Simulation and Design of Lead Acid Pspice Battery Model with Bidirectional Converter

Zainab M. Kubba* and Zeena Mowafaq Al-Azzawi
Department of Physics, College of Science, Al-Nahrain University.
*E-mail : z.kubba@yahoo.com

Abstract

This search discusses the simulated and design of the battery model. The simulated is carried out using Personal Simulation Program for Integrated Circuits Emphasis PSPICE software for the complete model in order to get the results for the proposed battery model. The PSPICE lead acid battery model is consists of the charge efficiency and Battery voltage components. Details are also given to the method of measuring the charge efficiency then the battery model will be tested as input source to the bidirectional Buck-Boost converter to verify its validity.

Keyword: Lead Acid Battery, PSPICE, Bidirectional converter, charge efficiency.

Introduction

Battery, charge efficiency (C.E), State of Charge (SOC) and internal resistance (Rbat) are affected on the battery performance. Temperature also affects the life of the battery. Therefore, ideally, batteries should operate within a temperature range, SOC and charge efficiency that is optimum for performance and life.

The state of charge of a battery is useful in determining the available capacity of the battery. It is expressed as the percentage of the rated capacity of the battery. State of charge tells the user how much more energy the battery can deliver to the application before it needs recharging. Based on the physical parameter that is measured, SOC determination methods are classified into the following types: **[1]**

1. Direct Measurement
2. Voltage-Based SOC Estimation
3. Current-Based SOC Estimation
4. Specific Gravity Method

In this work the current based SOC estimation is used to modulate the battery.

Charge efficiency refers to how many amp-hours are absorbed by the battery compared to how many charge amp-hours are delivered. A charge efficiency factor of 94% means that for each 100 amp-hours of charge delivered, the battery increases charge by 94 amp-hours. Charge efficiency is typically very high when the battery is highly discharged and somewhat lower when the battery is near full charge. The factory default setting of 94% is a good average for typical systems. Charge efficiency refers to how many amp-hours are absorbed by the battery compared to how many charge amp-hours are delivered. Charge efficiency is typically very high when the battery is highly discharged and somewhat lower when the battery is near full charge. The factory default setting of 94% is a good average for typical systems.

An understanding of the behavior of lead acid batteries is of paramount importance for stand by applications. The 2002 Greg Waldo paper describing the PSPICE NiH_2 battery model, which is consists of charge efficiency and battery voltage components.**[2]** This paper provides theoretical studies to build lead acid battery model using Greg Waldo techniques. The battery model is simulated in PSPICE software in order to get the results for the proposed model. The battery model will be tested as input source to the bidirectional buck boost converter to improve its validity.

Lead-Acid Battery PSPICE Model

A widely used battery model is described by the following equation:**[3]**

$$E = E_o + I\,R_{bat} \quad \text{...(1)}$$

In the above equation, it is assumed that a battery has a constant open circuit potential and the potential of a loaded battery varies with the applied current.**[3]** Open circuit voltage is changed to different capacity levels (i.e. SOC). The nonlinear relation between open circuit voltage and SOC is important to be included in the model.**[4]** The PSPICE

Lead-acid battery model is based on the SPICE, which consists of the charge efficiency and battery voltage components. The charge efficiency component was originally developed at Lockheed Martin/ Sunnyvale. **[2]** The schematic of the PSPICE model is shown in Fig.(1).

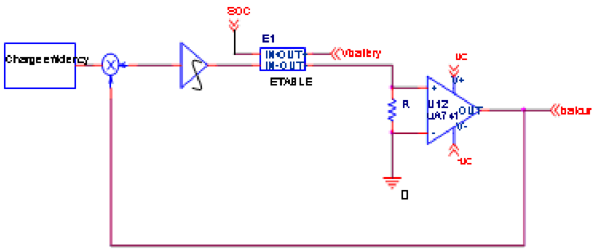


Fig. (1) PSPICE lead-acid battery model.

The voltage component of the model consists of amp-hour integrator which tracks the net current flowing into the battery terminal (Vbattery).The output of the integrator give us the SOC so, it is connected to a table driven voltage source, ETABLE, which generates the equivalent open circuit battery voltage (Vbattery) according to the piecewise linear curve shown in Fig.(2).**[5]** As the battery is charged, less and less charge current contributes to an increase (SOC) instead converted to heat. The model accounts for the changing battery efficiency by multiplying the battery current by a factor called charge efficiency.

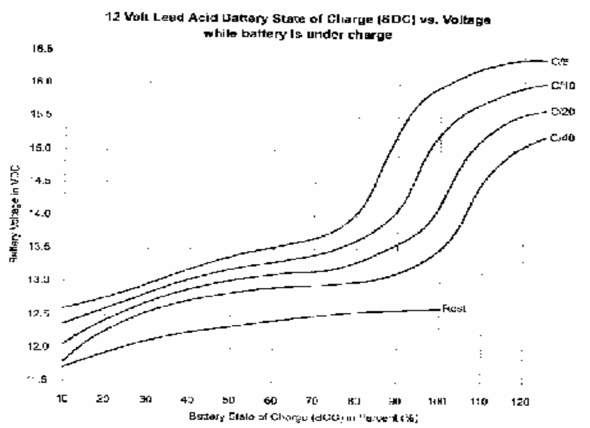


Fig.(2) Lead acid battery state of charge vs. voltage while battery under charge[5].

Charge efficiency Factor

Charge efficiency factor can vary from 0 to 1 and is dependent on the battery SOC, charge current and temperature. If battery SOC is negative, or battery is in discharge, then charge efficiency equal one, otherwise it becomes as eq.(1) **[2]**

$$\text{Charge efficiency} = \frac{1}{1+r} \quad \text{.....................(2)}$$

where

$$r = \left(\frac{-r_t}{e \; 2} \right) \quad \text{.................................(3)}$$

and

$$r_t = eterm_1 + eterm_2 + eterm_3 \quad \text{.................(4)}$$

These terms ($eterm_1$, $eterm_2$, $eterm_3$) represents the three parameters affected in a charge efficiency factor.**[2]**

$$eterm_1 = a_1 \times \log(e_1 \times batcur) \quad \text{..............(5)}$$

$$\text{eterm}_2 = -a_2 \times \log\left[\frac{SOC}{(KEBatcap \times batcap - SOC)}\right] \quad \text{.........................(6)}$$

$$eterm_3 = a_3 \times (25 - Temp) - a_4 \quad \text{..............(7)}$$

a_1, a_2, a_3, a_4, e_1 and e_2 are constants where there value are explained in table (1) and
KEBatcap=Battery theoretical capacity / nameplate capacity
Batcap = capacity (A.H) × ksecper (Hr)
Ksecperhr = second/hour =3600
The Analog behavioral molding (ABM) is used to define these three terms as shown in Fig.(3).

