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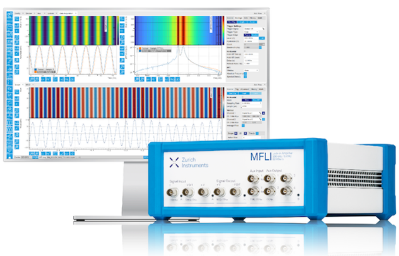

Overview of Machine Learning Applications to Battery Thermal Management Systems in Electric Vehicles

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Abstract. Electric vehicle (EV) is increasingly becoming an alternative vehicle of choice to replace an internal combustion engine-powered car. EV concept is clearly linked to sustainable development. Generally, there are four types of EVs: hybrid, plug-in hybrid, battery, and fuel cell EVs. The form of energy source and storage plays a key role for all EVs. Mostly, a lithium-ion battery (high-voltage battery) is used as energy storage due to its high energy density and long-life cycle. But, high rates of charging and discharging bring about high temperatures of the lithium-ion battery, reducing its useful lifetime. A battery thermal management system (BTMS) is crucial in improving EV performance. Here, in this work, we presented an overview of BTMS employed in the EV development, as well as applications of machine learning techniques to predict and optimize BTMS performance based on fast-charging protocols. Additionally, BTMS based on tropical environmental conditions like in Thailand was also discussed.

INTRODUCTION

Sustainable development is a modern concept of organizing human needs to be met without undermining the integrity and stability of the natural system. It covers all aspects of environmental, social, and economic. Transportation is also considered to be linked with sustainable development, as currently, it mainly consumes energy from fossil fuels and becomes one of the largest air pollution sources. To protect our environment, reducing the use of fossil fuels in transportation may possibly play a key role. This leads to increased attention in transportation driven by electricity generated from alternative and renewable energy sources as clean energy. In other words, the high demand for fossil fuels together with the aggravation of environmental problems resulting from the increasing use of internal combustion engines (ICEs) induces a growing interest in the development of electric vehicles (EVs) [1].

EV is fully or partially propelled by electric motors using energy from rechargeable batteries. It is increasingly becoming an alternative vehicle of choice to replace an ICE-powered car. Compared to ICEs, EVs use less energy consumption and may not emit CO_2 for their whole working life [2]. In general, there are 4 types of EVs: hybrid, plug-in hybrid, battery, and fuel cell EVs [3, 4]. Each of them is different in structure, as listed in Table 1. A hybrid EV consists of an electric motor consuming electricity from batteries and an ICE getting energy from petroleum-based fuels. They simultaneously rotate the transmission that drives the wheels. Similarly, a plug-in hybrid EV is a combination of electric motor and ICE, but its batteries can be also recharged from other outlet electricity, such as charging stations. Both battery and fuel cell EVs are purely driven by electricity. Battery EV runs entirely by an electric drivetrain powered by a large battery pack, which is plug-in charging from an electrical grid. It uses one or more electric motor(s) to drive the wheels. Fuel cell EV is considered to be a zero-emission vehicle. It employs fuel cell technology that is an energy conversion from chemicals to electricity. High-voltage batteries are mostly used in EVs, as they provide high energy density and long-life cycles. Therefore, a battery system is one of the most necessary parts that determine the performance of EVs [5].

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TABLE 1. Components of EVs in each type.

Components	Hybrid	Plug-in Hybrid	Battery	Fuel Cell
Battery	Yes	Yes	Yes	Yes
DC/DC converter	Yes	Yes	Yes	Yes
Electric traction motor	Yes	Yes	Yes	Yes
Power electronic controller	Yes	Yes	Yes	Yes
Thermal system (cooling)	Yes	Yes	Yes	Yes
Traction battery pack	Yes	Yes	Yes	No
Battery pack	No	No	No	Yes
Transmission	Yes	Yes	No	No
Transmission (electric)	No	No	Yes	Yes
Electric generator	Yes	Yes	No	No
Onboard charger	No	Yes	Yes	No
Fuel cell stack	No	No	No	Yes
Exhaust system	Yes	Yes	No	No
Charge port	No	No	Yes	No
Fuel filler	No	No	No	Yes
ICE (spark-ignited)	Yes	Yes	No	No
Fuel filler	Yes	Yes	No	No
Fuel tank (gasoline)	Yes	Yes	No	No
Fuel tank (hydrogen)	No	No	No	Yes
Charge port	No	Yes	No	No

