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REVIEW OF POSSIBLE MODIFICATIONS OF BATTERY CHARGING TECHNOLOGIES FOR USE IN SUPERCAPACITOR CHARGING

The article discusses the current technologies and methods of fast, safe, and efficient charging of modern high-capacity batteries. The aim of the research is to determine which of the currently used technological solutions are most suitable for use in charging of supercapacitor energy storage devices. Modern solutions applicable to battery technologies which due to the operating characteristics and working parameters of supercapacitors are not suitable to use for their charging have been listed and the potential problems and risks related to using them for supercapacitor and battery hybrid charging have been outlined. The aim is to seek methods of optimizing supercapacitor charging to maximize the safety and speed of the process, in the perspective of using them alongside batteries for automotive applications.

Keywords: supercapacitor, battery, charging, electric vehicle, BMS

1. INTRODUCTION

Two worldwide transport industry has been and continues to be heavily reliant on fossil fuels, to the detriment of human health and the environment. The negative effects of conventional vehicles with internal combustion engines (ICE) on human health have been known and studied for some time now. As the research into the effects of car-induced air pollution on human health, especially in urban agglomerations, continues to provide more data so do individual governments and international bodies continue to draft and tighten related regulations. Those regulations have been the driving force behind the major changes in the vehicle market in the western world, affecting every stage of vehicle manufacturing and even retail. Af-

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ter introducing a series of increasingly restrictive emission standards the EU has currently reached the Euro VI vehicle emissions standard for the type approval regulations. The US, China, and most other countries in the world have adopted their own vehicle emission standards accordingly. This has forced the manufacturers to develop and design new solutions for their conventional diesel and gasoline engines, maximizing their efficiency and minimizing emissions. This came along with a number of new aftertreatment technologies and a push towards new hybrid, and electric vehicles to become available for the customers. This shift in market marked a new trend towards the promotion and gradual rise of the new types of electric vehicles (EV), which quickly began growing in sales. The market share of electric and hybrid vehicles worldwide continues to steadily increase along with the rising concerns about air pollution and the global warming. The observed trends in the sales of various electric and hybrid vehicles in different countries are the result of multiple factors, ranging from various forms of legislative action taken by governments up to the individual environmental awareness of the car owners. The popularity of such solutions is greatly affected by the financial incentives but also often heavily limited by the lack of appropriate infrastructure or the geography of the country in question. It is easy to assume that financial incentives for purchasing electric and hybrid vehicles would have a direct impact on their sales across a country, but the results of analysis performed by Sierzchula et al. [2014] indicate that this may not be as simple a correlation as once assumed. Sierzchula's results, shown in Fig. 1, reveal that the amount of money spent on promoting the purchase of hybrid and electric vehicles does not always result in a significant rise in their market share.

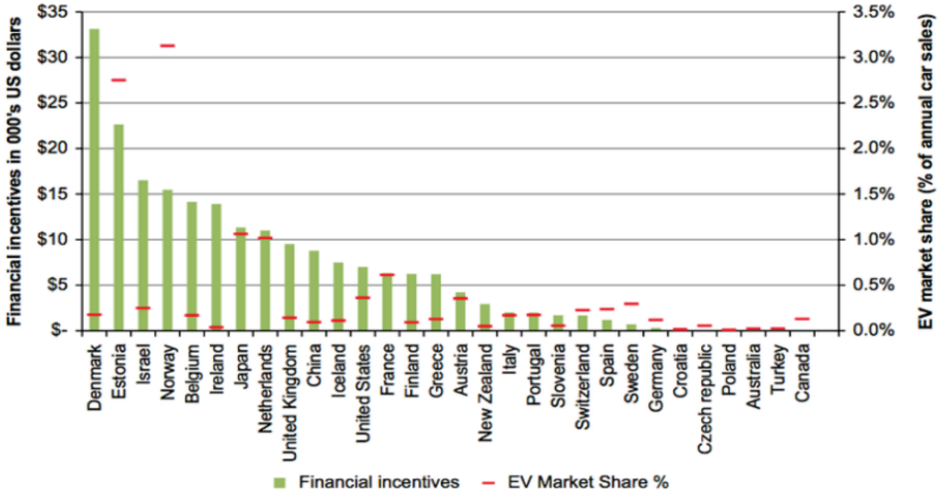

Fig. 1. Representation of EV market share relative to the financial incentives offered in different countries [Sierzchula et al, 2014]

