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Modelling and simulation of the dynamics within the $LiFePO_4$ battery charger

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***Abstract*— This is a case study of the transients within a simple charger/discharger circuit synthesized for a $LiFePO_4$ battery. Given the restriction of the variations of the input voltage (coming from the DC/DC converter) and the load resistance (with 2.5 V $<V_{os}<$ 6.5 V, and 0.25 Ω $<R_L<$ 1.25 Ω), we created a simple controlling circuit that charges the battery loaded by R_L so that the output voltage remains as 3.3 V $<V_{out}<$ 3.6 V. Than using a model of the battery from literature, we simulated the circuit and created some knowledge about the charging process.**

Keywords—$LiFePO_4$ battery, modelling, simulation, charging, discharging

I. Introduction

Electrochemical batteries play a crucial role in various electrical systems by storing chemical energy that can be converted into electrical energy and supplied when needed. The growing demand for portable devices, such as mobile phones, PDAs, digital cameras, and laptops, has spurred advancements in battery technologies, including nickel-cadmium (NiCd), nickel-metal hydride (NiMH), lithium-ion (Li-Ion), and polymer Li-Ion batteries. One such technology, namely, Lithium Iron Phosphate ($LiFePO_4$), will be examined in this context. This rechargeable battery features a unique chemistry that offers high energy density, a long-life cycle, and outstanding thermal stability.

In the sequel we will first, discuss the modeling of this type of batteries intended to be used in electronic circuits simulation. Then we will develop a simple circuit that allows for the study of the charging and discharging as concurrent processes.

II. Modelling the battery

The battery is a unique electrical component because it does not follow the fundamental laws of electrotechnics, such as Ohm's law, Faraday's law, or the current-voltage relationship of capacitors. Instead, it operates based on intricate electrochemical and thermal processes.

Battery modeling employs various approaches to achieve specific objectives, such as battery design, performance estimation, and circuit simulation. Electrochemical models (as described in [1]), which are mainly used to optimize the physical design of batteries, capture the fundamental mechanisms of power generation. These models connect battery design parameters with both macroscopic data (e.g., voltage and current) and microscopic data (e.g., concentration distribution). However, they are complex and time-consuming, involving coupled, time-varying, spatial partial differential equations. As a result, they require lengthy simulation times, sophisticated numerical methods, and detailed, often proprietary, battery data that can be difficult to obtain.

Mathematical models (e.g., [2]), while more abstract and less practical, remain useful for system designers. They rely on empirical equations or techniques such as stochastic methods to estimate system-level behaviors like battery runtime, efficiency, temperature, or capacity. One of the primary functions of such models may include predicting the temperature of battery cells under various operating conditions and analyzing heat release under fluctuating loads. However, these models do not provide I-V data, which is essential for circuit simulation and optimization. Additionally, most mathematical models are tailored to specific applications.

Electrical models aim to strike a balance between the accuracy of electrochemical and mathematical models, with error rates typically ranging from 1-5%. These are macromodels developed using a black-box modeling approach, which combines voltage sources, resistors, and capacitors to create a nonlinear circuit suitable for simulation, primarily with standard circuit simulation tools. Various electrical models are available for different battery types, such as lead-acid and polymer Li-Ion batteries, and they generally fall into three main categories: Thevenin-based, impedance-based, and runtime-based models.

The schematicof the model as given in [3] is depicted in Fig. 1.It is Thevenin-type and is built of two parts.

At the top, the battery lifetime is represented by an RC circuit. The resistor (R_{leak}) models self-discharge, while the capacitor (C_{cap}) tracks the stored energy.

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This capacitor is linear and is modelled as follows:

$$C_{\mathrm{cap}} = 3600 \cdot C_0 \cdot f_1(N_\mathrm{c}) \cdot f_2(T) \quad (1)$$

where C_0 is the nominal capacity of the battery expressed in Ahr, f_1 is a function of the number of charging/discharging cycles (N_c), and f_2 is a function of temperature (T). In the following, the last two functions will be assumed to be equal to one.

The charging and discharging process is modeled using a unity-gain linear current-controlled current source (CCCS), which links the battery current i_B (as the controlling variable) to the charge monitoring voltage (v_s), commonly known as the "state of charge" (SOC). To avoid confusion with the notation (e.g. System On …), the term SOC will not be used here.

The right-hand side of the model consists of nonlinear components, with the voltage-controlled voltage source (VCVS) denoted as $v_\mathrm{o}(v_\mathrm{s})$ being the most significant. This VCVS represents the coupling between the internal and external "world" of the battery. Three resistors (R_o, R_ts, and R_tl) are connected in series, with two of them bypassed by capacitors ($C_\mathrm{ts}$and C_tl).

