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Design and analysis of aluminum/air battery system for electric vehicles

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Abstract

Aluminum (Al)/air batteries have the potential to be used to produce power to operate cars and other vehicles. These batteries might be important on a long-term interim basis as the world passes through the transition from gasoline cars to hydrogen fuel cell cars. The Al/air battery system can generate enough energy and power for driving ranges and acceleration similar to gasoline powered cars.

From our design analysis, it can be seen that the cost of aluminum as an anode can be as low as US$ 1.1/kg as long as the reaction product is recycled. The total fuel efficiency during the cycle process in Al/air electric vehicles (EVs) can be 15% (present stage) or 20% (projected) comparable to that of internal combustion engine vehicles (ICEs) (13%). The design battery energy density is 1300 Wh/kg (present) or 2000 Wh/kg (projected). The cost of battery system chosen to evaluate is US$ 30/kW (present) or US$ 29/kW (projected).

Al/air EVs life-cycle analysis was conducted and compared to lead/acid and nickel metal hydride (NiMH) EVs. Only the Al/air EVs can be projected to have a travel range comparable to ICEs. From this analysis, Al/air EVs are the most promising candidates compared to ICEs in terms of travel range, purchase price, fuel cost, and life-cycle cost.

Keywords: Aluminum/air batteries; Life-cycle analysis; Electric vehicles; Cost analysis

1. Introduction

The Al/air battery system has a high theoretical voltage (2.7 V), high theoretical energy density (8.1 kWh/kg-Al), low cost, an environmentally benign and recyclable product. It turns out to be a promising system for EVs. The Al/air yields energy densities that exceed many other couples (Table 1) [1,2].

Al/air batteries have the potential to be used to produce power to operate cars and other vehicles. These batteries might be important on an interim basis as the world passes through the transition from gasoline cars to hydrogen fuel cells cars. The Al/air battery system could generate enough energy and power for driving ranges and acceleration similar to gasoline powered cars. The major problem in using this system is the low coulombic efficiency of aluminum in strong alkaline media resulting from its high corrosion rate (hydrogen evolution reaction) and high level of polarization during discharge. Use of high grade (99.99 or 99.999%) aluminum doped with other minor elements such as Ga, In, Sn, Mg, Pb, Hg, Mn, Tl, etc. [3–7] can reduce corrosion but increases the material cost. To demonstrate the ability of this system for vehicle applications, the range and acceleration capability similar to internal combustion engine vehicles (ICEs) on an economically sound basis must be provided. Thus, the analysis and estimation of the performance, cost and efficiency of the fuel (aluminum anode), the batteries, and the vehicles powered by this system are all important parts of this study.

2. Fuel cost and efficiency

2.1. Fuel cost

The presence of certain impurities in aluminum can markedly affect the electrochemical behavior. For example, the corrosion rate is particularly sensitive to the concentration of iron [5]. Typically the anode uses aluminum of high purity 99.995 and 99.999% with small amount of other elements, usually in combinations as ternary or quaternary alloys to achieve activation and inhibition of corrosion. The production of aluminum, the cost of aluminum required by the Al/air battery system are reviewed and estimated in this section.

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The Water Intensity of the Plugged-In Automotive Economy

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Abstract:

Converting light-duty vehicles from full gasoline power to electric power, by using either hybrid electric vehicles or fully electric power vehicles, is likely to increase demand for water resources. In the United States in 2005, drivers of 234 million cars, light trucks, and SUVs drove approximately 2.7 trillion miles and consumed over 380 million gallons of gasoline per day. We compare figures from literature and government surveys to calculate the water usage, consumption, and withdrawal, in the United States during petroleum refining and electricity generation. In displacing gasoline miles with electric miles, approximately 3 times more water is consumed (0.32 versus 0.07–0.14 gallons/mile) and over 17 times more water is withdrawn (10.6 versus 0.6 gallons/mile) primarily due to increased water cooling of thermoelectric power plants to accommodate increased electricity generation. Overall, we conclude that the impact on water resources from a widespread shift to grid-based transportation would be substantial enough to warrant consideration for relevant public policy decision-making. That is not to say that the negative impacts on water resources make such a shift undesirable, but rather this increase in water usage presents a significant potential impact on regional water resources and should be considered when planning for a plugged-in automotive economy.