A stark contrast can be seen between Denmark and Norway, where despite much larger financial incentives Denmark's share of EVs remains very small in comparison. EV share in Ireland is minimal despite fairly large incentives and yet France, despite only offering about half the financial incentive value of Ireland's has reached a much higher market share. This serves only as an indicator that the barriers to the growth of the EV market vary in nature and must thus be approached differently.

Car manufacturers have come up with multiple EV powertrain designs. When talking about hybrid and electric vehicles they are divided into: hybrid electric vehicles (HEV), battery electric vehicles (BEV), plug-in electric vehicles (PEV), plug-in hybrid electric vehicles (PHEV), and range extended electric vehicles (REEV). The choice of which type of vehicle to purchase is dictated by the specific needs and expectations of the customers, resulting in vehicles that are specialized for operation in certain environments. Current and predicted sale rates for some of these vehicle types are shown in Fig. 2.

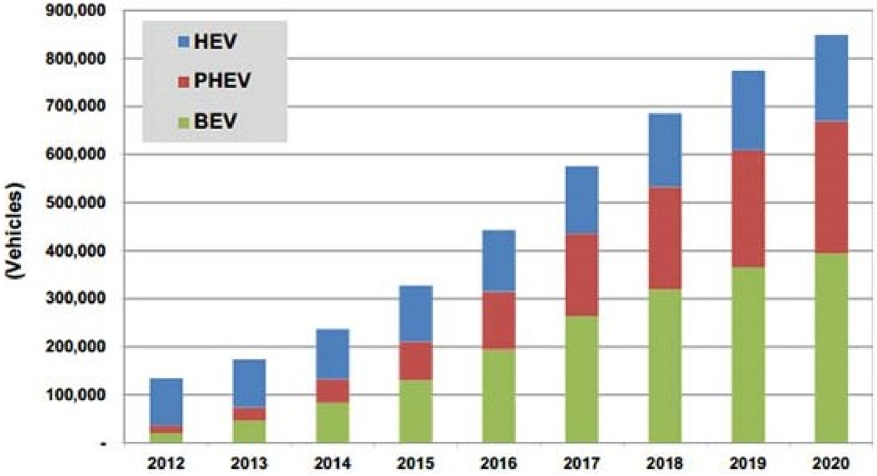

Fig. 2. HEV, PHEV and BEV sales on European markets (2012-2020) [Electric Cars Report 2013]

One of the major problems for the competitiveness of purely electric vehicles is their limited range, a result of the limited power storage capacity of the current battery technologies. This also results in a high HEV market share, where hybrid solutions become to go-to choice of customers who require a vehicle capable of traversing large distances without the need for recharging. This is a real problem since the only real way to event try to compete with the range provided by an ICE would be to avoid long-distance travel (such as by providing a competitive public transport option), and in cases where that is impossible to provide both a frequent and cheap infrastructure for charging the vehicle along with new much faster charging methods. Even if there was a free plug-in parking spot on every gas station set up in regular intervals along the travelled road plug-in users would still not choose such an arrangement due to the obscene recharge time of such vehicles, making long-distance travel simply unrealistic. This, however, presents an opportunity for further development of energy storage technologies. Automotive battery charging time has been a focal issue of battery technology development as of late, along with maximizing the battery energy density. This has led to the more unusual solutions being proposed of replacing, combining, or hybridizing currently used battery technologies with supercapacitors.