Figure 1 shows the main components of EVs; (i) A battery or energy storage system is an energy supply when driving, heating, cooling, and running all of accessories. It is also used to control electrical current flow both in and out of the battery, (ii) A thermal system is a temperature controller for the battery system. It is applied to prevent the battery from overheating when recharging or discharging, (iii) An electric motor or powertrain transforms electrical energy to mechanical power driving the vehicle. (iv) An onboard battery charger or charging system is used to avoid damage in batteries or electrical circuits when connecting electric current into a battery storage system, as well as to convert alternating to direct currents, (v) An electronic controller is to operate between battery and motor to control the speed and acceleration of EVs. Lithium-ion battery is usually used for energy storage in EVs, as its technical and economic features [6]. However, one of the challenges for commercialization of EVs is an appropriate energy storage system that can support high mileage, fast charging, and high-performance driving [7–9]. Battery thermal management system (BTMS) is a technique used to optimize battery's temperature which will improve the performance of an EV. BTMS is designed to help increasing the lifetime of lithium-ion cells by regulating the level and distribution of batteries' temperature. It is especially necessary when batteries are used at high rates of recharging and discharging, as well as when EV is operated in very high or low ambient temperatures [10]. Even through several studies on BTMS have been undertaken, an overview of applying machine learning (ML) techniques on predicting and optimizing BTMS performance remains scarce.

Therefore, in this work, typical BTMS was summarized and comprehensively compared to advanced BTMS combined with application of ML on fast-charging protocols and designing heat dissipation. Furthermore, BTMS based on tropical environmental conditions like in Thailand was also discussed.

BATTERIES

Battery as energy storage plays a key role in powering and driving EVs. Currently, its capacity reaches very close to the theoretical values in terms of high storage with an extended lifespan for life cycles of batteries [11]. In the 1880s, the use of batteries for EVs occurred approximately 20 years after the discovery of the lead-acid battery. However, EVs declined in popularity resulting from rising up of high-efficiency ICEs coupled with lower oil prices as well as longer driving distances. Since the 1970s, the use of EVs has grown as the battery has been developed for many more types:

1. Lead battery: a lead-acid battery is the most common type of battery used in typical automotive vehicles. It is rather cheap and its manufacturing is simple. Lead-acid battery possesses low energy density, poor cold-temperature performance, and short life cycles [12]. Even if advanced high-power lead-acid batteries have been developed, they are only used in commercially available EVs as secondary batteries.
2. Nickel battery: a nickel-cadmium (Ni-Cd) and nickel-metal hydride (Ni-MH) battery appears to be popular nowadays. Its advantage is no requirement for maintenance. Yet, this battery type is costly rather than a

lead-acid battery, and it comes with the memory effect. This makes nickel battery not widely used for EVs [13].

3. Lithium battery: a lithium-ion battery is the most popular for being used in EVs. It has many advantages over others. For example, lithium-ion battery does not suffer from the memory effect while has a really high energy density and quite long life cycles although it needs a time of recharging [3, 14].