Table (1)
The constants value of charge efficiency factor [3].

Parameters	***Value***
(a_1)	0.009
(a_2)	–0.028
(a_3)	2.677e–4
(a_4)	0.10566
(e_1)	–0.0055×KSecperHr/(KEBatcap ×batcap)
(e_2)	0.005
KEBatcap	0.84
Temp	50
KsecperHr	3600
batcap	288000

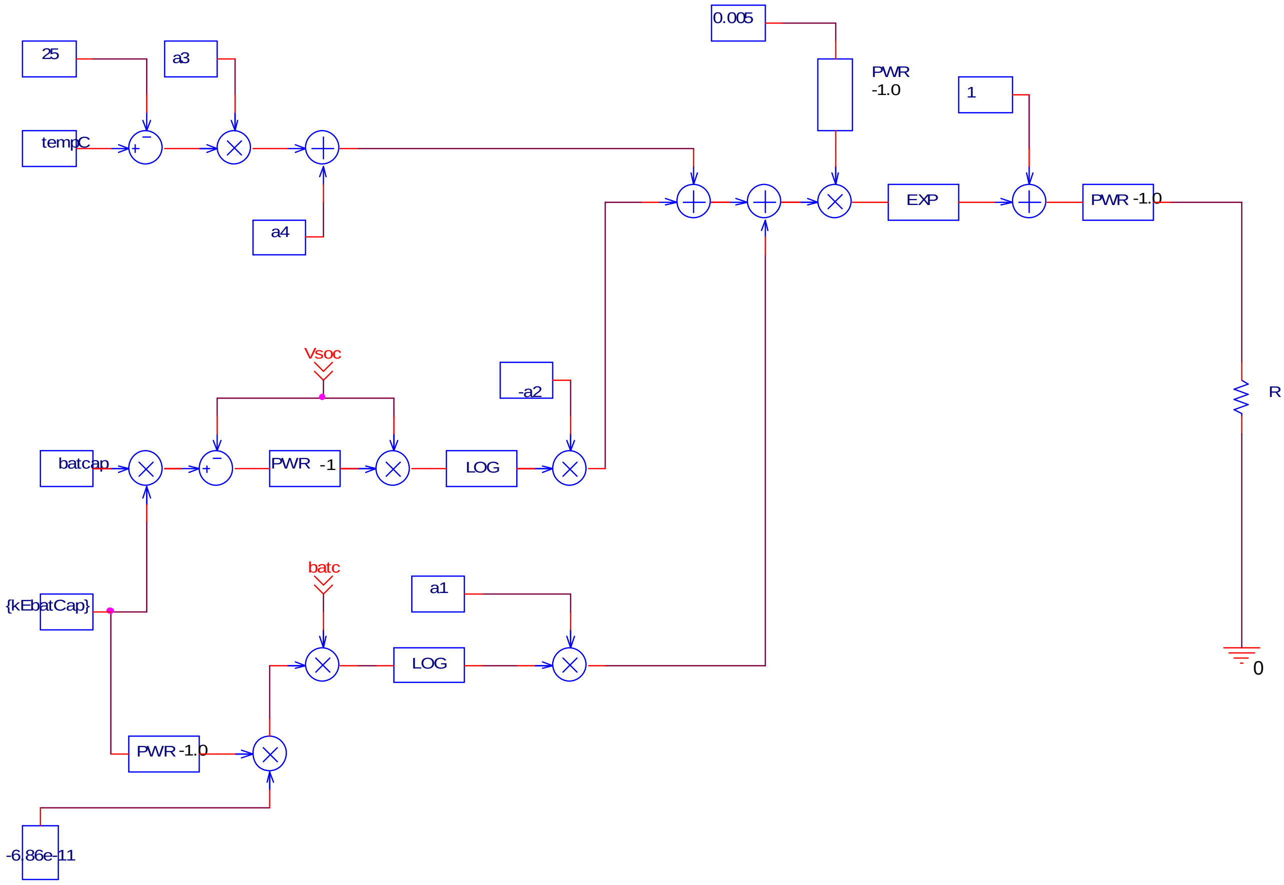


Fig.(3) The charge efficiency factor as represented in PSPICE.

Battery Voltage Components

The voltage component of the battery PSPICE model is shown in Fig.(4). The output of the charge efficiency factor is applied to the integrator OP1 (uA741) after multiplying it by the battery current (bat curt the output of OP2) in order to change the battery efficiency. The nominal battery resistance (Rbatt) is connected between the two terminals of (OP2). The output of the integrator is applied to the ABM part (gain of 5) for expand the range of SOC to 75. The Etable part (E1) is used to generate the battery voltage. This part use a transfer function described by a table. The table consists of the pairs of values, the first of which is an input, and the second of which is the corresponding output linear interpolation is performed between entries. For values of outside the table's range, the devices output is a constant with a value equal to the entry with the smallest (or largest) input. The characteristic can be used to impose an upper and lower limit on the output.