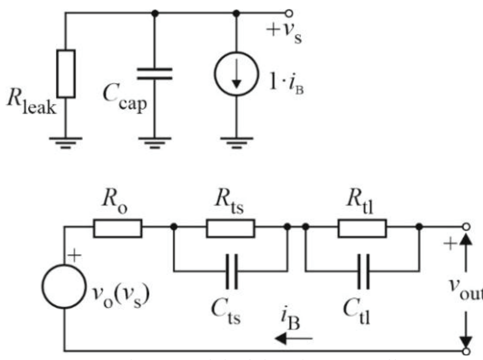

Fig. 1 Model of the $LiFePO_4$ cell

To describe the behavior of the nonlinear elements the following set of equations is used:

$$v_\mathrm{o}(v_\mathrm{s}) = -1.031 \cdot \mathrm{e}^{-35 \cdot v_\mathrm{s}} + 3.685 + 0.2156 \cdot v_\mathrm{s} - 0.1178 \cdot v_\mathrm{s}^2 + 0.3201 \cdot v_\mathrm{s}^3 \;[\mathrm{V}] \quad (2)$$

$$R_\mathrm{o}(v_\mathrm{s}) = 0.1562 \cdot \mathrm{e}^{-24.37 \cdot v_\mathrm{s}} + 0.07446 \;[\Omega] \quad (3)$$

$$R_\mathrm{ts}(v_\mathrm{s}) = 0.3208 \cdot \mathrm{e}^{-29.14 \cdot v_\mathrm{s}} + 0.04669 \;[\Omega] \quad (4)$$

$$R_\mathrm{tl}(v_\mathrm{s}) = 6.603 \cdot \mathrm{e}^{-155.2 \cdot v_\mathrm{s}} + 0.04984 \;[\Omega] \quad (5)$$

$$C_\mathrm{ts}(v_\mathrm{s}) = -752.9 \cdot \mathrm{e}^{-13.51 \cdot v_\mathrm{s}} + 703.6 \;[\Omega] \quad (6)$$

$$C_\mathrm{tl}(v_\mathrm{s}) = -6056 \cdot \mathrm{e}^{-27.12 \cdot v_\mathrm{s}} + 4475 \;[\Omega] \quad (7)$$

As observed, these elements are highly nonlinear, and in some circuit simulators, modeling a nonlinear capacitor can be problematic or even impossible. For instance, LTspice can only handle nonlinear capacitors if their charge is expressed as a function of the controlling voltage. To obtain the charge, it is necessary to integrate the expression of the voltage-controlled nonlinear capacitance in a closed form.

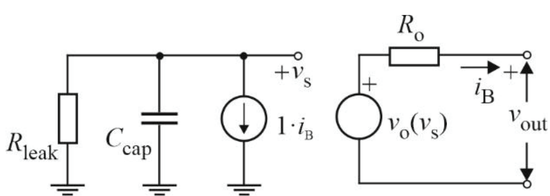

Fig. 2 Reduced model of the $LiFePO_4$ cell

The battery is regarded as fully charged when the internal voltage v_s is set to 1, and fully discharged whenv_s=0.

A comprehensive list of alternative functions for $v_\mathrm{o}(v_\mathrm{s})$, based on various literature sources, is provided in [4].

In this work, we will use the simplified version of the model shown in Fig. 1, which is further illustrated in Fig. 2, as described in [5]. In this model, only the transfer characteristic is nonlinear.

The authors presented the transfer characteristic in the form shown in Fig. 3. Instead of using a nonlinear VCVS as an analytical function, they employed a piecewise approximation of the curve, as outlined in Table 1. This table was then used to define the VCVS within the subcircuit in LTspice, which represents the macro-model of the cell. Additionally, the cell's nominal capacity was set to C_0=180 F, and the leakage resistance was chosen as R_leak=10^{12} Ω. The series resistance at the output was specified as R_o=0.6 mΩ, and the initial value $v_\mathrm{s}(0)$=1 V was used. This concludes the description of the model employed in the simulation, the results of which will be presented below.

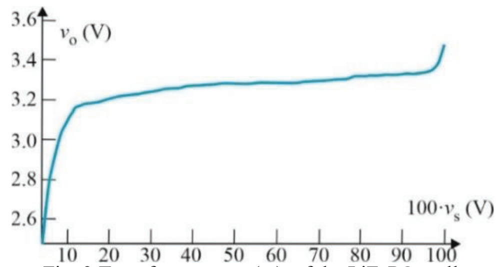

Fig. 3 Transfer curve, $v_\mathrm{o}(v_\mathrm{s})$, of the $LiFePO_4$ cell

III. The circuit and the simulation results

The simulated circuit is shown in Fig. 4. A voltage source (v_os) at the input represents the output of the converter, providing the necessary power. Note the series resistance denoted R_os = 1 Ω, which represents the internal resistance of the source. We consider the presence of this resistance when simulating power systems is of crucial importance having in mind the large currents which are processed. A diode is included, as is typical, to prevent reverse power flow. Two switches are connected in series, and their operation is controlled by comparators (not shown). The first switch turns on when the output voltage (v_out) falls below the specified minimum value, $V_\mathrm{out\_min}$. The second switch turns off when the output voltage exceeds the specified maximum value, $V_\mathrm{out\_max}$. Both switches remain on when the output voltage is within the range of $V_\mathrm{out\_min} < v_\mathrm{out} < V_\mathrm{out\_max}$.

