameters of numerical image. The parameter C_S at each state of charge is determined from emf relation.

Du Won M260 DC motor were used to investigate change of battery voltage during operation of simple DC

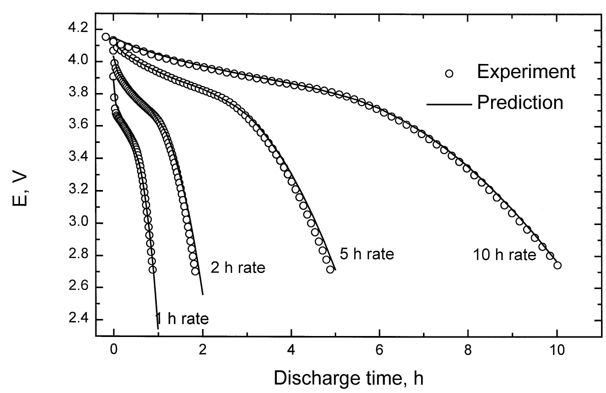

Fig. 4. Dependence of battery terminal voltage on the state of charge during discharge at various discharge rates, calculated on the basis of non-linear model derived from circuit in Fig. 1 and experimentally obtained numerical image of Sony 18650 Li-ion battery.

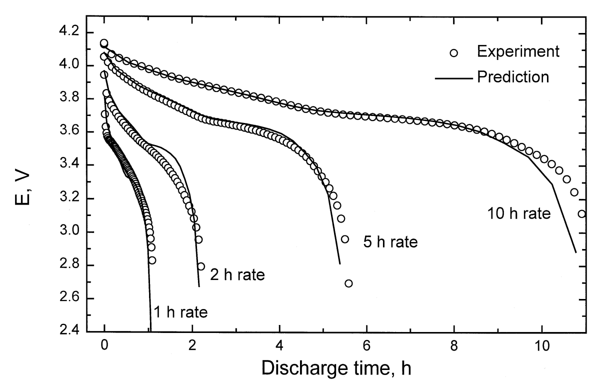

Fig. 6. Dependence of battery terminal voltage on the state of charge during discharge at various discharge rates, calculated on the basis of non-linear model derived from circuit in Fig. 1 and experimentally obtained numerical image of Sanyo 18650 Li-ion battery.

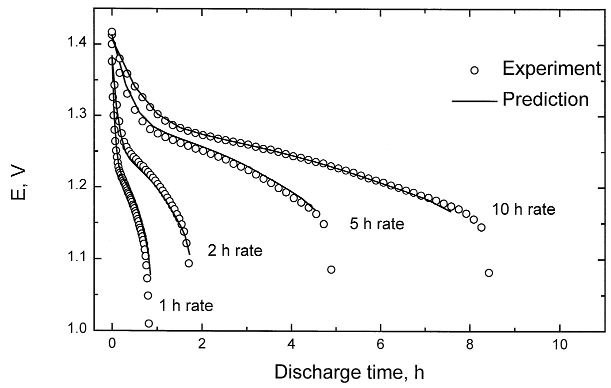

Fig. 7. Dependence of battery terminal voltage on the state of charge during discharge at various discharge rates, calculated on the basis of non-linear model derived from circuit in Fig. 1 and experimentally obtained numerical image of Hitachi AA-size Ni-MH battery.

motor circuit. The voltage of battery was measured by using Keithley 2000 digital multimeter and home-made software. The rotation speed of the motor was monitored by stroboscopic technique using a chopper attached to the motor shaft, laser light source, silicon detector and frequency counter.

4. Comparison of numerical and experimental results

In order to evaluate the performance of presented battery parameterization method, a parameterization of Sony, Matsushita and Sanyo 18650-size Li-ion batteries as well as Hitachi AA-size Ni-MH battery has been performed using described steps. Experimental impedance spectra for different discharge levels measured at Sony Li-ion battery are shown as an example in Fig. 3 and a numerical image of the battery as a set of parameters is shown in Table 1.

The obtained numerical images were used to predict battery discharge curves for series of different load conditions. For all calculations, transmission lines were replaced to chain-connected two-port networks with $N_d = 8$ for a diffusion inside particles and $N_t = 4$ for a mass transport through porous active mass, as described previously. Voltage response has been calculated by direct solution of non-linear differential state equations in combination with an electric element representing particular load (for example, current source in case of constant current discharge) using Livermore stiff ODE solver.