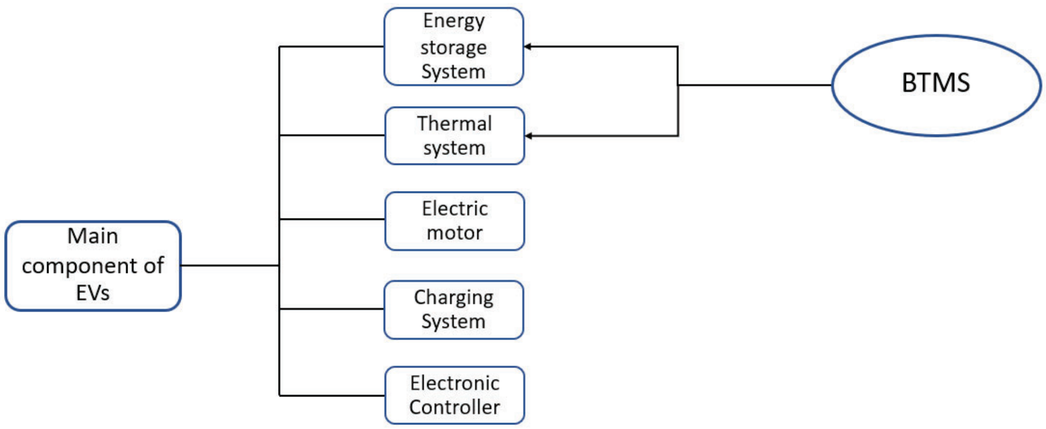


FIGURE 1. Main components of EVs and importance of BTMS [15].

BATTERY THERMAL MANAGEMENT SYSTEM

BTMS is specially designed for controlling battery's temperatures. It involves in the reliability, safety, life-cycle, and performance of the battery [16]. BTMS is expected to be able to remove heat from the battery, optimize the battery's temperature, and ventilate hazardous gases from the battery [17]. There are six types of BTMS, as shown in Fig 2. How each type works is presented in Fig 3.

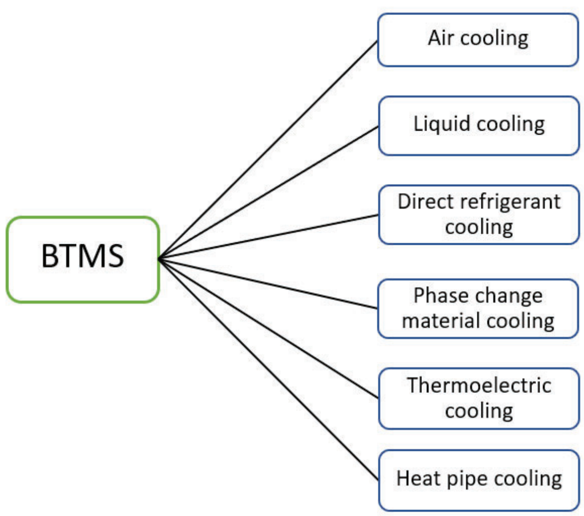
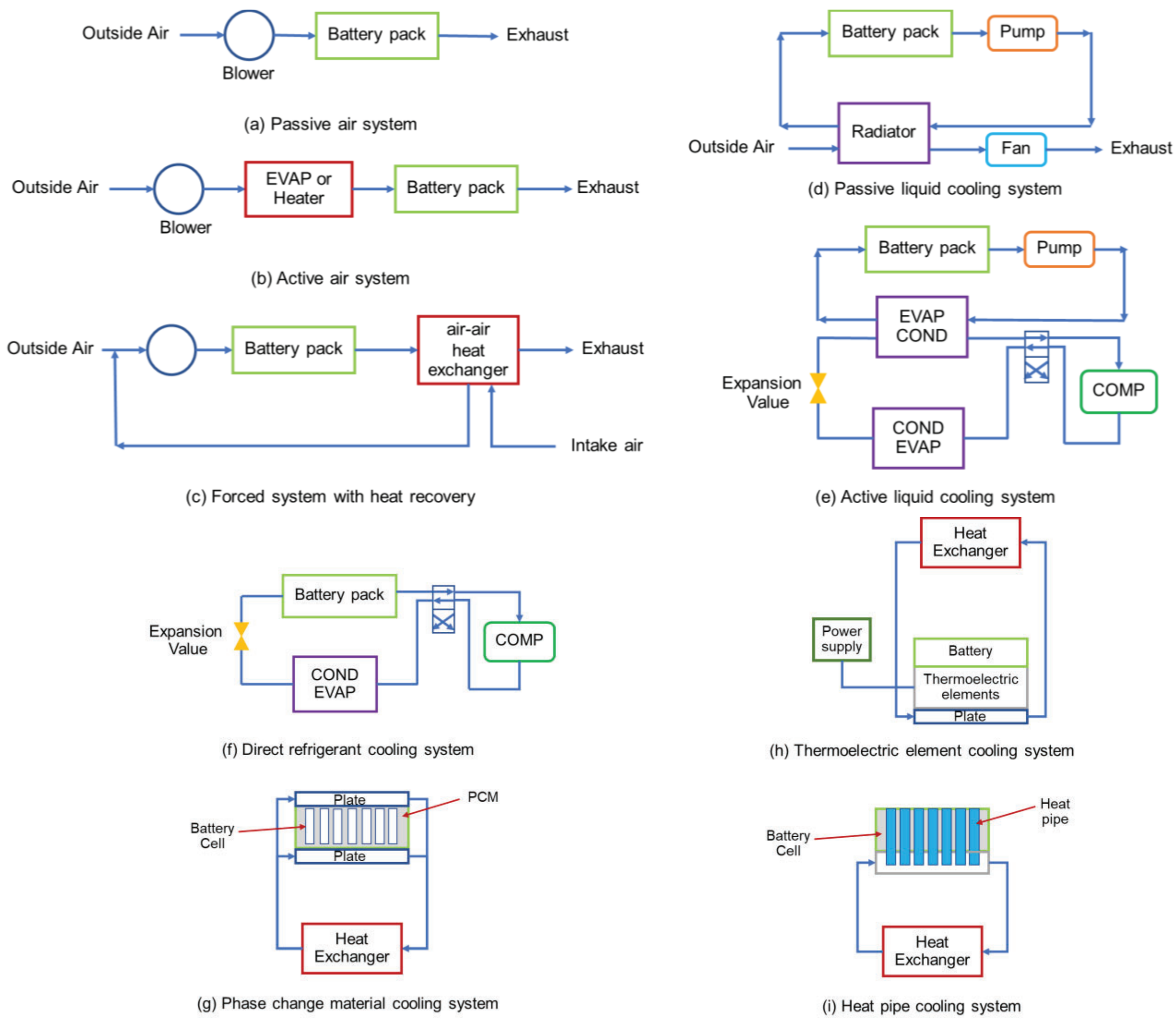