The load resistor's value jumps abruptly between: R_L= R_L1= $0.5 \cdot R_\mathrm{L2}$ Ω and R_L= R_L1+R_L2= 3 Ω. The input voltage waveform is constant voltage (V_const= 5 V) to which a sinusoidal disturbance is added so that: 3V<v_os< 6V. The thresholds were set as $V_\mathrm{out\_min}$ = 3.3 V and $V_\mathrm{out\_max}$= 3.6 V.

The initial simulation results are shown in Fig. 5, where the waveforms of the currents within the circuit are depicted. That includes the input (voltage source current), the battery current and the current of the R_L2 resistor. The last current is complimentary to the battery current which in the periods when the input supply voltage is disconnected becomes negative i.e., the battery gets discharged through the load resistor.

TABLE 1.Sampled transfer curve of theLiFePO4 cell as LiFePO4 cell as depicted in Fig. 3

v_s	0	.03	.05	.075	.1	.12	.2	.3	.4	.5
v_o	2.5	2.8	2.9	3	3.1	3.17	3.2	3.23	3.28	3.29
v_s	.6	.65	.7	.76	.8	.9	.95	.97	.98	1
v_o	3.3	3.3	3.31	3.32	3.33	3.38	3.35	3.37	3.38	3.5

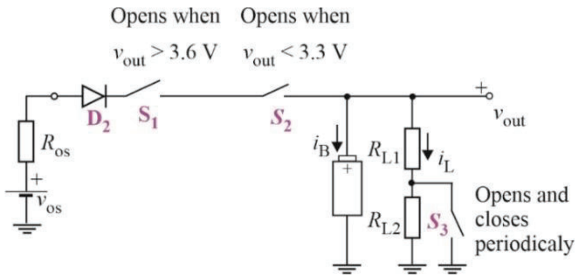

Fig. 4 The “charger_battery_load” circuit, The diode used is DNA30EM2200PZ

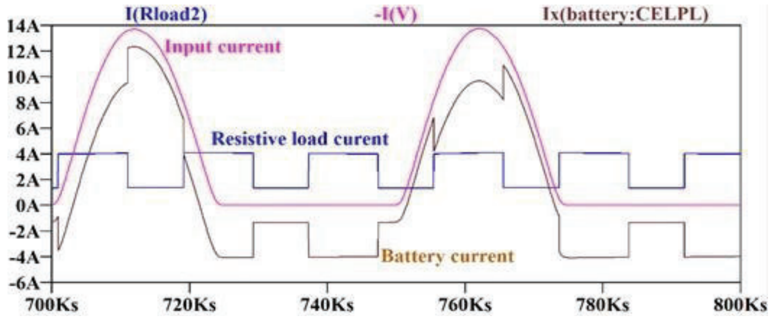

Fig. 5 Currents within the“charger_battery_load” circuit

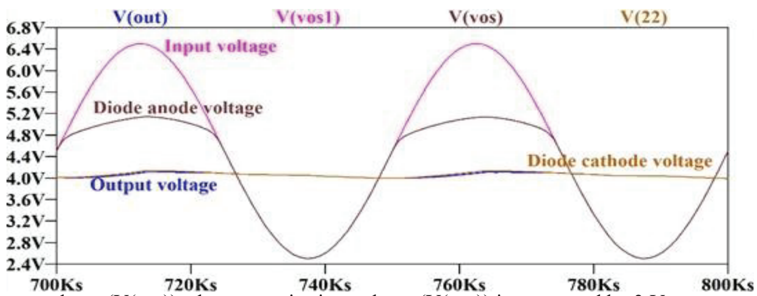

Fig. 6 Output voltage (V(out)), charge monitoring voltage (V(soc)) incremented by 3 V, and the increment of the load resistance of the“charger_battery_load” circuit