2. SUPERCAPACITOR AUTOMOTIVE APPLICATIONS

The role of supercapacitors in most hybrid and electric vehicles is to be based on their specific properties in which they are superior to conventional modern batteries. For hybrid vehicles these uses have been described in [Camara et al. 2008] as:

- assisting the batteries during hard transient states,
- increasing the batteries' lifespan and decreasing their size,
- offering performances independent of the battery state,
- increasing the available power and, consequently, the hybrid vehicle autonomy,
- improving the energetic efficiency while regenerative braking is employed.

Leading vehicle manufacturers currently find themselves pressured to further develop each of these aspects to meet the demands of their customers. Battery lifespan, additional peak power, more efficient regenerative braking, and higher vehicle autonomy are all key features when selling new hybrid and electric vehicles. Many studies have been carried out comparing the benefits and drawbacks of various energy storage devices in the perspective of their automotive applications [Du Pasquier et al. 2003]. As battery and supercapacitor technologies continue to be developed their properties also change, meaning that further tests and research of their potential applications and mutual comparison remains an important aspect of further innovation in this field. Due to the negative effects of transient states on the battery life and efficiency the use of supercapacitors is thought to be the primary solution for the future designs of vehicles. Achieving that goal, however, still requires further changes and development of the energy management systems and algorithms. A number of methods had been proposed to achieve this goal. A DC/DC converter system is among the most commonly offered, due to its relative simplicity and low costs [Camara et al, 2009]. A promising solution seems to be the circuit-based bidirectional DC/DC converter, such as the full-bridge/push-pull converter described in [Yamamoto et al. 2006]. This solution also indicates the benefits of using additional lossless capacitors for zero voltage switching (ZVS), as well as offering adequate protection against voltage/current surges by synchronous rectification in push-pull stage. Other proposed solutions included incorporating photovoltaic devices for charging supercapacitors, with the use of Maximum Power Point Tracking (MPPT) and a series of possible designs for the charging circuit [Jinlong, Jiuhe and Xibao 2012]. The availability of such solutions indicates that incorporating supercapacitors as standard addition to battery-based automotive energy storage systems as well as the required charging system adjustments can be readily achieved when necessary.

2.1. DC converter supercapacitor charging

For direct charging using a cable and an AC/DC converter several methods can be considered. Battery charging is normally carried out through the constant current-constant voltage method (CC-CV charging), although in some cases multistage constant current (MCC) is used [Zhang 2006, Shen, Vo and Kapoor 2012]. Some forms of charging systems have been designed to accommodate the differences between batteries and supercapacitors [Shin D et al. 2011], but these methods are not necessarily easily applicable for automotive solutions.

Various control algorithms for energy management have been tested with adjustments often proposed for specific manufacturer requirements. [Nguyen, Lauber and Dambrine 2014] presents an example of simulations that can be performed for the changes in control algorithms necessary when adding a supercapacitor to a previously battery-based system.

The rate of charging is the result of the adopted charging procedure. But the numbers listed by the car manufacturers are not definitive. All the most important parameters for cars with electric drives are the result of deliberate choice in optimization, and not a technical limitation. Recent events in the USA provide examples of how these choices affect the end user. In light of the hurricane Irma's arrival on the coast of Florida, Tesla announced the release of a software update for their Model S and X vehicles that unlocked the full battery capacity increasing the vehicle ranges by 40-65 miles. The reason why the range of these vehicles was purposefully restricted with the use of software is to preserve the battery and extend its lifespan. More demanding operating conditions equate to accelerated wear and ageing in the case of batteries, mostly due to their energy storage mechanism. In batteries electric energy is stored chemically, by the formation of bonds between ions in the electrolyte with the electrodes, which can then be broken to release that energy. Supercapacitors store energy by physically separating the charges, which eliminates the need for chemical reactions to take place. Chemical release of energy is slower to get going, thus making supercapacitors superior in responding to sudden power demand spikes. Chemically active materials also tend to wear down as the repeated reactions take place, leading to the degradation of the battery energy storage capacity [Barre et al. 2013]. This provides a limitation to how quickly batteries can charge and discharge safely, without risking permanent damage. Because supercapacitors have significantly lower response time they can be used to compensate for the limitations of the battery technologies. This holds true for the charging process, where despite a lower total energy density supercapacitors can charge much more rapidly. This remains a problem for electric vehicles as well as any plug-in vehicles. All electric charging systems for vehicles are forced to compete in convenience and ease of use with conventional vehicles, which can be refueled in minutes, instead of hours. A comparison can be made between currently available electric and plug-in vehicles to show the number of kilometers of travel range added every hour that the vehicle is charging (Table 1).

