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Research Article

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Investigation on Electric Air-Conditioning System Energy Consumption of an Electric Vehicle Powered by Li-ion Battery

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Abstract

One of the main problems to be considered in an electric vehicle is the way to maintain a good climate conditions in order to ensure a thermal comfort in the passenger compartment to provide an optimum performance of the batteries. In this paper, the influence of the electric air-conditioning system on the power consumption of a Lithium-ion battery was studied. The model of the air conditioning system was developed based on the thermal loads variations caused by the external temperature. In order to optimize the autonomous efficiency of the batteries, a thermal management system must be installed. The model was coded on the Matlab/Simulink platform and simulated.

Keywords: Electric vehicle; Electric air-conditioning system; Thermal comfort; Energy storage; Li-ion battery

Introduction

According to the US Department of Transportation's estimate, there are about 800 million cars in the world [1,2]. These cars are powered by gasoline and diesel fuel. The issues related to this trend become evident because transportation relies heavily on oil. Not only are the oil resources on earth limited, but also the emissions from burning oil products have led to climate change contributing significantly to the increase in the atmospheric carbon dioxide concentrations, thus intensify the prospect of global warming., poor urban air quality, and political conflict [2-5].

The urge for energy security of supply, air quality improvement in urban areas and CO_2 emissions reduction are pressing decision makers/manufacturers to act on the road transportation sector, introducing another technologies and more efficient vehicles on the market and diversifying the energy sources [6].

The transition to these technologies results in the electrification of some parts of the vehicle combustion. The best example is the traction chain where the integration of electric motors with high mass torque associated with power converters and powerful computers can lead to vehicles with good performance and lower energy consumption [7].

Automotive air-conditioning system for thermal comfort in passenger cabins is now a thing of necessity rather than luxury, and cooling is especially needed when travelling in summer or throughout the year in countries of hot and humid climate [8].

The development of the electrical AC system provides several advantages to the EV performance. The electric AC system is driven by an electric compressor which includes a compressor and an electric motor. The electric compressor is developed and installed in the EV or the hybrid vehicle for the past decade [9,10]. Because of the electric compressor, the electric AC system can operate at arbitrarily rotating speed according to the controller which can provide adequate and sufficient refrigeration performance. Therefore, the energy consumption of the AC system can be controlled precisely which is helpful to improve the vehicle driving mileage [11].

These previous works, however, focused on parametric studies and they did not take the power consumption of cooling systems into consideration, which affects vehicle's electric economy.

In this study, the simulation of an air-conditioning system and the analyzing of its effect on the power consumption and the autonomy of a Li-ion battery is undertaken by using Simulink/Matlab.

Electric Vehicle Air-Conditioning Architecture

The main purpose of an automotive air-conditioning system is to adjust the condition of air to achieve a certain comfortable environment to the passengers during vehicle driving in varied atmospheric conditions. It has become an essential part of the vehicles of all categories worldwide.

Among the important issues related to the electric vehicles development, the air conditioning compressor is a key element. Air conditioning compressors are already used in internal combustion vehicles but are mainly composed of mechanical parts. Electrification of this body was found necessary to improve its efficiency and compactness in the case of electric vehicles.

The below diagram illustrates a typical electric vehicle air conditioning system layout (Figure 1).

The compressor is integrated in the air conditioning loop composed by condenser, the evaporator and the expansion valve.

Lithium-Ion Battery

Among various types of batteries, lead–acid battery, nickel-based batteries, such as nickel/iron, nickel/cadmium, and nickel–metal hydride (Ni–MH) batteries, and lithium-based batteries such as lithium–polymer (Li–P) and lithium–ion (Li–I) batteries [12-14], the lithium-ion (Li-ion) batteries have always been regarded with great interest and become the most promising battery candidate for EV applications due to its lightweight that has a high electrochemical potential permeating

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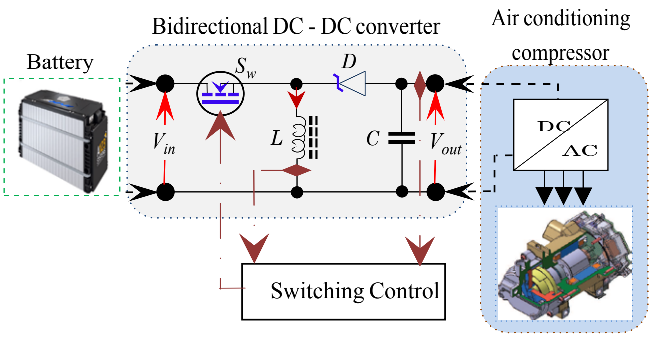

Figure 1: Electric air conditioning system.