Economic and environmental comparison of conventional, hybrid, electric and hydrogen fuel cell vehicles

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Abstract

Published data from various sources are used to perform economic and environmental comparisons of four types of vehicles: conventional, hybrid, electric and hydrogen fuel cell. The production and utilization stages of the vehicles are taken into consideration. The comparison is based on a mathematical procedure, which includes normalization of economic indicators (prices of vehicles and fuels during the vehicle life and driving range) and environmental indicators (greenhouse gas and air pollution emissions), and evaluation of an optimal relationship between the types of vehicles in the fleet. According to the comparison, hybrid and electric cars exhibit advantages over the other types. The economic efficiency and environmental impact of electric car use depends substantially on the source of the electricity. If the electricity comes from renewable energy sources, the electric car is advantageous compared to the hybrid. If electricity comes from fossil fuels, the electric car remains competitive only if the electricity is generated on board. It is shown that, if electricity is generated with an efficiency of about 50–60% by a gas turbine engine connected to a high-capacity battery and an electric motor, the electric car becomes advantageous. Implementation of fuel cells stacks and ion conductive membranes into gas turbine cycles permits electricity generation to increase to the above-mentioned level and air pollution emissions to decrease. It is concluded that the electric car with on-board electricity generation represents a significant and flexible advance in the development of efficient and ecologically benign vehicles.

1.2 Engineering philosophy of EVs

Engineering integrates science, technology and management to solve real world problems effectively and economically, while usually asks for 'how' and 'what for', pursues 'best solution' and emphasizes 'teamwork'. As EV engineering is multidisciplinary, specialists in those areas of engineering must work together; electrical engineers, electronic engineers, mechanical engineers, chemical engineers and mainstream automotive engineers must pool their knowledge in the main areas that must be integrated: body design, electric propulsion, energy sources, energy refuelling and energy management.

1.2.1 EV CONCEPT

Although the EV was around before the turn of the 20th Century, the modern EV is a completely new machine that is totally different from the classical EV. It is not only a transportation vehicle, but also a new type of electric equipment. The modern EV concept is summarized as follows:

- The EV is a road vehicle based on modern electric propulsion which consists of the electric motor, power converter and energy source, and it has its own distinct characteristics;
- The EV is not just a car but a new system for our society, realizing clean and efficient road transportation;
- The EV system is an intelligent system which can readily be integrated with modern transportation networks;
- EV design involves the integration of art and engineering;
- EV operating conditions and duty cycles must be newly defined;
- EV users' expectations must be studied, hence appropriate education must be conducted.

The system architecture of EVs is very different from that of ICEVs, similar to the fact that the system architecture of quartz-based electronic watches is very different from that of spring-based mechanical watches. In short, their appearances are very similar whereas their principles are very different. The EV system architecture consists of mechanical subsystems, electrical and electronic subsystems, and information subsystems. Concerning those mechanical subsystems, namely the body and chassis, propulsion structure and transmission as well as energy source frame, relevant factors include road characteristics, crash worthiness, interior space, assembly time, serviceability and cost. Concerning those electrical and electronic subsystems, including the power network, motors, controllers and energy source system, relevant factors are safety, regulation, standards, efficiency, reliability, weight and cost. Concerning those information subsystems, handling the driver's desire, vehicle operating status, energy source status, motor status, controller status and charger status, relevant factors are communication network, data processing algorithms as well as communication links for diagnostic and charging control.

1.2.2 EV ENGINEERING PHILOSOPHY

The EV engineering philosophy essentially is the integration of automobile engineering and electrical engineering. Thus, system integration and optimization are prime considerations to achieve good EV performance at affordable cost. Since the characteristics of electric propulsion are fundamentally different from those of engine propulsion, a novel design approach is essential for EV engineering. Moreover, advanced energy sources and intelligent energy management are key factors to enable EVs competing with ICEVs. Of course, the overall cost effectiveness is the fundamental factor for the marketability of EVs.

The design approach of modern EVs should include state-of-the-art technologies from automobile engineering, electrical and electronic engineering and chemical engineering, should adopt unique designs particularly suitable for EVs, and should develop special manufacturing techniques particularly suitable for EVs. Every effort should be made to optimise the energy utilisation of EVs. The following points are those typical considerations for EV design:

- To identify the niche market and environment;
- To determine the design philosophy;
- To determine the technical specifications including the driving cycle;
- To determine the infrastructure required including the recycling of batteries;
- To determine the overall system configuration—EV, HEV or fuel cell EV configurations;
- To determine the chassis and body;
- To determine the energy source—generation or storage, single or hybrid;
- To determine the propulsion system—motor, converter and transmission types, single or multiple motors, gearless or geared, mounting methods, and ICE systems in case of an HEV;
- To determine the specifications of electric propulsion (power, torque, speed) and energy source (capacity, voltage, current) according to various driving cycles; for example, Fig. 1.7 shows that the torque-speed requirement of Federal Urban Driving Schedule (FUDS) is very different from that of Federal Highway Driving Schedule (FHDS);
- To adopt intelligent energy management system;
- To analyse the interaction of EV subsystems by using the quality function matrix, hence understanding the degree of interaction that affects the cost, performance and safety;
- To optimize the efficiency of the motor drive according to the selected driving pattern and operating conditions;
- To optimize the overall system using computer simulation.