Table 1. Maximum charging power and vehicle travel range added per hour charging, comparison for a range of electric vehicles [Wnuk 2014]

Model	Max Charge	Vehicle range added per hour	Vehicle type
Audi A3 e-tron	3.3 kW	18 km	PHEV
BMW i3	7.4 kW	40 km	100% Electric / REx
Cadillac ELR	3.3 kW	18 km	PHEV
Chevy Spark EV	3.3 kW	18 km	100% Electric
Chevy Volt	3.3 kW	18 km	PHEV
Fiat 500e	6.6 kW	35 km	100% Electric
Ford C-Max Energi	3.3 kW	18 km	PHEV
Ford Fusion Energi	3.3 kW	18 km	PHEV
Ford Focus Electric	6.6 kW	35 km	100% Electric
Honda Accord Plug-in Hybrid	6.6 kW	35 km	PHEV
Honda Sonata Plug-in Hybrid	3.3 kW	18 km	PHEV
Kia Soul EV	6.6 kW	35 km	100% Electric
Mercedes B-Class Electric	10 kW	47 km	100% Electric
Mercedes S550 Plug-in Hybrid	3.3 kW	18 km	PHEV
Mercedes C350 Plug-in Hybrid	3.3 kW	18 km	PHEV
Mitsubishi i-MiEV	3.3 kW	18 km	100% Electric
Nissan LEAF	3.3 kW / 6.6 kW	18 km / 35 km	100% Electric
Porsche Cayenne S E-Hybrid	3.6 kW / 7.2 kW	19 km / 39 km	PHEV
Porsche Panamera S E-Hybrid	3 kW	16 km	PHEV
Smart Electric Drive	3.3 kW	18 km	100% Electric
Tesla Model S	10 kW / 20 kW	47 km / 93 km	100% Electric
Tesla Model X	10 kW / 20 kW	47 km / 93 km	100% Electric
Toyota Prius Plug-in	3.3 kW	18 km	PHEV
Volkswagen e-Golf	3.6 kW / 7.2 kW	19 km / 39 km	100% Electric

These results are, however, not fully representative, due to the existence of fast charger technologies. These are charging methods that provide DC electricity directly to the battery system using a special charging port, thus bypassing the onboard charger and AC/DC converter. There are three types of fast chargers currently made available by manufacturers, these are:

– CHAdeMO chargers (50 kW output) used by Nissan dealerships and mostly dedicated to Nissan Leaf, but also used by Mitsubishi i-MiEV and Kia Soul EV,

– SAE Combo chargers (50 kw output) used with the BMW i3, Chevy Spark EV, and Volkswagen e-Golf,

– Tesla Superchargers (120 kW output) used only by the Tesla models.

It is important to note that the availability of fast chargers has a major impact on the popularity and ease of use of electric vehicles that can use them. Note that plug-in hybrids (PHEV) currently do not have the ability to use fast chargers. Taking these fast charging points into account the number of kilometers a vehicle can travel after an hour of charging changes significantly (Table 2).