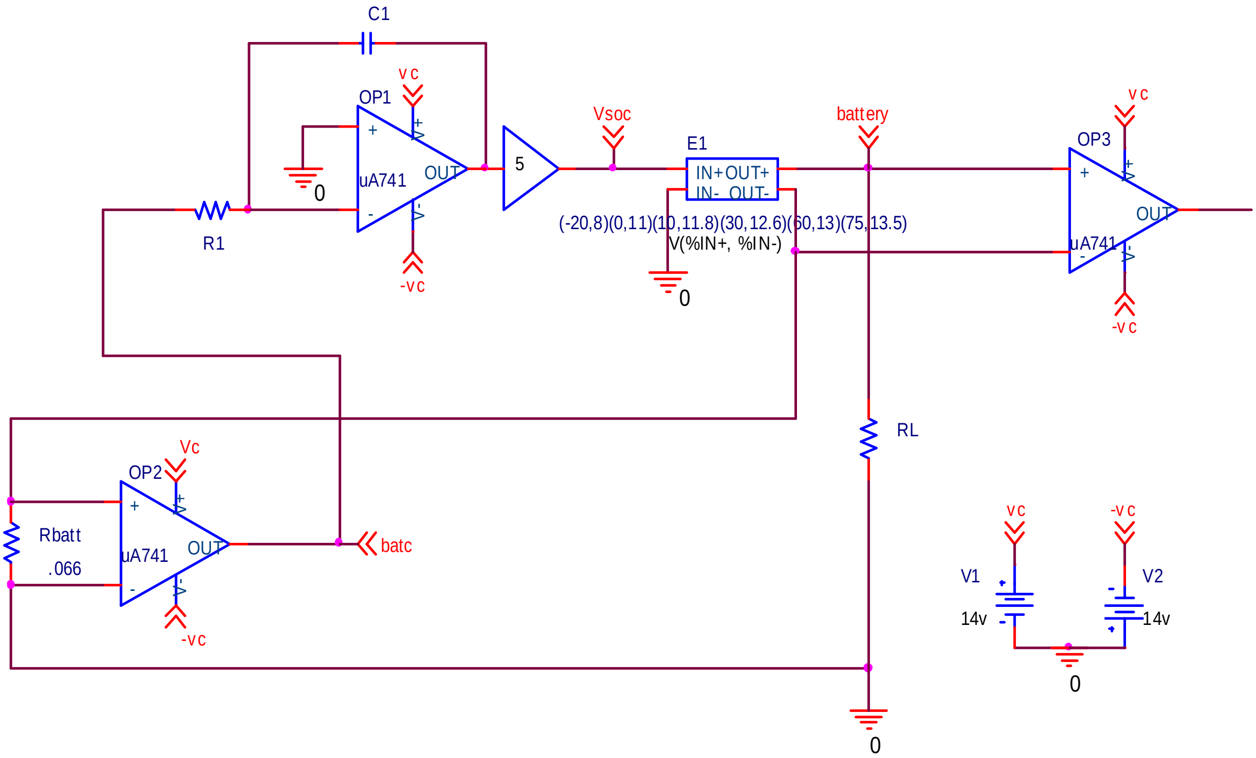


Fig.(4) The battery voltage component as represented in PSPICE.

Battery model Simulation

The model described in the previous paragraph has been implemented in the orcad-pspice. The complete model shown in Fig.(5) has been verified and used to find the optimal operation.

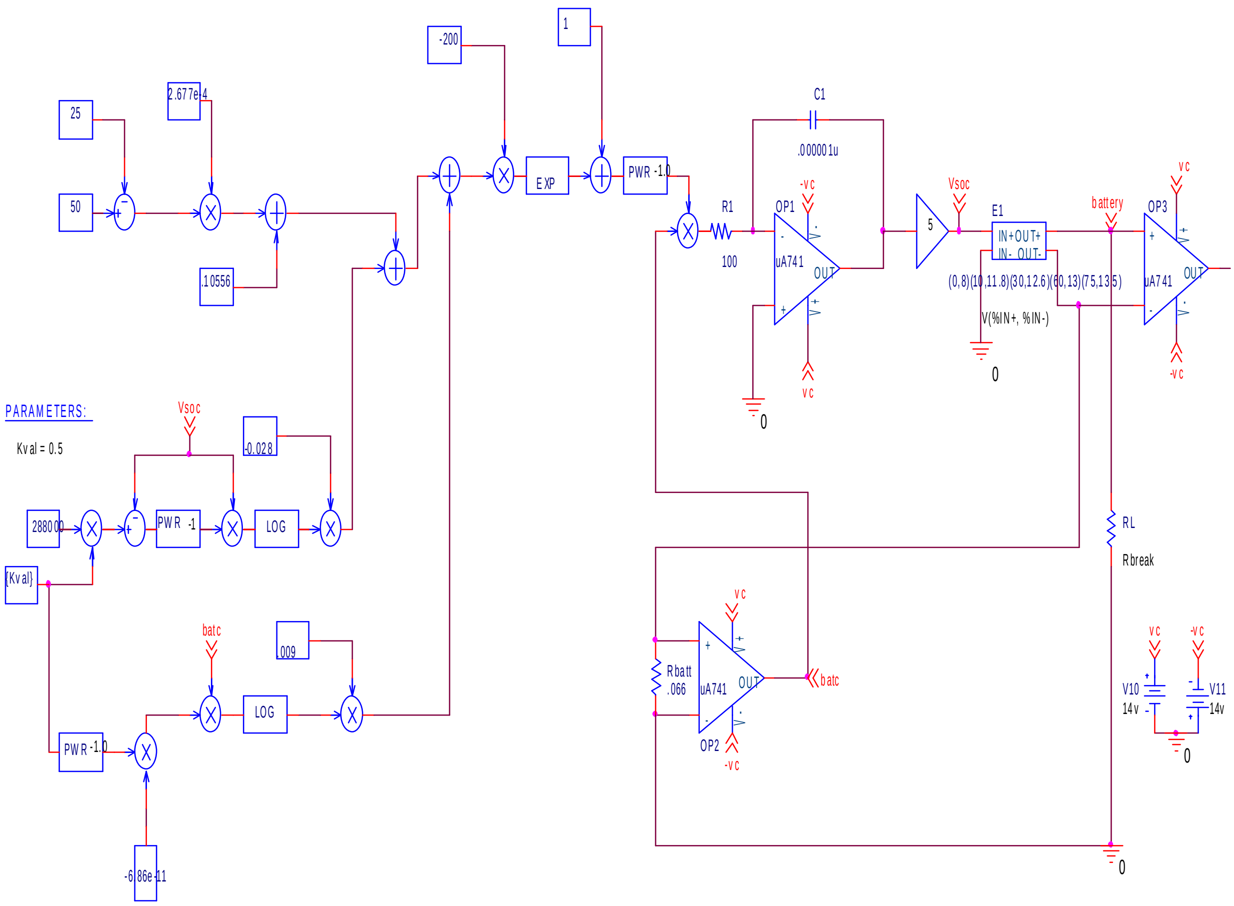


Fig.(5) The complete circuit of the battery as Represented in PSPICE.