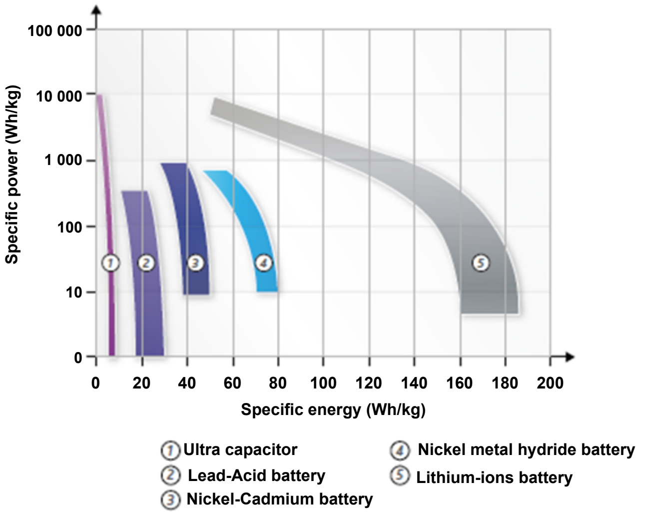

Figure 2: Comparison of power density and energy density [17].

it to transform easily into ion (Li^+), high specific energy, high specific power and high energy density [15,16]. In addition, lithium batteries have no memory effect and do not have poisonous metals, such as lead, mercury or cadmium [16]. From the thermal management viewpoint, Li-ion battery is advantageous because Li-ion battery have lower internal resistance compared with Lead-acid battery [14]. As can be seen in Ragone diagram (Figure 2), Li-ion battery has higher energy and power density which results in weight advantage over the other types of batteries for the same battery capacity.

A typical Li-ion battery operates by shuttling lithium ions between the anode (negative electrode) and the cathode (positive electrode) through an electronically insulating, ion-conductive electrolyte (Figure 3). Generally, Li-ion batteries often used employ the graphite (LiC_6) as an anode, the layered $LiCoO_2$ (LCO) as a cathode and the organic liquid of LiPF6/ethylene carbonate (EC)/dimethylene carbonate (DMC) as an electrolyte [18]. During the electrochemical process of charging, lithium ions leave the LCO host structure and migrate through the electrolyte to the graphite, while the associated electrons driven by an external power flow from the cathode to anode. On discharging, Li ions and electrons move reversely. The total reaction can be expressed according to the following equation [19]:

$$Li_xCoO_2 + C_6 \leftrightarrow CoO_2 + Li_xC_6 \quad (1)$$

And the reactions of oxido-reduction on the positive and the negative electrodes are respectively given by:

$$Li_xCoO_2 \leftrightarrow Li_{1-x}CoO_2 + xLi^+ + xe^- \quad (2)$$

$$C_6 + xLi^+ + xe^- \leftrightarrow Li_xC_6 \quad (3)$$

Active materials, in order to be considered suitable candidates for Li-ion batteries, should fulfill the requirements of reversible capacity, good ionic and electrical conductivity, long cycle life, high rate of lithium diffusion into active material and conclusively low cost and eco-compatibility [20].