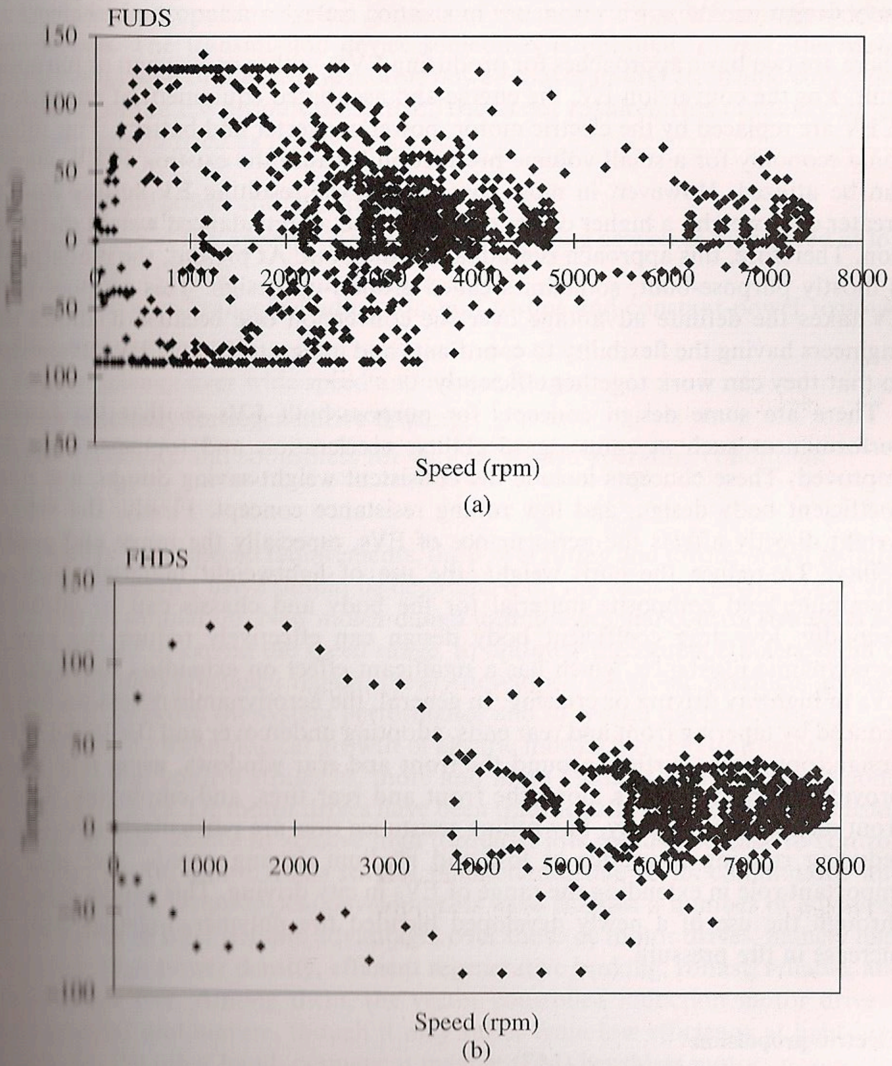

Fig. 1.7. Torque-speed requirements of typical driving cycles.

1.3 KEY EV TECHNOLOGIES

The key technologies of EVs include automotive technology, electrical technology, electronic technology, information technology and chemical technology. Although the energy source is the most crucial area, body design, electric propulsion, energy management and system optimization are equally important. In fact, the integration of all these areas is the key to success (Chan, 1993).

Body design

There are two basic approaches for producing EVs—either conversion or purpose-built. For the conversion EV, the engine and associated equipment of an existing ICEV are replaced by the electric motor, power converter and battery. This offers some economy for a small volume production because the existing ICEV chassis can be utilized. However, in most conversions, the resulting EV suffers from a greater curb weight, a higher centre of gravity and an unbalanced weight distribution. Therefore, this approach is gradually fading out. At present, the modern EV is mostly purpose-built, sometimes called ground-up design. This purpose-built EV takes the definite advantage over the conversion one because it allows the engineers having the flexibility to coordinate and integrate various EV subsystems so that they can work together efficiently.