Three parameters affect the results of this model R_L, Rbatt and KEbatcap. First the model will be tested by varying the load, therefore R_L defined as Rbreak, Rbatt=0.066Ω and KEbatcap=0.88.From the transient analysis Fig.(6) shows the battery voltage for three cases(0.1Ω, 0.3Ω, 0.5Ω). A good similarity between this curves but Vbattery decreases as R_L increased.

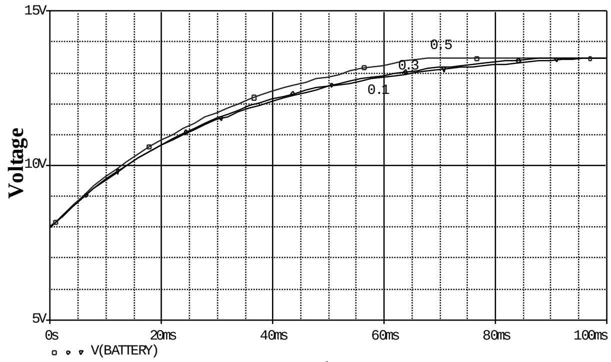


Fig.(6) Battery voltage as a function of time at different R_L (0.1Ω, 0.3 Ω, and 0.5 Ω).

Next the following Figs. (7) (8) describe the state of charge and charge efficiency for three cases of R_L respectively. Fig.(7) indicates that the SOC increases gradually with charge time but charge efficiency decreases gradually with time in Fig. (8). SOC and charge efficiency are decrease as R_L increase.

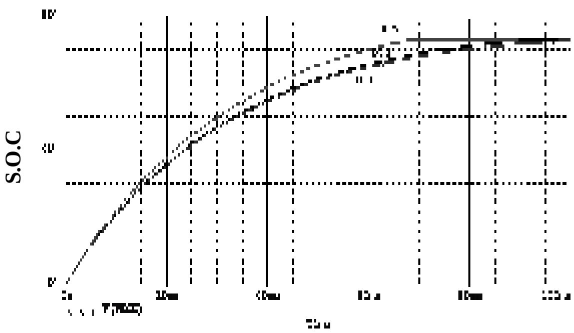


Fig.(7) State of charge as a function of time at different R_L (0.1Ω, 0.3Ω and 0.5 Ω).

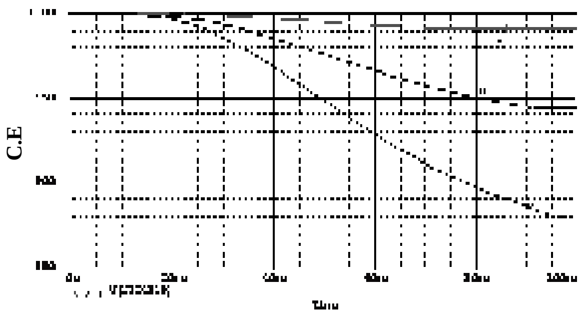


Fig.(8) Charge efficiency as a function of time at different R_L (0.1Ω, 0.3Ω and 0.5Ω) .

The battery voltage vs. the SOC is described in Fig.(9) for R_L=0.5Ω, it reveals that the battery voltage increased as the SOC increased. Fig.(10) shows a plot of charge efficiency vs. SOC for RL=0.5Ω and Rbat=0.066Ω.

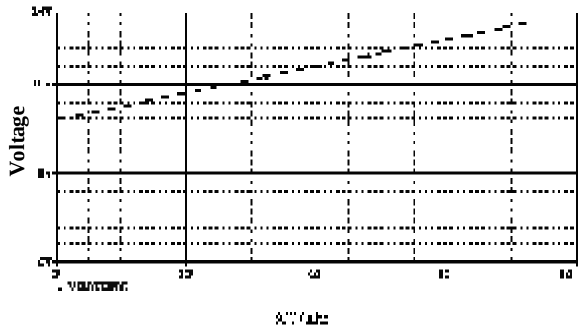


Fig.(9) Battery voltage as a function of state of charge at R_L=0.5Ω.

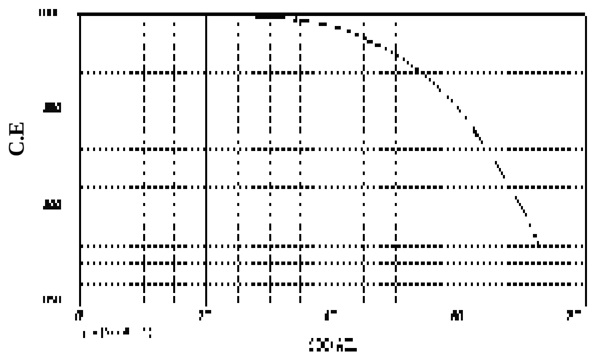


Fig.(10) Charge efficiency as a function of state of charge at R_L=0.5Ω.

Now, the model will be tested by varying KEbatcap so, this factor defined as Kval (varying parameter), Rbatt=0.066Ω and R_L=0.7Ω.The same figures which explained in the first test are repeated here in Figs. [(11), (12), (13), (14) and (15)]. These figures differs from the first test that the battery voltage, SOC and charge efficiency increases as the KEbatcap increased. Also in Fig. (13) the charge efficiency of smallest value of KEbatcap reaches zero faster than the biggest value.

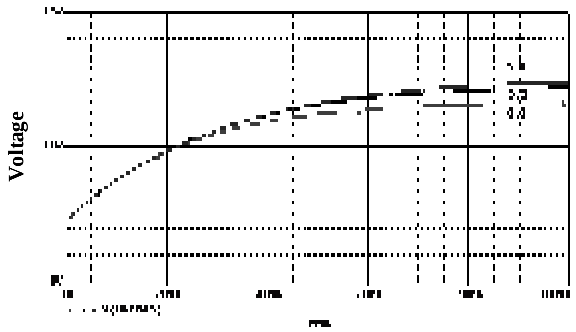


Fig.(11) Battery voltage as a function of time at different Kval (0.1, 0.2 and 0.3).