Great achievements have been made recently in cathode materials. State-of-the-art mainly include layered lithiated transition metal oxides (e.g., $LiCoO_2$ and LiNi1-x yCoxMnyO$_2$ ($0 \leq x, y \geq 1$)), Mn-based spinels (e.g., $LiMn_2O_4$), vanadium pentoxides, and polyanion-type materials (e.g., phosphates, borates, fluorosulphates, and silicates) [18]. While graphite is definitely the most used anode [21,22] owing to its excellent features, such as flat and low working potential vs. lithium, low cost and good cycle life. However, graphite allows the intercalation of only one Li-ion with six carbon atoms, with a resulting stoichiometry of LiC_6 and thus an equivalent reversible capacity of 372 mAh g^{-1}. In addition, the diffusion rate of lithium into carbon materials is between 10-12 and 10-6 cm^2 s-1 (for graphite it is between 10-9 and 10-7 cm^2 s^{-1}), which results in batteries with low power density [23-24]. Hence, there is an urgency to replace graphite anodes to materials with higher capacity, energy and power density by introduction of [20]:

- Intercalation/de-intercalation materials, such as carbon based materials, porous carbon (800-1100 mAh g^{-1}), carbon nanotubes (1100 mAh g^{-1}), carbon nanofibers (450 mAh g^{-1}) , grapheme (960 mAh g^{-1}), Titanium oxides (TiO_2 (330 mAh g^{-1}), $Li_4Ti_5O_{12}$ (175 mAh g^{-1})), etc.
- Alloy/de-alloy materials such as Silicon (4212 mAh g^{-1}), Germanium (1624 mAh g^{-1}), Antimony (660 mAh g^{-1}), SiO (1600 mAh g^{-1}), Tin (993 mAh g^{-1}), Tin oxide (790 mAh g^{-1}) etc;
- Conversion materials like transition metal oxides (500-1200 mAh g^{-1}) (Mn_xO_y, NiO, Fe_xO_y, CuO, Cu_2O, MoO_2 etc.), metal sulphides, metal phosphides and metal nitrides (500-1800 mAh g^{-1}).

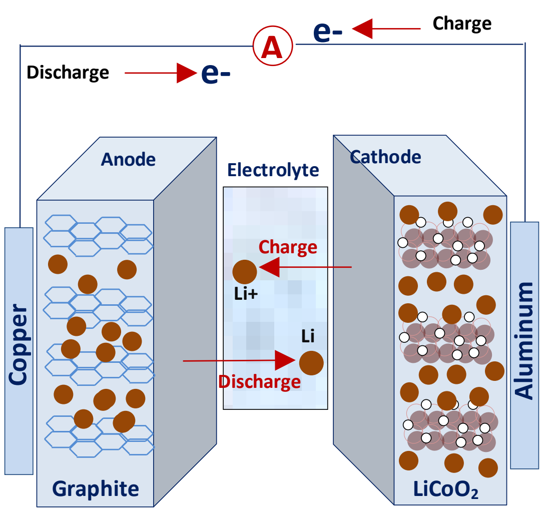

Figure 3: Schematic illustration of a Li-ion battery employing graphite as anode and layered $LiCoO_2$ as cathode.

Equivalent circuit

Figure 4 presents the equivalent circuit of Lithium-ion battery.

For the charged model

$$E_{duscharge} = E_0 - K.\frac{Q}{it+0.1.Q}i^* - K.\frac{Q}{Q-it} + A..\exp(-B.it) \quad (4)$$

For the discharge model

$$E_{charge} = E_0 - K.\frac{Q}{Q-it}i^* - K.\frac{Q}{Q-it} + A..\exp(-B.it) \quad (5)$$

Where, E_{batt} is the nonlinear voltage (V), E0 is the constant voltage (V), K is the polarization constant (Ah^{-1}) or Polarization resistance (Ohms), *i** is the low frequency current dynamics (A), i is the battery current (A), *it* is the extracted capacity (Ah), Q the maximum battery capacity (Ah), A is the exponential voltage (V), and B is the exponential capacity (Ah).

State of charge and depth of discharge

A key parameter in the electric vehicle is the state of Charge (SOC) of the battery. The SOC is a measure of the residual capacity of a battery. To define it mathematically, consider a completely discharged battery. The battery is charged with a charging current of $I_{batt}(t)$; thus from time t_0 to t, a battery will hold an electric charge of :

$$\int_{t_0}^{t} I_{batt}(t).dt \quad (6)$$

The total charge that the battery can hold is given by:

$$Q_0 = \int_{t_0}^{t_1} I_{batt}(t).dt \quad (7)$$

Where t1 is the cutoff time when the battery no longer takes any further charge. Then, the SOC can be expressed as:

$$SOC = \frac{\int_{t_0}^{t} I_{batt}(t).dt}{Q_0} x100\% \quad (8)$$

Typically, the battery SOC is maintained between 20 and 95% [2].