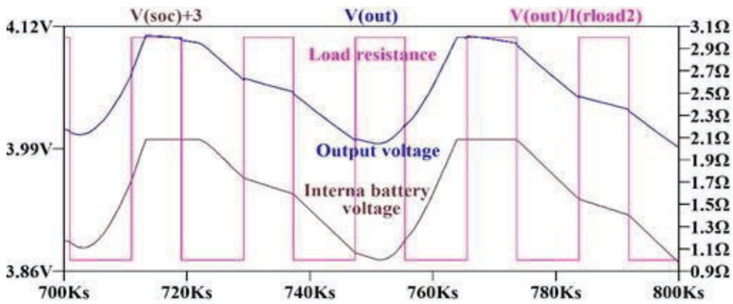

Fig. 7 Voltages within the “charger_battery_load” circuit

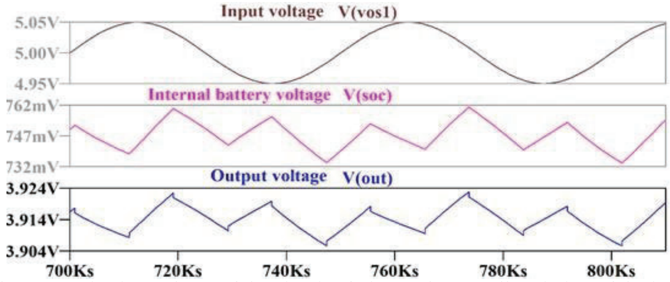

Fig. 8 Input and output voltage and charge monitoring voltage of the circuit of Fig. 4 when small variation of the input voltage is present

Fig. 6 depicts three waveforms: The input, diode anode and cathode, and the output voltage.

The time domain response of the charge monitoring voltage(v_s) together with the output voltage (v_{out}) of the circuit are depicted in Fig. 7. The increment of the load resistance (R_{L2}) is also shown. One may recognize the time period when the battery gets discharged and v_s is falling below unity. Note, apart from the absolute value, the two voltages have the same waveform.

It is interesting to observe what the situation would be in a more realistic scenario, where the input voltage does not fluctuate as much. We set v_{os_max} to 5.01 V and v_{os_min} to 4.95 V, resulting in a maximum variation (peak-to-peak) of 200 mV.

The simulation results for this case (with all other parameters unchanged as shown in Fig. 7) are presented in Fig. 8. As observed, the maximum variation of the output voltage (peak-to-peak) was reduced to approximately 12 mV.

Further, the power distribution inthe circuit was observed by simulation of the same circuit with R_{os}=0 Ω, R_1= 0.25 Ω, R_2= 1.25 Ω and the input voltage waveform as depicted in Fig. 9 as V(vos).

The same figure illustrates the corresponding responses for the diode current and the output voltage.

The main results, here, is Fig. 10 where powers are depicted. One may observe that when the input voltage is below threshold, the battery is taking over to get the instantaneous power of the resistor sustained. The zero valued battery power is indicated by a black horizontal line in the bottom diagram.

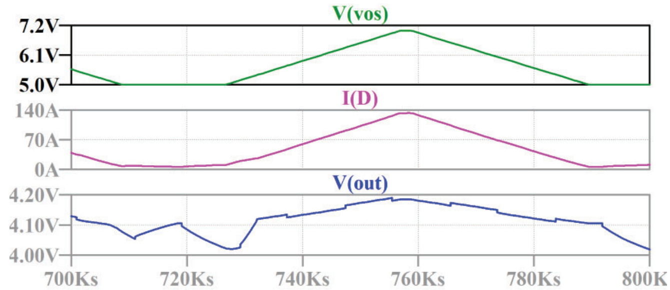

Fig. 9. Input and output voltage, and the input current for R_{os}=0

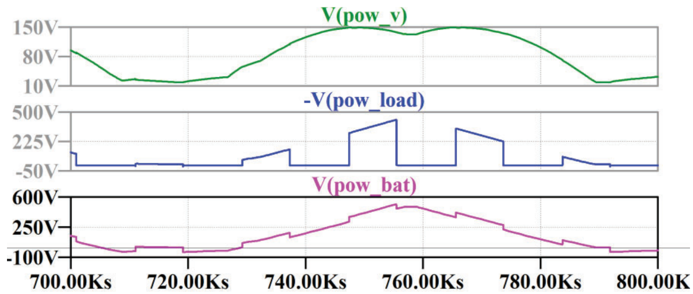

Fig. 10 Powers dissipated (in Watts) at the battery (pow_bat), at the load (pow_load) and at the input (pov_voos)

IV. Conclusion

Simulation of the transients within the charging circuitry of a $LiFePO_4$ battery is of importance from the point of view of the possibilities offered by the charger and the waveforms arising within it. The circuit charging single battery presented here may be considered as a reference for simulation of battery packs of any complexity. There are two possibilities when doing so: to use repetitively the model of a single battery as many times as necessary in order to complete the pack's structure or to create an equivalent-battery-pack model. In any case the experience produced here will be a valuable asset.

The regulation circuit implemented here is the simplest of all. Implementation of more complex feedback (e.g. PWM, as is frequently done in [6]) may produce even better results as compared to the ones depicted in Fig. 8.

Acknowledgments

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