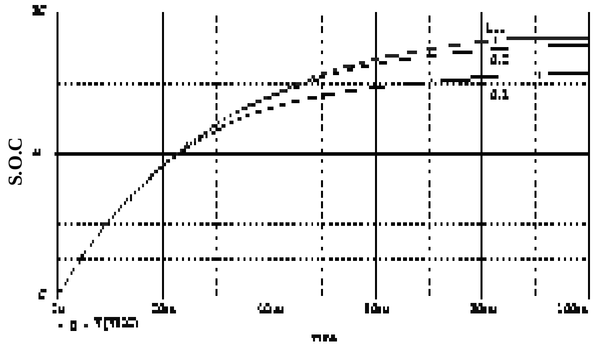


Fig.(12) State of charge as a function of time at different Kval (0.1, 0.2 and 0.3).

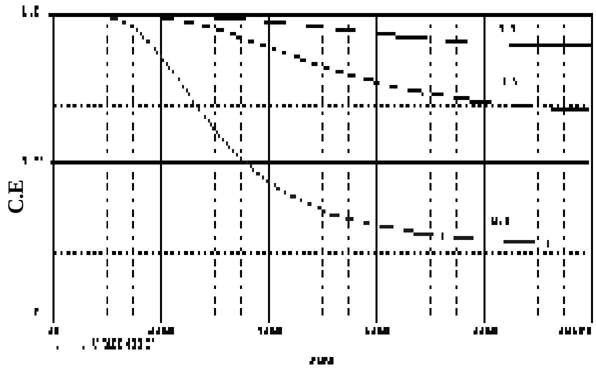


Fig.(13) Charge efficiency as a function of time at different Kval (0.1, 0.2 and 0.3).

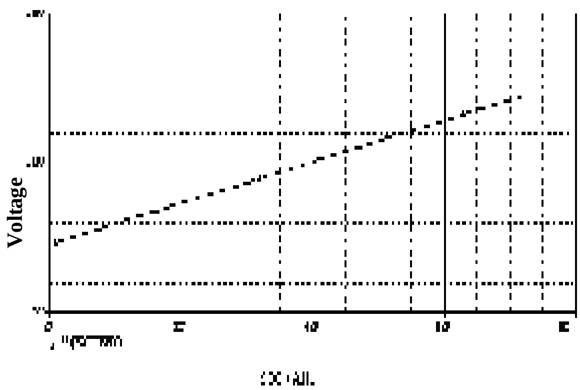


Fig.(14) Battery voltage as a function of state of charge at Kval=0.3.

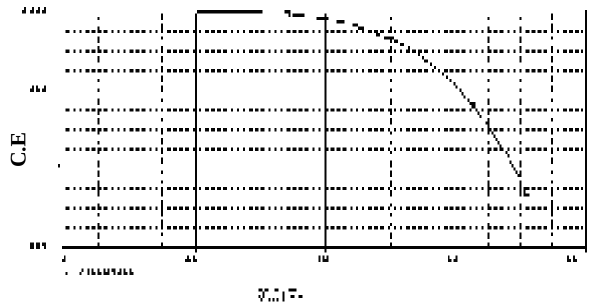


Fig.(15) Charge efficiency as a function of state of charge at Kval=0.3.

The last test is determined by defined Rbatt as Kval while the other factor is constant (RL=0.7Ω, KEbatcap=0.3). The battery voltage is affected by Rbatt value as shown in Fig.(16) but the SOC and charge efficiency gives a little affect as Rbatt increased as shown in Fig.(17), (18) respectively.

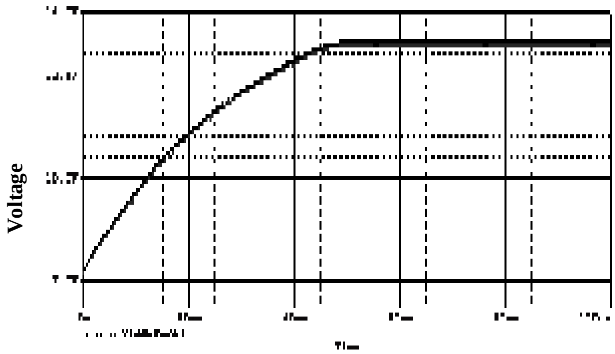


Fig.(16) Battery voltage as a function of time at different Rbatt (0.066Ω, 0.086 Ω and 0.106Ω).

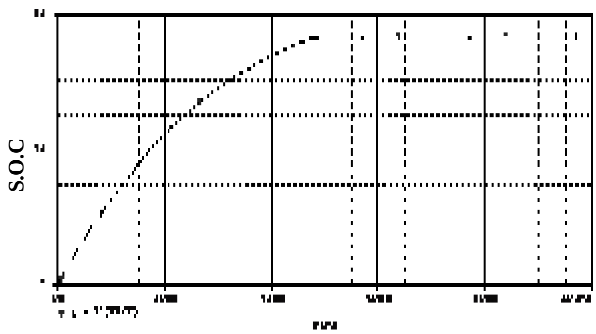


Fig.(17) State of charge as a function of time at different Rbatt (0.066Ω, 0.086Ω and 0.106Ω).

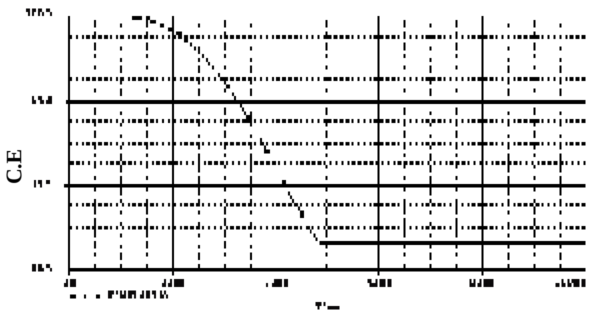


Fig.(18) Charge efficiency as a function of time at different Rbatt (0.066, Ω 0.086 and 0.106).

The battery parameters (battery voltage, SOC and charge efficiency) are affected by temperature and this effect is explained in Fig. (19), (20) and (21) respectively.

