Journal of Physics: Conference Series **1448** (2020) 012014 doi:10.1088/1742-6596/1448/1/012014

Increasing driving range for electric vehicles at sub-zero temperatures by optimizing a hybrid storage configuration using supercapacitors

J A Dominguez-Jimenez[1], and J Campillo[1]

[1] Facultad de Ingeniería, Universidad Tecnológica de Bolívar, Cartagena de Indias, Colombia

E-mail: jdominguez@utb.edu.co

Abstract. One of the main challenges electric vehicles manufacturers face is the perceived limited operational range of cars, commonly referred to as "range anxiety". Furthermore, effective range in these vehicles is affected by multiple factors, including driving behavior, battery size, operating temperature, among others. Particularly, Lithium-based batteries the most used in the industry today, experience significant electrochemical changes when operating at sub-zero temperatures, which reduces their overall energy capacity. Furthermore, cycling operation under these conditions, could also severely reduce the batteries' expected lifetime. This work uses a model-based approach to simulate a reduced current rate from lithium-based batteries, operating at sub-zero temperatures, during high-acceleration modes by including super-capacitors. By adding super-capacitors, the power supplied to the motors from the battery pack during short-time acceleration periods, can be reduced. This approach suggests that the effective range in Electric Vehicles increases by using an optimal hybrid energy storage system. Simulations were carried out to estimate the impact of subzero temperatures on the range of the vehicle. Results showed that the overall range increases with the addition of the the storage system. Furthermore, reduced current rates at sub-zero temperatures would also increase the battery pack's expected lifetime. These results offer great insights for designing more efficient energy storage systems for electric vehicles.

1. Introduction

Over the last decade, several factors have increased the adoption of alternative fuel powered cars, principally, a large interest in reducing transportation dependency on the oil industry. Nowadays, sustainable road transportation is possible throughout the electrification of propulsion systems [1], as it depicts a potential way to fulfill the traced goals by the United Nations in the Paris agreement. Battery-electric vehicles (BEV) provide several advantages over their Internal combustion engines (ICE) powered vehicles counterpart: for instance, they can be charged using renewable energy, which help significantly reduce their greenhouse gases (GHG) footprint, furthermore, regenerative braking, and high-efficient motor and power conversion technologies increase their operation efficiency, and finally, consumer reports have declared feeling an overall better experience [2]. As a consequence, multiple strategies, including short and long term policies have been implemented to increase the market uptake of BEVs [3].

However, BEVs have to face multiple limitations to reach larger market uptake. First, high price acquisition compared with the ICE counterpart. Secondly, batteries represents a significant

Journal of Physics: Conference Series **1448** (2020) 012014 doi:10.1088/1742-6596/1448/1/012014

share of the overall cost, and hence, users need to consider a significant cost to replaced when needed [4]. Furthermore, their limited operational range led users feel the feat to run out of power the battery pack before reach the desired destination, an usual phenomena on electric vehicle (EV) users, named as range anxiety. This phenomena increases during extreme cold conditions, because as electric cars rely on lithium batteries, their performance at these conditions is reduced significantly [5, 6].

Several studies have been conducted to evaluate the impact of sub-zero temperature on the EVś overall performance. Keilś, *et al*, proposed two configurations for a hybrid energy storage system (HESS). They enabled driving at minus 20 degrees. Both maximized the driving range under sub-zero temperatures, which was not possible without hybridization [7]. Zhang, *et al.* proposed improving lithium battery's performance bu using the self-heating characteristics at low temperatures. They added a nickel foil inside the battery, which enable rapid transition from -20 °C to 0 °C in 12.5 seconds, warming-up the battery pack 56% faster. Energy savings accounted for 24% compared with previous approaches [8].

Although the market uptake of BEVs is increasing, most of the public information available comes from demonstration projects, whereas highly detailed operational profiles data-sets for EVs are often proprietary, fixed to specific operation conditions [9]. Hence, it is necessary to build models, able to analyze different driving strategies under several conditions. To achieve this, the authors used an open-source, object-oriented, mathematical modeling library presented in [10], for simulating the energy consumption of BEVs, using the modeling language Modelica.

In this paper, the impact of hybridizing energy storage systems for improving BEVs performance under subzero temperatures is presented. The main contribution of this work is to allows users to rapidly select different configurations of HESS for maximizing the driving range at subzero temperatures by selecting and dragging components, taking advantage of the object-oriented nature. The aim of this paper is to support the design process of energy storage systems for future electric vehicles. Accordingly, section 2, the proposed library is defined using a hierarchically-structured object-oriented modeling approach and the mathematical definition of the equations for each component of the model is described;s ection 3 highlights the main findings obtained after analyzing the resulting data from several simulation runs, based on pre-defined scenarios where the vehicle runs with and without the proposed HESS; section 4 summarizes the results and discusses the implications of adopting the proposed HESS on real-life situations.