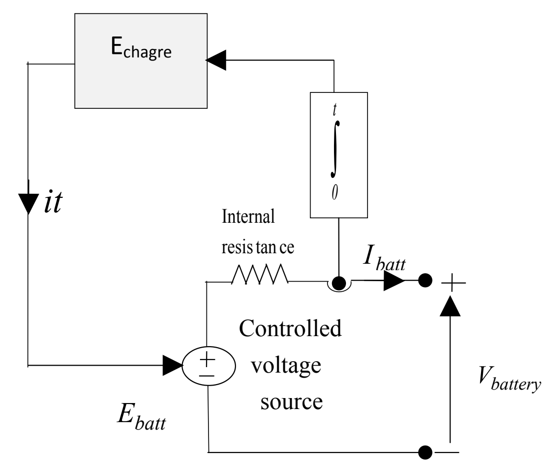

Figure 4: The equivalent circuit of the battery.

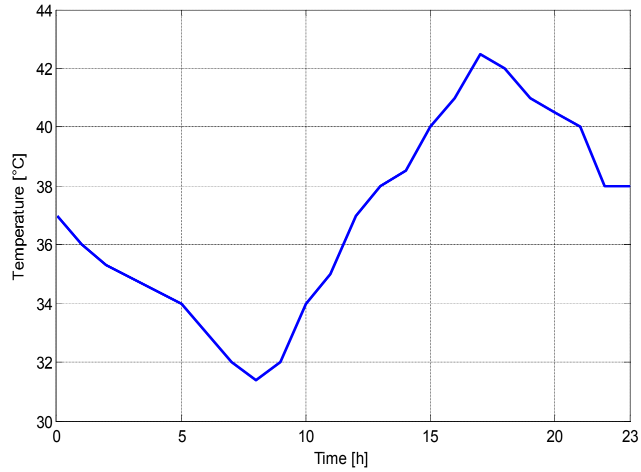

Figure 5: Temperature change during the day.

The depth of discharge (DOD) is the percentage of battery capacity to which the battery is discharged. The DOD is given by

$$DOD = \frac{Q_0 - \int_{t_0}^{t} I_{batt}(t).dt}{Q_0} x100\% \quad (9)$$

Thermal Loads

In order to provide a sufficient cooling/heating ability to the passengers, the specifications of the electric compressor should be chosen carefully, therefore, the thermal load to the vehicle cabin was analyzed firstly [11]. Thermal loads depend on many variables, such as sun radiation, interior surface radiation, temperature difference between cabins and ambient, heat from moving parts, combustion heat, human thermal load and fresh air entering the cabin [11,25,26]. Many works are performed for calculation of thermal loads in automobile [27,28]. The model of these heat sources were modeled according to the heat transfer pattern and coded in the simulation program [26]. The derived equations are usually function of many parameters and are complex to calculate. For the control purpose it is simpler to estimate the important loads by either sensors or empirical equations.

In this article, the thermal loads are estimated by the following model [13]:

$$P_{AC} = 0.25.T_{ext} - 6 \quad (10)$$

Results and Interpretations

We present in this section the results of our simulations giving the importance to the power consumption, the state of charge and the depth of discharge. Ours simulations are performed on a summer day (15th August 2013). The temperature values that have been used in this study are taken from [29] for Bechar city located on the southwest of Algeria. Indeed, the temperature profile of the day considered is illustrated in the following Figure 5

Power consumption

Figure 6 presents the variation of the power delivered by the Li-ion battery throughout the day considered. In the first time, the AC system demands a considerable power of 3.5 KW from the battery i.e. a voltage and a current of 217V and 17A respectively (Figures 7 and

8). This demand is corresponding to the start-up of the system. After, the power consumption decreased until reaching 946 W. We observe also that the AC power follows the trend of the daily temperature. The power required by the air conditioning system is a maximum 1.6 KW at 15 hours, this power demand is corresponding to the maximal temperature of the day that is 42.5°C at Bechar city in 15 August. Under these conditions corresponding to the daily highest temperature (15:00-18:00 hours), the Li-ion battery delivers much more of power in order to creating a comfort feeling of the passengers (temperature of 24°C in the cabin).