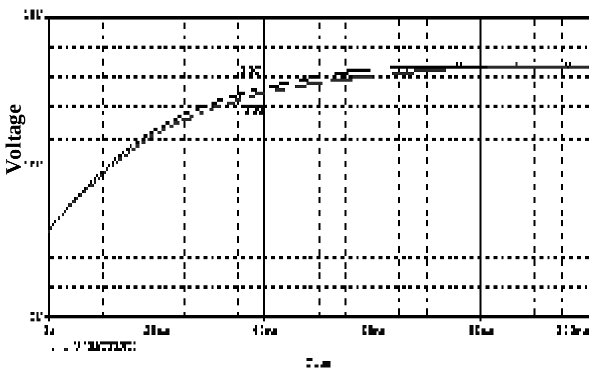


Fig.(19) Battery voltage as a function of time at different temperature.

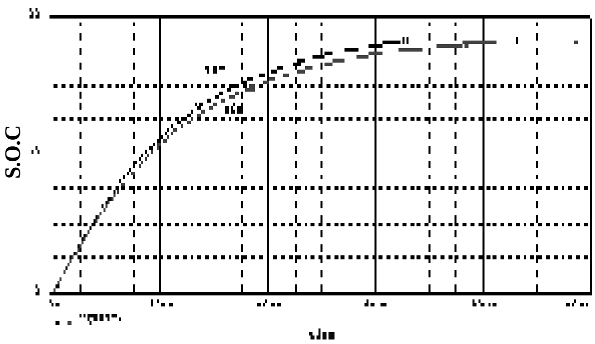


Fig.(20) State of charge as a function of time at different temperature.

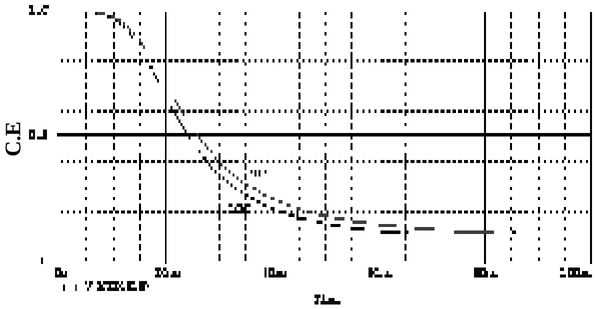


Fig.(21) Charge efficiency as a function of time at different temperature.

Converter Circuit Design

The bidirectional boost converter operates in continuous condition mode has been design for output voltage 12V, switching frequency 1 kHz, duty cycle .4 and power 12W. Fig. (3-22) shows the non isolated single-phase bidirectional boost as represented in PSPICE. This converter is consist of two MOSFT (IRF460), the connection of blocking diode after the MOSFT is necessary to prevent any leakage current passing through the MOSFT that might interfere with the operation of the converter, inductor (L_1), capacitors (Cbatt, Cbus) and resistance (R_2). As it was mentioned before, the battery pack's nominal voltage (Vdc) is 12V. The frequency of 1 kHz has been arbitrarily chosen in order to minimize current ripple, while maintaining low commutation loses and operating the MOSFT within its recommended range. Power flows from the auxiliary power unit to the DC bus when Q2 and M1are active, and Q1 and M2 are inactive, and the power flows from the DC bus when the pack Q1 and M2 are active and Q2 and M1are inactive.

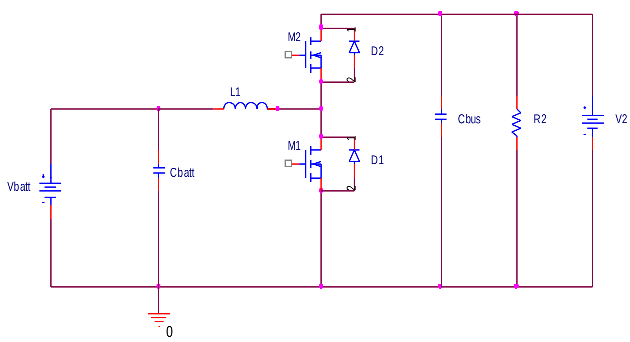


Fig.(22) Non-Isolated Single-Phase Bidirectional Buck Boost converter.

A ripple of 0.6A was established as the maximum desired value. Therefore, the inductance value L1 is calculated according to the equation below (at least 6mH).**[6]**

$$\Delta i_b = \frac{V_{dc}}{L_s f} D(1-D) \qquad \text{..................(8)}$$

The capacitance value is C_{bus} (20.8µf) and C_{batt} (10.4µf)

Pulse Width Modulation (PWM) and Gate Drive Circuit

This unit generates the signal with necessary duty ratio to drive the switching devices of the converter. The PWM generator is shown in Fig. (23). The error amplifier U3 (AD741) detects the error output result from the difference between the reference voltage (V1) and the actual voltage (battery); this error level is applied to the comparator U4 (AD741) which compare with the saw tooth signal that properties (Vpeak =15V, Tperiod = 2ms), the output of the PWM generator is connected to the buffer circuit U9 (AD741) which isolate the output PWM to transistor Q1. The transistor Q1 operates as not gate and figured as MOSFT Gate drive circuit. The transistor Q1 supplied pulse of sufficient voltages and drove current to the gate of the switching device M2 (IRF460) through a resistance R4.