2. Methodology

2.1. Hybrid energy storage system

Simulations were conducted using an accurate Li-ion electrical battery model proposed in [11]. This model is able to calculate the battery's operating variables (*e.g.* current, voltage, SoC, etc). The equations are SoC-dependent altogether.

Lithium battery offer poor performance at low temperatures. Several studies have been conducted to show that a pre-heating stage on the battery pack could increase the performance regarding current rate changes, as Zhang demonstrated [8], however, the preheating process would still require using energy from the battery pack that could be otherwise used on the drivetrain for the vehicle's propulsion. Our proposal is to include supercapacitors (SC) as an additional energy storage unit for handling high current demands in short-time intervals. Furthermore, one of the main advantages of their usage is that their R_s is considerably lower than lithium batteries counterpart.

A blocking diode was included to prevent the SC charging from the battery pack. As proposed by Martinez, *et al.* [12], four SC units were used, able to deliver peak currents over 1000 A for short burst of time, accounting to 0.573 KWh.

2.2. Object-oriented modeling

Differently from conventional languages counterpart, this work relies on an object-oriented model-based programming where each physical component and connection is represented as a single object, which can interact with other objects to build more complex models resulting in a hierarchical structured mathematical modeling. This approach is helpful when handling large complex systems. Object-oriented modeling allows the user building new simulation models and strategies, by setting the corresponding parameters.

We used the modeling language Modelica to evaluate the battery performance under sub-zero temperatures of different vehicles. Figure 1 illustrates a general description of the Modelica model developed. The main advantage using this language, is that no predefined causality is required, therefore, a considerably reduction in time is obtained during the modeling process since by using equations and mathematical functions, the models become acausal. In short, any system can be defined from ordinary differential equations (ODE) without taking into account to which domain each one belongs to [13].

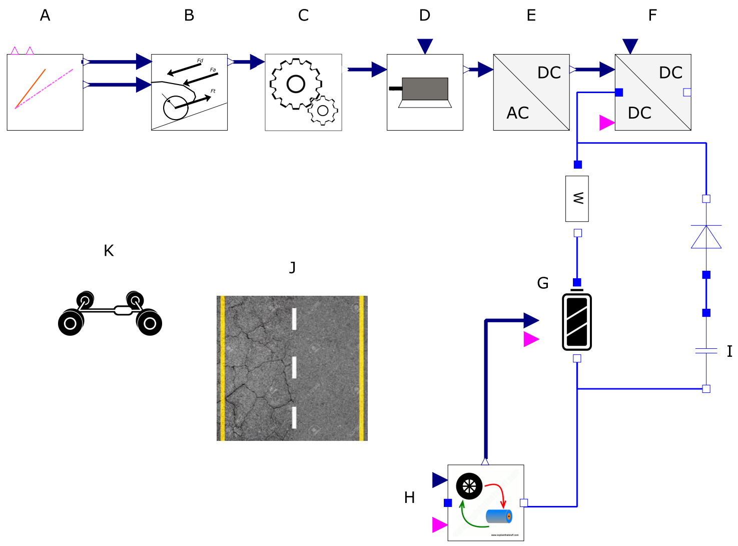

Figure 1. Modelica implementation for evaluating the performance of the battery at sub-zero temperatures.

A more detailed description of the library, is presented in [10]. However, the representation of each block is presented as follows:

- A: Driving profile
- B: Kinematics
- C: Powertrain
- D: Motor
- E: On board charger
- F: DC-DC converter
- G: Battery pack
- H: Regenerative braking
- I: Supercapacitor
- I: Road conditions

Journal of Physics: Conference Series **1448** (2020) 012014 doi:10.1088/1742-6596/1448/1/012014

2.3. Thermal modeling

The thermal approach proposed by Mahamud, *et al.* in [14] was included. They proposed a thermal modeling for computing the heat generation of a battery cell. The heat production is provided by Equation (1), the sum of reversible (entropy) and irreversible (Joule) process. The first term is the Joule heating based on the power dissipated by the internal series resistance, contained in Equation (2). The second term is represented by Equation (3), which models the internal series resistance as a function of the cell temperature. Finally, Equation (4) models losses regarding entropy, where $\frac{dV_{oc}}{dt}$ is the entropy coefficient and was fixed at -0.3 mV/K as proposed by Mahamud's study [14]. To compute the amount of increased heat, the resulting heat generated was divided by the total weight of the battery pack and the specific heat, which was set at 0.95 from literature values.

