# Simple mathematical formula models lithium-ion battery aging

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Hybrid electric vehicles combine the efficiency of electric vehicles with the power and longevity of gasoline-powered vehicles because they have both a gasoline-fueled conventional internal combustion engine and an electric motor powered by batteries. Credit: Volvo

Hybrid electric vehicles, cell phones, digital cameras, and the Mars Curiosity rover are just a few of the many devices that use rechargeable lithium-ion batteries. Now a team of Penn State researchers has a simple mathematical formula to predict what factors most influence lithium-ion battery aging.

Lithium-ion batteries function by moving lithium ions from the negative electrode to the positive electrode and in the opposite direction when the battery charges. How often and exactly how that battery is used determines the length of a battery's life. Complex models that predict battery aging exist and are used for battery design. However, faster, simpler models are needed to understand the most important factors that influence aging so that battery management systems in hybrid electric vehicles, for example, can better control lithium-ion batteries.

"We started out by making models specifically for Volvo's batteries that were tuned to their specific chemistry and showed that the models matched experimentally," said Christopher Rahn, professor of mechanical engineering, Penn State. "We then focused on simplifying the aging models. Now, we have the ultimate simplified aging model down to a formula."

According to Rahn, a battery ages, or degrades, whether it is sitting on a shelf or used. The main cause of lithium-ion battery aging is the continuous formation of the solid electrolyte interphase (SEI) layer in the battery. The SEI layer must form for the battery to work because it controls the amount of chemical reactions that occur in the battery. As the battery is continually used, however, small-scale side reactions build up at the SEI layer, which decreases battery capacity—how much of a charge the battery can hold. Models allow researchers to understand how different factors affect this degradation process so that longer-lasting, more cost-efficient batteries can be made.

Hybrid electric vehicles combine the efficiency of electric vehicles with the power and longevity of gasoline-powered vehicles because they have both a gasoline-fueled conventional internal combustion engine and an electric motor powered by batteries. The electric motor uses regenerative brakes, which take the energy that was moving the car forward and convert it to mechanical energy, putting the electric motor into reverse and slowing down the car. The electric motor acts as a generator and takes the electricity that is generated to store in batteries for future use. This is in contrast to conventional braking systems in which braking energy is wasted when friction converts the energy into heat.

According to the researchers, this new simple aging formula takes into account only the factors shown to most influence lithium-ion battery aging by affecting growth of the SEI layer, which include state of charge, how often the battery charges/discharges completely, operating temperature, and current.

"Car companies can use this formula to quantify which factors are contributing the most in aging and focus more on them and less on all of the other factors that don't play as much of a role," added Tanvir Tanim, graduate student in mechanical engineering, Penn State.

As part of the study, Tanim and Rahn compared the accuracy of their formula to that of more complex models using commercially available batteries. They found that their simple formula works just as well.

"Whenever you simplify a model, there are some things lost," said Rahn. "We have complicated models because they are very accurate. As you simplify, you have to justify every assumption that you make. I wasn't sure we could simplify the model down to a formula. It's pretty amazing to explicitly see how things depend on one another."

Rahn and Tanim have already seen the benefits of having a simple formula to model battery aging by using it to show that increasing the temperature of lithium-ion batteries in hybrid electric vehicles extends the life of the battery, which is contrary to what most researchers think.

This effect was something that Volvo had previously seen with their batteries, and using this aging formula, Rahn and Tanim could explain why.

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