There are some design concepts for purpose-built EVs so that the overall performances such as range, gradeability, acceleration and top speed can be improved. These concepts include the consistent weight-saving design, low drag coefficient body design, and low rolling resistance concept. Firstly, the vehicle weight directly affects the performance of EVs, especially the range and gradeability. To reduce the curb weight, the use of lightweight materials such as aluminium and composite material for the body and chassis can be adopted. Secondly, low drag coefficient body design can effectively reduce the vehicle aerodynamic resistance, which has a significant effect on extending the range of EVs in highway driving or cruising. In general, the aerodynamic resistance can be reduced by tapering front and rear ends, adopting undercover and flat under-floor design, optimizing airflow around the front and rear windows, using rear spats, providing airflow streaks along the front and rear tires, and employing slanted front nose design. Thirdly, low rolling resistance tires are particularly effective in reducing running resistance at low and medium driving speeds, and play an important role in extending the range of EVs in city driving. This can be achieved through the use of a newly developed blended tire polymer, together with an increase in tire pressure.

Electric propulsion

The electric propulsion system of EVs is responsible for converting electrical energy to mechanical energy in such a way that the vehicle is propelled to overcome aerodynamic drag, rolling resistance drag and kinetic resistance. Since the torque-speed characteristic of an engine covers only a narrow range, the required torque-speed performance of the vehicle has to be achieved through gear changing. On the other hand, in a modern motor drive, high-torque low-speed and constant-power high-speed regions can be achieved through electronic control. Moreover, the EV propulsion design can be more flexible, namely single or multiple motors, with or without reduction gearing, with or without differential gearing, and axle or wheel motors.

The electric propulsion system consists of the motor drive, transmission device and wheels. The transmission device sometimes is optional. In fact, the motor drive, comprising of the electric motor, power converter and electronic controller, is the core of the EV propulsion system. The major requirements of the EV motor drive are summarized as follows:

- High instant power and high power density;
- High torque at low speeds for starting and climbing as well as high speed at low torques for cruising;
- Very wide speed range including constant-torque and constant-power regions;
- Fast torque response;
- High efficiency over wide speed and torque ranges;
- High efficiency for regenerative braking;
- High reliability and robustness for various vehicle operating conditions;
- Reasonable cost.

To satisfy these special requirements, the power rating and torque-speed requirements of the motor drive should be determined on the basis of driving cycles and system-level simulation. New motor design technologies and control strategies are being pursued to extend the speed range, to optimize the system efficiency and to enlarge the high-efficiency region. Newly developed electronic products are also adopted to improve the system performance and to reduce the total cost.

Based on the technological growth of electric motors, power electronics, microelectronics and control strategies, more and more kinds of motor drives become available for EVs. Dc motor drives have been traditionally used for EV propulsion because of their ability to achieve high torque at low speeds and easy to control. However, the dc motor needs careful maintenance due to its commutator and brushes. Recent technological developments have enabled a number of advanced motor drives to offer definite advantages over those dc motor drives, namely high efficiency, high power density, efficient regenerative braking, robust, reliable, and maintenance free. Among them, the vector controlled induction motor drive is most popular and mature, though it may suffer from low efficiency at light-load ranges. On the other hand, permanent magnet (PM) brushless motors possess the highest efficiency and power density over the others, but may suffer from a difficulty in flux weakening control for the constant-power high-speed region. The PM hybrid motor is a special type of PM brushless motors. In this motor, an auxiliary dc field winding is so incorporated that the air-gap flux is a resultant of the PM flux and field-winding flux. By adjusting the field-winding excitation current, the air-gap flux can be varied flexibly, hence offering optimal efficiency over a wide speed range. Switched reluctance (SR) motors offer promising features for EV applications because of their simplicity and reliability in both motor construction and power converter configuration, wide speed range, favourable thermal distribution, 'limp-home' capability, and efficient regenerative braking. However, they may suffer from torque ripples and acoustic noise problems.

In summary, for EV motor drives, dc motor drives have been gradually superseded by induction motor drives, PM brushless motor drives with various configurations and SR motor drives. These advanced motor drives must be specially designed to meet the EV special requirements. For transmission devices, conventional gearing can no longer satisfy the needs of EVs. Recently, planetary gearing has been accepted as the transmission device of the latest EVs.