$$S_{r,i} = Q_{irr} + Q_{rev} \tag{1}$$

$$Q_{irr} = I^2 Rs \tag{2}$$

$$R_s = -0.0001T^3 + 0.0134T^2 - 0.5345T + 12.407 \tag{3}$$

$$Q_{rev} = -IT\frac{dV_{oc}}{dt} \tag{4}$$

2.4. Sensitivity analysis

The battery's internal resistance varies with several factors, including state of the charge, ambient temperature, changes in chemical reaction among others. In this work, we used the models proposed by Mahamud, *et al.* in order to obtain a function that models R_s depending on the cell temperature and the SOC. We used a sigmoid function to merge both equations smoothly in order to obtain the function contained in Equation (5), listed below:

$$\begin{aligned} f(T, SoC) = & \frac{-0.0001T^3 + 0.0134T^2 - 0.5345T + 12.407}{1 + e^{1000T}} \\ & + \frac{0.1562e^{-24.37SoC} + 0.07446}{1 + e^{-1000SoC}} \end{aligned} \tag{5}$$

Figure 2 illustrates the effect of sub-zero temperatures and the SoC on lithium batteries' internal resistance. As the operating region of this study considers SoC over 20%, variations in R_s are not significant, whereas significant changes are remarkable regarding the effect of subzero temperatures.

To validate the statements mentioned above, we conducted a global sensitivity analysis to quantify the variance explained in the R_s by changes in temperatures and the SoC. Both were modeled as Gaussian distributions, sub-zero values (μ = -15, σ = 10) and SoC (μ = 0.7, σ = 0.2). From first-order SOBOL index, results showed 0.98 and 0.02 sensitivity values for sub-zero temperatures and Soc respectively. Hence, for modeling the R_s we just considered fluctuations in temperature.

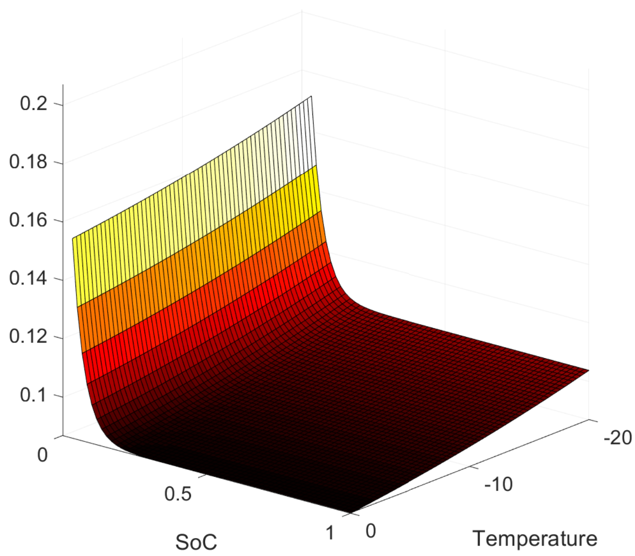

Figure 2. Internal resistance behavior regarding subzero temperatures and the SoC.

3. Results

This section presents the results of this work regarding BEV's performance with and without the proposed HES and the operational range. Simulations were carried out to run out of power and bring the battery pack down to a deep of discharge of 80%. Figure 3 illustrates the current rate change and the temperature in Celsius-degrees for an electric car with and without the proposed HESS. Ta and Ia represent the temperature and current without the HESS, respectively, whereas Tb and Ib represents those same variables including the HESS, and Ic is the SC's current.

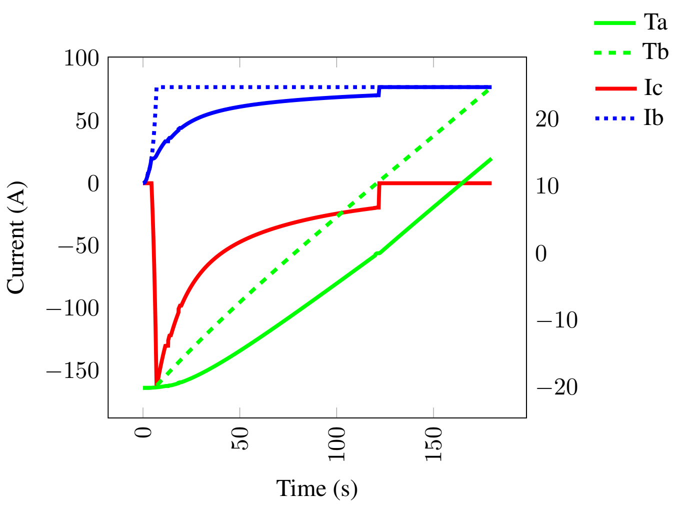

Figure 3. Results for a test run with and without the HESS.