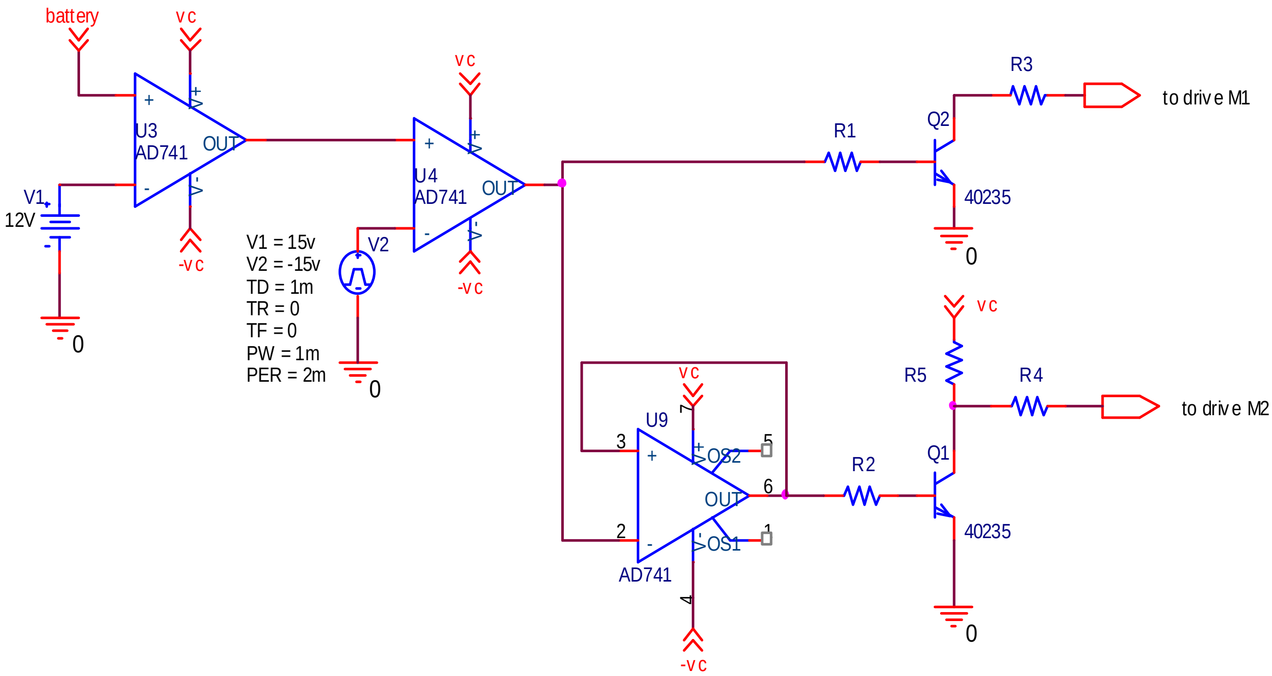


Fig.(23) The system of the PWM generator and gat drive circuit.

Bidirectional converter with Battery model results

After modeling and simulating the battery model in the previous section, now this model will be tested as an auxiliary source to the bidirectional converter. The proposed system is shown in Fig.(24). This system was simulated with Rbatt=0.066, RL=7Ω and KEbatcap=0.2.

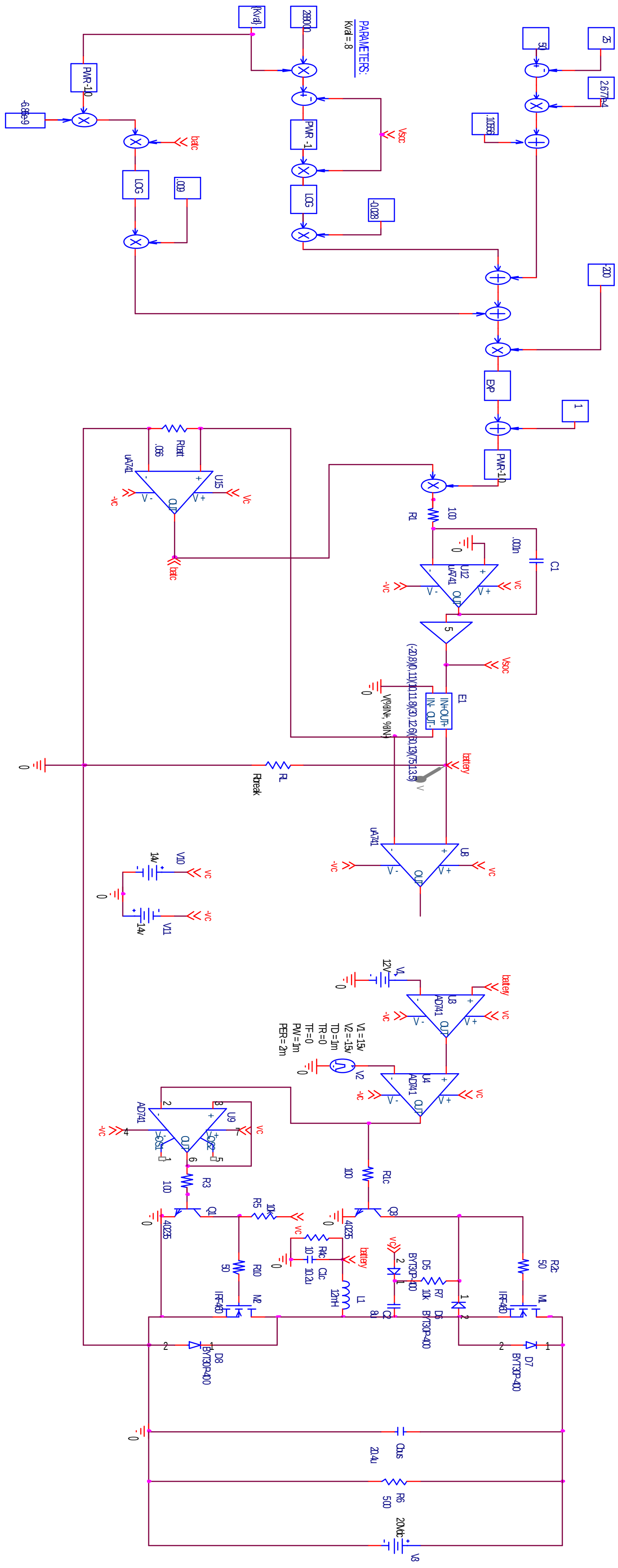
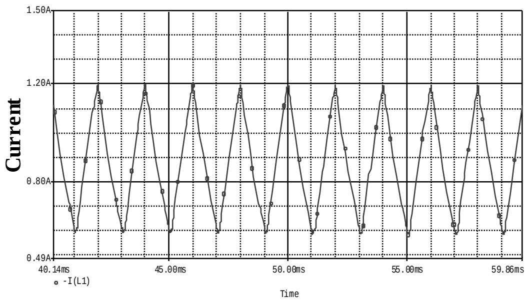
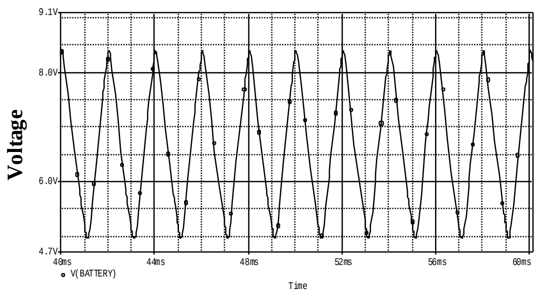


Fig.(24) Total circuit of the battery and converter as represented in PSPICE.