To ensure the behavior of the model at wide range of discharge levels and discharge rates, numerical calculation of battery terminal voltages during discharge at discharge rates of C/10, C/5, C/2 and 1C was performed. Calculated voltage dependencies on the state of charge for Sony, Matsushita, Sanyo Li-ion and Hitachi Ni-MH batteries are shown in Figs. 4–7 in comparison with experimentally measured curves. Table 2 gives a quantitative description of prediction quality in terms of average relative standard deviation of voltage, relative deviation of end-of-discharge time and total dissipated energy.

The calculation of pulse response of Sony battery was performed in order to investigate the behavior of the model in transient conditions. For this purpose the non-linear circuit was terminated with time-dependent current source.

Table 2
Comparison of numerical prediction and experiment for discharge at different discharge rates for Sony, Matsushita, Sanyo Li-ion and Hitachi Ni-MH batteries from measured experimental data

Battery	Discharge rate (C)	Discharge time (h)			Total energy (W h)			Voltage average relative standard deviation (%)
		Prediction	Experiment	Relative deviation (%)	Prediction	Experiment	Relative deviation (%)	
Sony, 18650 size, Li-ion	1	0.879	0.893	1.59	3.926	3.860	1.70	0.26
	1/2	1.835	1.923	4.80	4.351	4.155	4.70	0.88
	1/5	4.908	5.033	2.55	4.745	4.633	2.40	1.43
	1/10	10.13	10.18	0.45	4.809	4.867	2.33	0.77
Matsushita, 18650 size, Li-ion	1	1.052	1.109	1.11	5.147	4.867	5.74	1.22
	1/2	2.101	2.254	2.25	5.331	5.104	4.44	0.33
	1/5	5.425	5.650	4.30	5.507	5.310	3.70	2.18
	1/10	10.88	10.90	1.56	5.313	5.325	0.24	0.16
Sanyo, 18650 size, Li-ion	1	1.104	1.028	6.88	4.640	4.753	2.38	3.53
	1/2	2.215	2.154	2.75	4.822	4.864	0.86	1.34
	1/5	5.587	5.423	2.94	5.145	5.264	2.25	0.64
	1/10	11.11	10.87	2.26	5.194	5.318	2.33	0.83
Hitachi, AA size, Ni MH	1	0.751	0.823	4.59	1.074	0.979	9.70	0.52
	1/2	1.680	1.781	6.01	1.162	1.108	4.88	0.72
	1/5	4.889	4.951	2.09	1.237	1.209	2.31	0.17
	1/10	8.160	8.602	2.42	1.269	1.244	1.98	0.23

For Li-ion 18650 size batteries, C is 1350 mA, and for AA-size Ni-MH, 1100 mA.

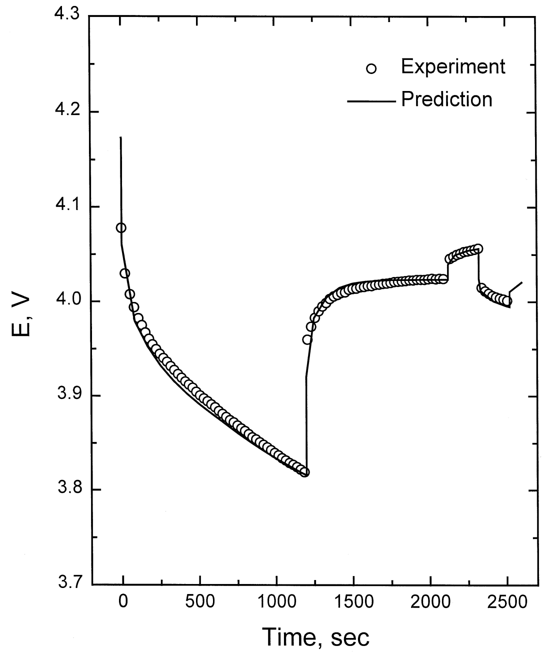

Fig. 8. Prediction and experimental data of a Sony 18650 size battery response to current load pattern, consisting of $I_1 = -650$ mA/ $t_1 = 1200$ s; $I_2 = 0$ mA/ $t_2 = 900$ s; $I_3 = 100$ mA/ $t_3 = 200$ s; $I_4 = -100$ mA/ $t_4 = 200$ s.

Pulse pattern consists of high discharge current which was changed to open-circuit condition followed by low charging current and then by low discharging current. The predicted terminal voltage curve is compared in Fig. 8 with an experimental result.