Energy sources

At present, the main obstacles of the commercialization of EVs are the relatively high initial cost and short driving range. The EV energy source has been identified to be the major cause of these problems. Thus, the present and foreseeable future most important EV development issue is on how to develop various EV energy sources. Those development criteria are summarized as follows:

- High specific energy and energy density;
- High specific power and power density;
- Fast charging and deep discharging capabilities;
- Long cycle and service lives;
- Low self discharging rate and high charging efficiency;
- Safety and cost effectiveness;
- Maintenance free;
- Environmental sound and recyclable.

Currently, there is no sole EV energy source that can fully satisfy all of these criteria. When batteries are selected, there are various compromises among those criteria. For examples, the lead–acid battery offers the merits of relatively low cost and high specific power, and the demerits of relatively short cycle life and low specific energy; whereas the nickel–metal hydride battery exhibits the relatively high specific energy but with relatively high cost. In general, all batteries face a compromise among the specific energy, specific power and cost. In the foreseeable future, the lithium-based batteries such as lithium-ion and lithium-polymer should have good prospects for modern EVs. On the other hand, emerging energy sources including ultracapacitors and ultrahigh-speed flywheels provide promising EV applications because of their exceptionally high specific power. Recently, fuel cells have been identified as one of the most important EV energy sources that can fundamentally solve the key EV problem—short driving range. Provided that the high initial cost of fuel cells can be significantly reduced, it is anticipated that fuel cell EVs can directly compete with the existing ICEVs in the next generation of road transportation.

Rather than based on one energy source, the use of multiple energy sources, so-called hybridization of energy sources, can eliminate the compromise between

the specific energy and specific power. For the hybridization of two energy sources, one is selected for high specific energy while the other for high specific power. For examples, there are the battery & battery hybrid, battery & ultracapacitor hybrid, battery & ultrahigh-speed flywheel hybrid, and fuel cell & battery hybrid. In fact, the HEV is a special case of this hybridisation, namely the petrol is of high specific energy for the long driving range while the battery is of high specific power for assisting fast acceleration and providing emission-free operation.

Energy management

Compared with ICEVs, EVs offer a relatively short driving range. Thus, in order to maximize the utilization of on-board stored energy, an intelligent energy management system (EMS) needs to be adopted. Making use of sensory inputs from various EV subsystems, including sensors for temperatures of outside and inside air, current and voltage of the energy source during charging and discharging, current and voltage of the electric motor, vehicle speed and acceleration as well as external climate and environment, the EMS can realise the following functions:

- to optimize the system energy flow;
- to predict the remaining available energy and hence the residual driving range;
- to suggest more efficient driving behaviour;
- to direct regenerative energy from braking to receptive energy sources such as batteries;
- to modulate temperature control in response to external climate;
- to adjust lighting brightness in response to external environment;
- to propose a suitable battery charging algorithm;
- to analyse the operation history of the energy source, especially the battery;
- to diagnose any incorrect operation or defective components of the energy source.

When the EMS is coupled with a navigation system, it can plan energy efficient routes, locate charging facilities for extended trips, and modify range predictions on the basis of traffic conditions. In summary, the EMS has the distinct features of integrated multi-functions, flexibility and adaptability (just like the brain of EVs) such that the limited on-board energy can be used wisely.

System optimization

As mentioned before, the EV system has a complex architecture that contains multidisciplinary technologies. Since the EV performance can be affected by many multidisciplinary interrelated factors, computer simulation is the most important technology to carry out the optimization for performance improvement and cost reduction. Also, EV simulation can help those manufacturers to minimize prototyping cost and time, and to provide rapid concept evaluation. Since the whole EV system consists of various subsystems clustered together by mechanical link, electrical link, control link and thermal link, the simulation should be based on the concept of mixed-signal simulation. Hence, the system optimization can be carried out in the system level in which there are many trade-offs among various subsystem criteria. Generally, numerous iterative processes are involved for the preferred system criteria.

In summary, the system-level simulation and optimization of EVs should consider the following key issues:

- As the interactions among various subsystems greatly affect the performance of EVs, the significance of those interactions should be analysed and taken into account.
- As the model accuracy is usually coherent with the model complexity but may be contradictory to the model usability, trade-offs among the accuracy, complexity and usability as well as simulation time should be considered.
- As the system voltage generally causes contradictory issues for EV design, including the battery weight, motor drive voltage and current ratings, acceleration performance, driving range and safety, it should be optimized on the system level.
- In order to increase the driving range, multiple energy sources may be adopted for modern EVs. The corresponding combination and hybridization ratio should be optimized on the basis of the vehicle performance and cost.
- Since EVs generally adopt fixed gearing, the gear ratio can greatly affect the vehicle performance and driveability. An optimal ratio should be determined through iterative optimization under different driving profiles.

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