Battery parameters

Figure 9 explains the different state of discharge curve; the first section represents the exponential voltage drop when the battery is charged. Depending on the battery type, this area is more or less wide. The second section represents the charge that can be extracted from the battery until the voltage drops below the battery nominal voltage. Finally, the third section represents the total discharge of the battery, when the voltage drops rapidly.

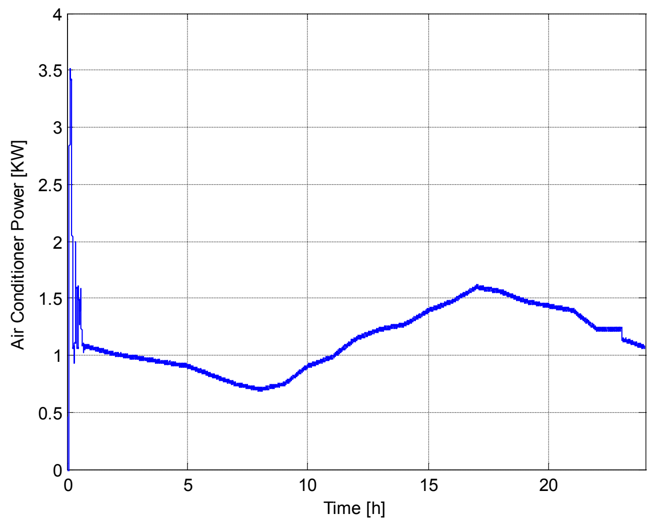

Figure 6: Evolution of Li-Ion battery power.

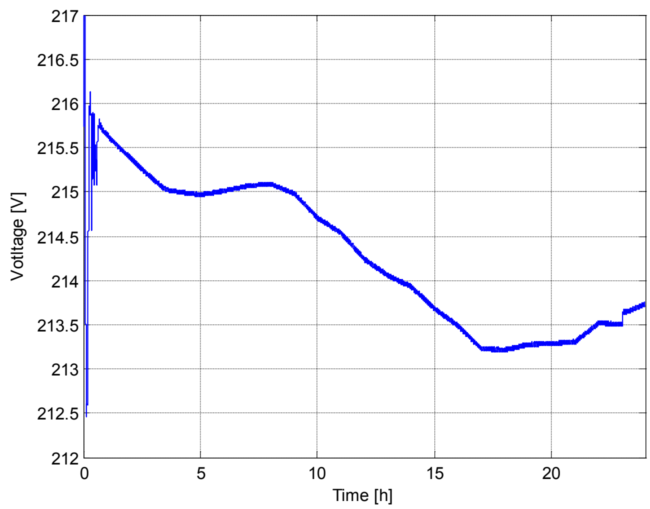

Figure 7: Li-ion battery voltage.

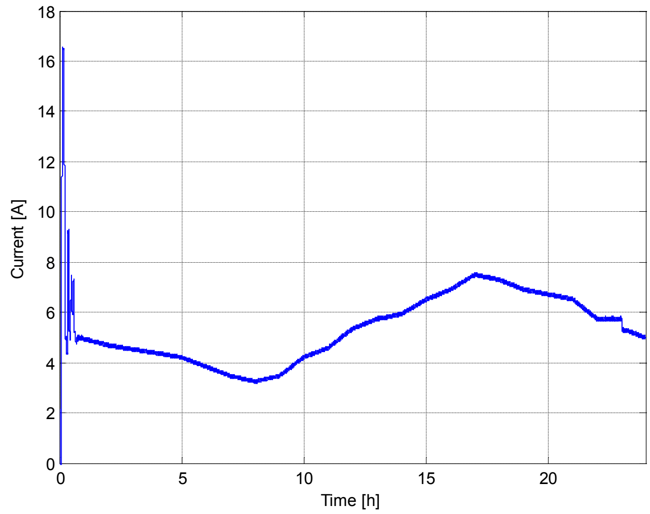

Figure 8: Li-ion battery current.