FIGURE 2. Types of BTMS [6, 10].



FIGURES 3. BTMS for each type [10, 17, 18].

1. Air cooling: this system uses air as medium in thermal management. The intake air can be either from the environment or from the cabin, as well as could be conditioned by heater or evaporator. It can be an active or passive system, Fig 3 (a) [10]. But an active system needs an external power source, Fig 3 (b). For this system, fresh air enters one end of the package and leaves the other end [19]. Or, the same total airflow rate is equally divided into series-parallel parts in a single mode. By different geometries and sizes of modules, the series-parallel combination can be adjusted. A more stable temperature distribution in BTMS is observed [20]. The change in flow direction does not affect the battery's temperature, but the rate of air entering into the batteries does significantly, shown as Fig 3 (c) [21].
2. Liquid cooling, Fig 3 (d) and (e): this system applies liquid as heat transfer fluid. Two groups of liquids are generally used: dielectric (direct-contact liquid) and conductive (indirect-contact liquid) liquids. Layout is designed differently based on those two groups. For the direct contact, the battery modules are submerged in mineral oil. While, for the indirect contact, the battery modules can be enclosed by jackets or tubes that circulate the fluid, or they can be placed on cooling/heating plates, which are possibly combined with fins [18]. However, the indirect contact system appears to have better isolation and being much safer for the contact of battery modules and surroundings. The indirect heating/cooling can also be conducted by means of an intermittent pipe system around each module, with a channel or a pipe system which the liquid can circulate around [18, 22, 23].