Amore detailed diagram of the charging process is shown in Fig.(25). It is seen that the battery current is reduced .6A, resulting in a reduction of the battery voltage from 8.5 to 5, then battery voltage rises towards 8.5 because of the battery SOC increase.



(a)



(b)

Fig.(25) Current and battery voltage as a function of time.

The variation in SOC and charge efficiency factor with time is shown in Fig.(26) and Fig.(27). Fig.(28) shows the relation between charge efficiency and state of charge. Fig.(29) shows the extracted battery voltage Vbatt (SOC).

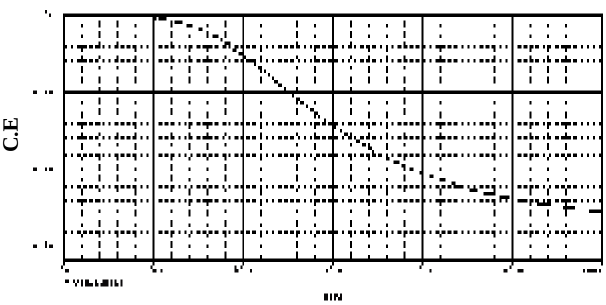


Fig.(26) Charge efficiency as a function of time.

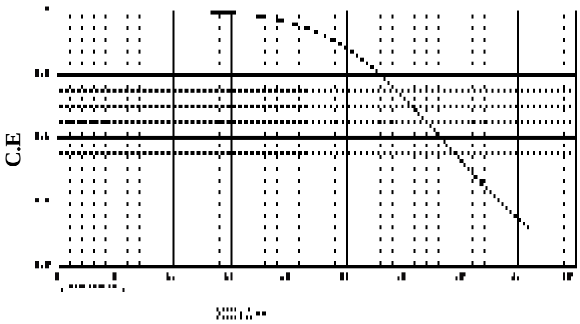


Fig. (27) Charge efficiency as a function of state of charge.

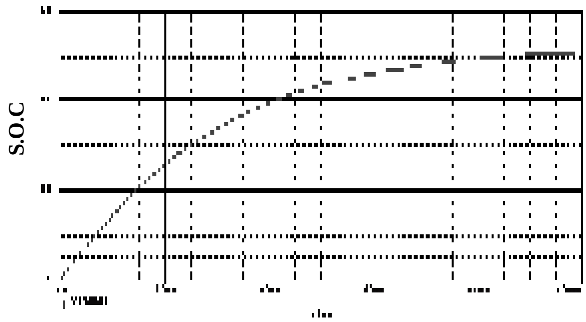


Fig.(28) State of charge as a function of time.

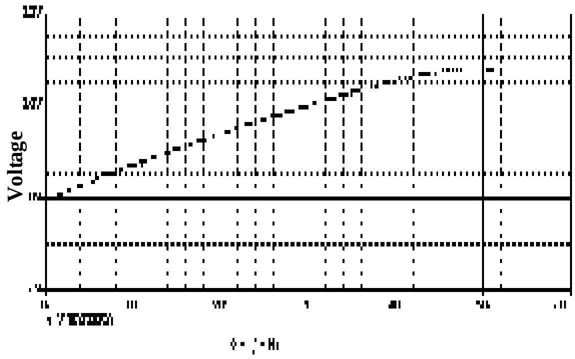


Fig.(29) Battery voltage as a function of state of charge.

Next, the following Figs. (30) and (31) depict the results of the simulation at different temperature for state of charge and charge efficiency respectively.

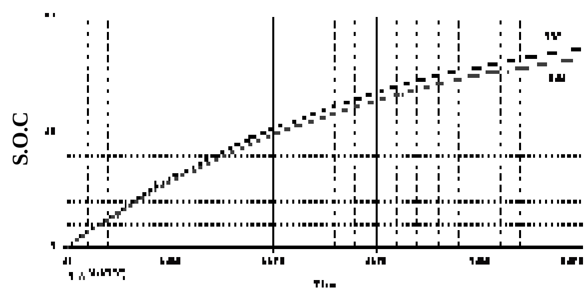


Fig.(30) State of charge as a function of time at different temperature.

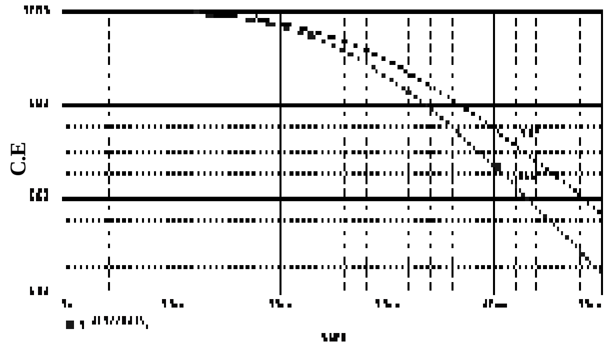


Fig.(31) Charge efficiency as a function of time at different temperature.

Conclusion

Some of the individual achievements and conclusions have been outlined in the following points:

1. An accurate, intuitive and comprehensive electrical model has been proposed to capture the entire dynamic characteristics of a battery, from nonlinear open circuit voltage, SOC and charge efficiency.
2. The model can be used for training personnel in the basic operation of solar energy system or other hybrid systems.
3. A battery modal was installed in a Buck-Boost Converter to prove the validity of the battery model.

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الخلاصة

هذا البحث يناقش تصميم وتحليل موديل للبطارية. التحليل تم باستخدام برنامج PSPICE لغرض الحصول على نتائج الموديل. موديل PSPICE لمركم حمضي رصاصي (lead acid) يتكون من فعالية الشحنة ومكونات فولتية البطارية. ايضا تم اعطاء تفاصيل طريقة حساب فعالية الشحنة ومن ثم اختبار الموديل كمصدر في مدخل مغير(buck-boost) ثنائي الاتجاه لاثبات صحته.