Motivated by strong relevance of the developed parameterization approach to design of EVs using battery and electric motor, we tested the behavior of the model in a system including motor as passive load. An electric circuit (Fig. 9) representing simplified electric propulsion system, including equivalent circuit of battery, equivalent circuit of DC-motor and additional load resistance $R_1 = 10.40$ Ω

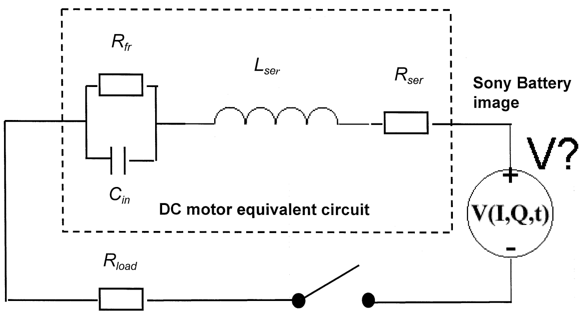

Fig. 9. Electric circuit of simplified electric propulsion device including Sony 18650 battery non-linear equivalent circuit, DC motor and additional load resistance. DC motor is represented as a circuit including friction resistance $R_{fr} = 15.04$ Ω, inertial pseudocapacitance $C_{in} = 37.44$ mF, wires resistance $R_{ser} = 4.26$ Ω and wires inductance $L_{ser} = 1.26$ mH.

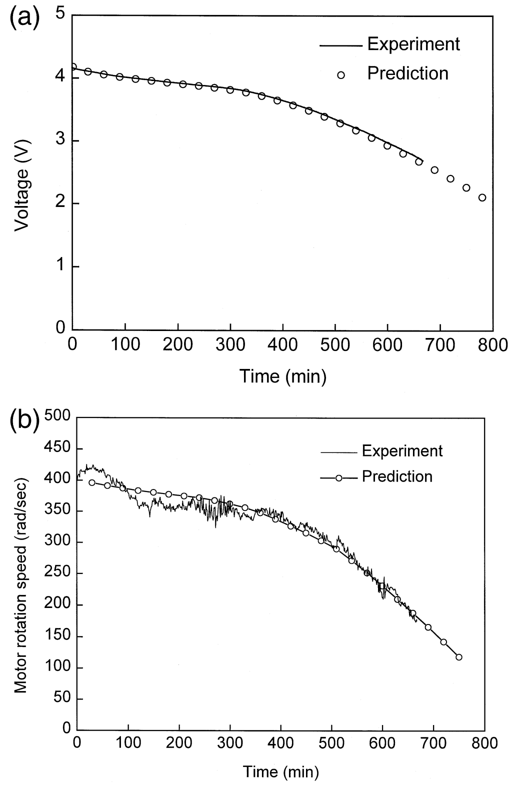

Fig. 10. Prediction and experimental data of voltage (a) and rotation speed (b) dependent on the operation time of a circuit including Sony 18650 battery and DC motor.

was used for calculations. Parameters for equivalent circuit representing the motor were obtained through impedance measurement on Du Won M260 DC motor as friction resistance $R_{fr} = 15.04$ Ω, inertial pseudocapacitance $C_{in} = 37.44$ mF, wire resistance $R_{ser} = 4.26$ Ω, and wire inductance $L_{ser} = 1.26$ mH. Discharge experiment was performed by running the DC-motor powered by the battery initially in full-charged state and until its complete discharge, while monitoring the battery voltage and rotation speed of the motor. Voltage at battery terminals and current through R_{fr} (ideally proportional to rotation speed) were calculated as described above and results are compared with experiment in Fig. 10.

5. Discussion

The goal of this work is to create a model which provides a practical and sufficiently exact representation of a battery at any load conditions including transient conditions and an automatic measurement procedure which provides all necessary parameters without destroying the battery or exactly knowing its internal chemistry and configuration. However, these two requirements can possibly be conflicting. To provide an exact representation of battery under transient conditions it is necessary to have physically relevant model, which correctly represents the transport mechanisms and thermodynamic relationships governing the battery behavior. On the other hand,conflicting because impedance measurement across both the cathode and anode does not allow to obtain their kinetic parameters separately. To resolve this problem we assume that cathode and anode have similar transport mechanisms and that total impedance of anode and cathode are of the same order of magnitude. As far as this assumption is valid, the total impedance of battery can be correctly represented as one transmission line instead of two transmission lines not only in small-voltage case (where this assumption is always valid) but also in non-linear case. Comparison of this approach with experimental results in cases of highly transient conditions (Fig. 8) and the presence of non-linearity in region where parameters are considerably varying during the discharge process (Figs. 4–7) confirms the validity of our assumption. Prediction does not show any expressed deviations from experimental result which would be observed if the physical relevance of the model is insufficient. However, additional tests especially in higher current region are necessary to check the limit of model validity.

Since various kinds of batteries with different chemistries are well described by the proposed method, the suggested operation mechanisms of battery appears to be generally valid. The experiments showed that if some of the kinetic steps are less significant in particular type of battery, it can be automatically removed from the model because fitting procedure assigns such values for corresponding kinetic rate parameters which effectively excludes them from transport path. This property can make the proposed model a good candidate for a standard method of parameterization and comparison with various types of batteries.