3. Direct refrigerant cooling, Fig 3 (f): a direct refrigerant system consists of an air conditioning evaporator that directly uses refrigerant as heat transfer fluid circulating through the battery pack. The advantage is more compact in design and less weight [24]. This system can effectively absorb a large amount of heat while maintaining the same temperature for the battery thermal management. Or, a very uniform temperature distribution of the battery would be achieved [17].
4. Phase change material cooling, Fig 3 (g): during a material melting, heat is absorbed by that material's phase change. The temperature is fixed at the melting point until the latent heat reaches the maximum. Typically, this technique is used as conductor and buffer in BTMS. It is always used in combination with air or liquid cooling systems to control battery's temperatures and for lithium-ion battery modules in fast charging and discharging conditions [25].
5. Thermo-electric cooling, Fig 3 (h): a thermo-electric set can be used to transform electric voltage into temperature difference or vice-versa. For EVs, with the former effect, heat is converted through the thermo-electric set by electricity input. Forced convection by fans can be used to improve heat transfer. Even if combining a passive air system with a thermo-electric module can be used to reduce battery's temperatures more efficient than the intake of fresh air, the system is still less than 1 kW [26, 27]. Thermo-electric cooling has many advantages over others, such as smaller size, lighter weight, higher reliability and more easily to do cooling and heating. Nevertheless, its limitation is costly and poor energy efficiency [28].
6. Heat pipe cooling, Fig 3 (i): in addition to thermo-electric modules, a heat pipe is another way that can be used to upgrade a passive air system. The flat copper envelope of the heat pipe is under partial vacuum. The capillary structure is made of sintered copper powder. The heat pipe uses water as the working fluid. The water becomes vapor at below 100 °C on the evaporator side by absorbing heat. The water on the condenser dissipates heat to the surroundings and become liquid again. This is a cycle of the heat pipe. A battery as heat source sits on the evaporating side, while a cooling fins as heat sinks is on the condensing side. Heat pipe cooling reduces thermal resistance by 20-30% [29]. Compared to a thermo-electric system, a heat pipe is more reliable, because there are no moving parts and no energy consumption, but a heat pipe is unable to heat the battery due to its fixed structural layout.

APPLICATION OF ML TO BTMS

In general, as it effectively works in a narrow range of temperatures [30], a lithium battery's performance is directly related to its temperature, which is mainly generated during recharge cycles [31]. However, at the present, fast charging technology is being developed markedly. It is expected to increase and expand the market of lithium batteries [32]. This technology is based on optimization of maximum charging speed and safety [33]. For BTMS, by fast charging technology, EVs' batteries can be recharged to 80% within 30 min or less, depending on battery sizes.

Nevertheless, simultaneously optimizing many design factors is a time-consuming experiment, especially in development of fast charging techniques. Attia et al. [34] proposed an application of ML on developing a closed-loop optimization of fast-charging protocols for batteries, in which 2 key elements were integrated into consideration for reducing the optimization cost: (i) ML with Gaussian process regression algorithm was applied to build an early-prediction model for predicting a final cycle life of batteries using data from the first few cycles. That can help decreasing the time per experiment. Then, (ii) a Bayesian optimization algorithm was employed to efficiently determine the parameter space of charging protocols. The Bayesian algorithm is a probabilistic model for optimizing limited and noisy datasets with small continuous spaces, and therefore, it can reduce the number of experiments for fast-charging battery protocols. It was demonstrated that ML can be used to efficiently optimize the space of parameters specifying the current and voltage profiles of six-step, 10-min fast-charging protocols while also maximizing battery cycle life, which can alleviate range anxiety for EV users. Furthermore, compared to state-of-the-art multi-fidelity optimization algorithms in the literature, their models outperformed in views of considering additional features recorded at every cycle (e.g., voltage). This result highlights the value of designing predictive models for the target application in multi-fidelity optimization.