On the one hand, a considerable reduction in the current rate change was founded with the HES. As the retentive capacity of batteries is strongly shaped by subzero temperatures, the self-heating effect of the battery pack from reversible and irreversible process was used to warm-up it until it reaches zero degrees. The BEV took 75 seconds to reach zero degrees, however, with the HESS it fulfilled this objective in 120 seconds. By this means, the car earned approximately 33% of the retentive capacity. On the other hand, Figure 4 illustrates that the range increased from 1894 to 2522 meters, almost by 25% by using the proposed system in comparison with the conventional counterpart.

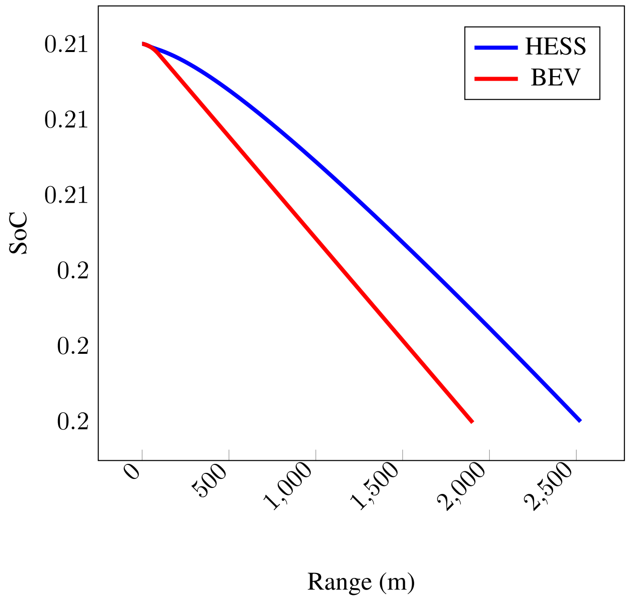

Figure 4. Range versus SoC with and without the HESS.

4. Conclusion

This work has presented the capabilities of an object-oriented open-source model developed using the modelling language Modelica, for assessing the impact of subzero temperatures on the operational range and the battery performance by optimizing a hybrid configuration using supercapacitors. Results suggested that remarkable increases the operational range can be achieved on BEVs by including supercapacitors and taking advantage of batteries' self-heating characteristics. These results offer great insights for improving energy storage systems to overcome environmental issues on EVs.

References

[1] Campillo J, Domínguez-Jimenez J and Cabrera J Sustainable boat transportation throughout electrification of propulsion systems: Challenges and opportunities *2nd Latin American Conference on Intelligent Transportation Systems (ITS LATAM)* (Bogotá: IEEE)
[2] Haustein S and Jensen A F 2018 *International Journal of Sustainable Transportation* **12(7)** 484
[3] Vassileva I and Campillo J 2017 *Energy* **120** 632
[4] Weldon P, Morrissey P and O'Mahony M 2018 *Sustainable Cities and Society* **39** 578
[5] Ji Y, Zhang Y and Wang C Y 2013 *Journal of The Electrochemical Society* **160(4)** A636
[6] Jaguemont J, Boulon L and Dubé Y 2016 *Applied Energy* **164** 99
[7] Keil P, Englberger M and Jossen A 2015 *IEEE Transactions on Vehicular Technology* **65(3)** 998
[8] Zhang G, Ge S, Xu T, Yang X G, Tian H and Wang C Y 2016 *Electrochimica Acta* **218** 149
[9] Akhavan-Hejazi H, Mohsenian-Rad H and Nejat A 2014 Developing a test data set for electric vehicle applications in smart grid research *IEEE 80th Vehicular Technology Conference (VTC2014-Fall)* (Vancouver: IEEE)
[10] Dominguez-Jimenez J A and Campillo J 2018 Object-oriented mathematical modeling for estimating electric vehicle's range using modelica *Colombian Conference on Computing* (Cartagena: Springer, Cham) p 444
[11] Chen M and Rincon-Mora G A 2006 *IEEE Transactions on Energy Conversion* **21(2)** 504
[12] Martinez W, Cortes C and Munoz L 2012 Sizing of ultracapacitors and batteries for a high performance electric vehicle *IEEE International Electric Vehicle Conference* (Greenville: IEEE)
[13] Fritzson P 2010 *Principles of object-oriented modeling and simulation with Modelica 2.1* (United States of America: John Wiley & Sons)
[14] Mahamud R and Park C 2011 *Journal of Power Sources* **196(13)** 5685