Formalization of battery model as non-linear circuit enables an application as a standard method in electronics to find a solution for terminal voltage change at arbitrary load conditions. Several relatively simple cases have been demonstrated in Section 4 including the calculation of simplified EV model. Calculation time for all cases do not exceed 10 min with common personal computer. In case of circuits including many batteries, further simplification of the model is possible. The numerical image always contains maximal possible information, which can be partly sacrificed for the price of calculation speed using automatic procedure inside the simulation engine, but still providing reasonably good prediction.

An operation of such established automatic procedure for battery parameterization does not require further deep understanding of electrochemical kinetics or specialty in impedance measurement. Multi-wave FFT galvanostatic impedance spectrometer used for this purpose turned out to be a reliable measurement system for various kind of batteries with minimal adjustments and high quality impedance spectra. Due to the restriction given by wave non-overlapping principle, however, only frequencies representing the lowest frequency multiplied by integer can be used, e.g., $2f_{\min}$, $3f_{\min}$, $4f_{\min}$, while higher number of frequencies in low-frequency region is preferred for the parameter estimation. The total parameterization process can be performed by fully automated control program. However, the non-linear fitting of impedance spectra of a new battery type where no information about approximate battery parameters is available sometimes requires manual adjustments of initial parameter values to ensure convergence to global minimum. Solving these problems will be a target of our further investigation.

6. Conclusion

A new method for numerical representation of a battery by measurements of impedance spectra and equilibrium voltage profile and by non-linear fitting of impedance spectra into physically relevant equivalent circuit for the battery is developed. An assumption to represent both cathode and anode as one transmission line turned out be a sufficiently correct approximation both for small-signal analysis (linear case) and processes including considerable battery discharge (non-linear case). Tests performed on several types of batteries including Li-ion, and Ni-MH batteries are compared with numerical predictions for the same batteries and confirmed general applicability of assumed mass transport mechanism during battery recharge to the present model. This suggests a possibility to use developed method as standard procedure for numerical description to compare battery characteristics of different types.

Formalization of developed model as non-linear electric circuit enables application of readily available mathematical and programming tools developed for obtaining the solution of electric circuits. Several examples of numerical solution for electric circuits including that for battery are demonstrated to show flexibility of this approach and compared with results of experimental measurement.

A system for battery parameterization including FFT multi-wave impedance spectrometer and automated processing software is demonstrated as a new widely applicable tool useful for battery manufacturer as well as battery consumers.

References

[1] B.A. Johnson, R.E. White, J. Power Sources 70 (1998) 48.
[2] Y.-H. Kim, H.-D. Ha, IEEE Trans. Ind. Electron. 44 (1997) 81.
[3] S. Maas, RF Design 18 (3) (1995) 58.
[4] S.C. Hageman, EDN 38 (22) (1993) 117.
[5] US Patent 5,428,560 A (1995).
[6] Z. Stoynov, T. Nishev, V. Vacheva, N. Stamenova, J. Power Sources 64 (1997) 189.

[7] C. Protogeropoulos, R.H. Marshall, B.J. Brinkworth, Sol. Energy 53 (6) (1994) 517.
[8] E. Barsoukov, J.H. Kim, J.H. Kim, C.O. Yoon, H. Lee, J. Electrochem. Soc. 14 (58) (1998) 2711.
[9] E. Barsoukov, J.H. Kim, J.H. Kim, C.O. Yoon, H. Lee, Solid State Ionics 116 (1999) 249.
[10] G. Paasch, K. Micka, P. Gersdorf, Electrochim. Acta 38 (1993) 2653.
[11] D. Aurbach, M.D. Levi, E. Levi, H. Teller, B. Markovsky, G. Salitra, U. Heider, L. Heider, J. Electrochem. Soc. 145 (9) (1998) 3024.
[12] C. Ho, I.D. Raistrick, R.A. Huggins, J. Electrochem. Soc. 127 (1980) 343.
[13] T. Jacobsen, K. West, Electrochim. Acta 40 (2) (1995) 255.
[14] C.A. Desoer, E.S. Kuh, Basic Circuit Theory, McGraw-Hill, 1969, p. 501.
[15] G.S. Popkirov, R.N. Schindler, Rev. Sci. Instrum. 63 (1992) 5366.
[16] G.S. Popkirov, E. Barsoukov, R.N. Schindler, J. Electroanal. Chem. 425 (1997) 209.
[17] J.R. Macdonald, J. Schoonman, J. Lehnen, Solid State Ionics 5 (1981) 137.