BTMS FOR TROPICAL ENVIRONMENTAL CONDITIONS

As BTMS is related to multiple factors, such as environmental temperature and heat transfer behavior, it is difficult to be designed effectively. Cheng et al. [35] applied advanced numerical simulation techniques to design finned forced air-cooled BTMS based on thermodynamics, fluid dynamics, and mechanical structures. Compared to a previous study [36], their new design of BTMS showed a better performance in terms of lower battery temperatures and pressure drops. They also applied multi-objective genetic algorithm to optimize the design of BTMS by determining a balance among cooling efficiency, system volume, and power consumption. Choi and Kang [37] employed multi-physic finite element methodology to predict and describe thermal behaviors of an air-cooled lithium-ion battery pack.

For tropical environmental conditions, special design of the BTMS may be needed. For example, in Thailand where average ambient temperature is within 25-40 °C, targeted EV number is aimed at 1.2 million yearly by the year 2036 [38]. This leads to Thailand to intensely study on designing BTMS for high-temperature environments.

Paisarn Naphon [39] reported that problems of battery consisted mainly of heat generated from charging and discharging, operating temperatures over 25-40 °C, and its life cycles. To control battery's temperatures, an air or liquid cooling system can be used to make heat dissipation, in which variables, such as flow rate, flow angle, pipe length, area of pipe-section, number of pipes, material, size of pump or fan can be varied. Numerical simulation with experiments was a tool for BTMS design.

Thailand's National Metal and Materials Technology Center and National Science and Technology Development Agency [40] proposed two prototypes of BTMS. The first one - a cooling system using water coolant from the radiator, while the second prototype - using refrigerant from an air conditioning system to directly cool down battery modules. Both prototypes can be used to control battery temperatures up to 40 °C. However, the first prototype had a slower response when the battery temperature rapidly rises. This was because the heat transfer in this prototype was from the sensible heat mechanism. From the experimental results, it was found that high flow rates of water coolant did not improve the system's cooling capacity. But, reducing the temperature of water, as well as designing the flow channel did significantly. Furthermore, the system required fresh air, making it more complicated, rather than using a radiator alone to maintain a temperature difference of all cells not more than 5 °C. One disadvantage of using this system was a leakage of water, which may cause a short circuit of electricity. The second prototype was less complicated. The system used a valve to disperse a refrigerant from an air conditioning system to cool down battery temperatures. It was very responsive as the heat transfer was from the latent heat mechanism. A short-circuit in a battery pack cannot occur from the leaked solution. However, this system was difficult to control temperature differences of all battery cells to be within 5 °C because the refrigerant had a very high heat extraction ability. The temperature was frigid at the inlet. The process had to wait until the first area was cold enough, or the heat cannot transfer to the refrigerant. After that, the liquid refrigerant would flow to cool a next area. Over time, the temperature distribution of all the cells was no more than 5 °C. This system also requires more energy than the first one. system using coolant from the radiator.

Punyawee Suksusron [41] reported a study on EVs' battery cooling by thermoelectric modules using ferrofluid and water as a coolant. They did experiments and collected variables resulting in the efficiency of heat transfer with ratios of 0.005 and 0.015% v/v. They designed and predicted heat transfer characteristics of the fluids and then determined the optimal form of the flow to produce coolant for cooling. Compared to others, the ferro-fluid at 0.015% of concentration had a batter efficiency of heat transfer approximately 20-30%.

To summarize, there have been some works on applying ML to BTMS of EVs, but very few has considered specific challenges for tropical climates like in Thailand.

CONCLUDING REMARK

In this paper, a brief overview of battery and BTMS for EVs is presented. We can conclude that:

- Lithium-ion battery is the most promising battery type for being employed in EVs.
- BTMS is important to control the thermal behavior of the battery, especially for lithium-ion batteries. It is related to cooling systems, including air cooling, liquid cooling, direct refrigerant cooling, cooling with phase change materials, and thermoelectric cooling.
- ML is becoming an alternative tool for investigation and optimization of fast-charging battery technology. Ten-min fast-charging protocols were successfully developed using ML to specify the current and voltage inputs of the battery.
- In tropical environmental conditions, the special design of the BTMS is needed. It is mainly liquid and refrigerant cooling systems. However, non-homogeneous thermal/temperature distribution in battery modules is still challenging for these systems.

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