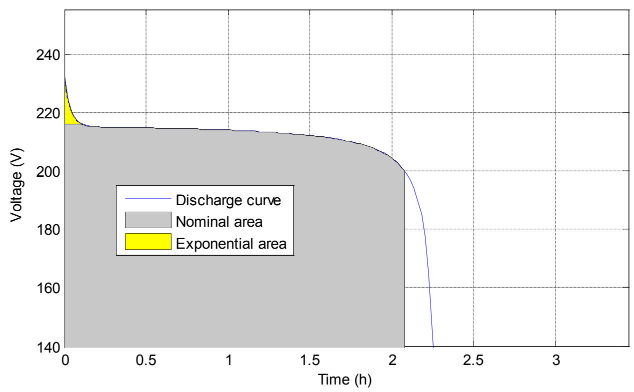

Figure 9: Li-ion battery typical discharge curve, E_0=216.6753, R=0.30769, K=0.17369, A=16.9917, B=9.3941.

Figures 10 and 11 shows variation of State of Charge (SOC) and Depth of Discharge (DOD) respectively. We can note that the SOC decreases rapidly when the air-conditioning system is on, i.e. throughout the day SOC ranging between 80.1% and 79.55 % from beginning at the end. We can explain this observation as follow: The vehicle is traveling in different climatic conditions of temperature all the day. This climate change presents an increase or decrease in the outside temperature from where the air-conditioning system requires a necessary power in order to ensure thermal comfort in the vehicle compartment and therefore the SOC decreases. We observe also that the SOC decrease of 1.55%. The depth of discharge represents the inverse of the state of charge.

Conclusions

In this paper, the study of an air-conditioning system and its impact on the power consumption of an electric vehicle powered by Li-ion battery were undertaken by way of simulation using Matlab environment. The power necessary to operate the air-conditioning system is related to the peak cooling load generally related to the outside temperature.

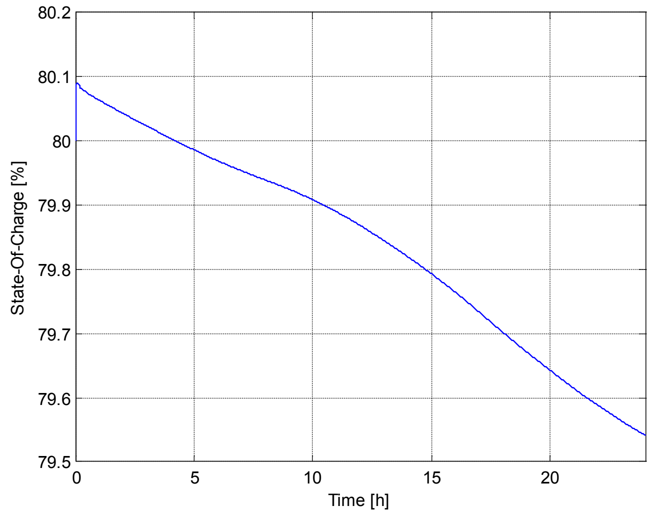

Figure 10: Evolution of the SOC.

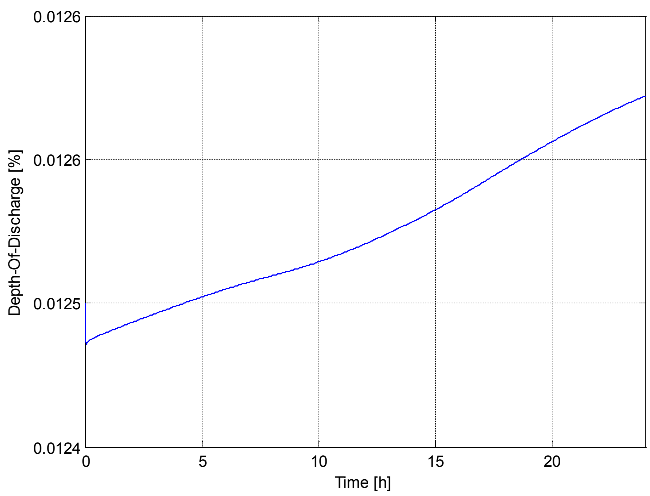

Figure 11: Evolution of the DOD.

The results of the study showed that the Li-ion battery has a good performance and gives good dynamic characteristics.

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