Table 2. Comparison of different EV range added per hour charging on fast chargers [Wnuk 2014]

Model	Fast charger type	Range gained per hour of charging
BMW i3	SAE Combo	242–322 km
Chevy Spark EV	SAE Combo	242–322 km
Kia Soul EV	CHAdeMO	242–322 km
Mitsubishi i-MiEV	CHAdeMO	242–322 km
Nissan LEAF	CHAdeMO	242–322 km
Tesla Model S	Supercharger and CHAdeMO*	547 km
Tesla Model X	Supercharger and CHAdeMO*	547 km
Volkswagen e-Golf	SAE Combo	242–322 km

*Range gained per hour of charging value given for supercharger technology only, CHAdeMO charger compatibility is optional in Tesla models

Due to the difficulty and cost of operating a fast charging unit these solutions can only be found in places where they are managed and paid for by their respective companies. It is highly improbable that such solutions would find their way into home charger market, as common house electricity grids cannot support such a device. Thus owners of electric vehicles will most likely not be able to use this technology at home. Fast chargers are generally used when traveling longer distances, since making charging stops mid-journey that last upwards of 6 hours would greatly reduce the competitiveness of EVs. This means that the new solutions using a combination of batteries and supercapacitors will need to be designed with this wide range of charging rates in mind. Supercapacitors have a relatively simple charging curve (Fig. 3), which makes the BMS design easier, but the discharge is linear, thus preventing the full use of energy.

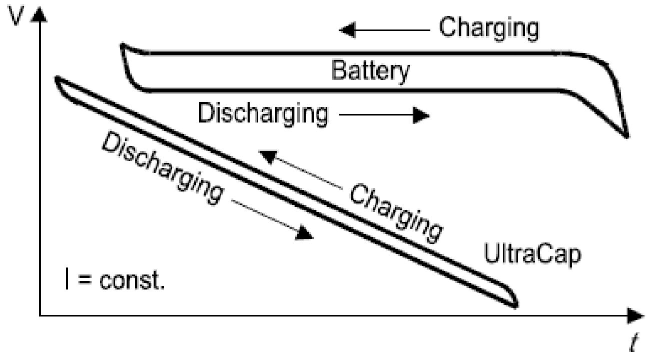

Fig. 3. General charge-discharge characteristics of batteries and ultracapacitors

Among the main disadvantages of supercapacitors is that they do not maintain a constant voltage throughout their discharge process. For this reason the design of the electric connection needs to be adjusted to compensate for these changes, especially if these supercapacitors are to be connected along and used with regular modern batteries. Similarly in the case of charging the circuit must be able to stabilize the voltage in order to use it effectively. This poses technical problems, the solutions to which will ultimately determine the viability and competitiveness of each drive employing batteries in conjunction with supercapacitors.

3. CONCLUSIONS

The usefulness and popularity of mixed battery/supercapacitor energy storage systems for automotive applications hinges on the effect of adding the supercapacitor technology into the vehicle on charging time and vehicle travel range. Due to the relative novelty of electric vehicles in common use on public roads and the still lackluster state of the vehicle charging infrastructure the range and applications of electric and hybrid-electric drive systems is limited. It is important to note, however, that all of these limiting factors are being steadily removed as the market and infrastructure catches up. Moreover the continued development of energy storage technologies drives the increase in the competitiveness of these vehicles. This should be considered on top of the widespread financial incentives provided for the purchase of electric and hybrid vehicles found in many countries and regions, most importantly the USA, the European Union and China. While some of the limitations in vehicle charging speed are the result of the energy grid setup which cannot be easily changed, many other aspects of EV and PHEV use can be improved upon through further research and engineering. The eventual ecological and economic benefits of switching from conventional drive vehicles to the new electric and hybrid solutions are certain to keep growing. Therefore, the domination of such vehicles on the public roads is mostly a matter of time. However, when considering the ecological and environmental aspects of switching to electric and hybrid vehicles it is essential to take the full well to wheel perspective on harmful vehicle exhaust emissions. This puts the efforts of car manufacturers into perspective, as even the most efficient electric vehicles will not become truly zero-emission until the electric energy production that they rely on is also made without harmful gas emissions. Especially since the reduction of global carbon dioxide emissions has been on the forefront of combating the climate change for decades.

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PRZEGLĄD MOŻLIWYCH MODYFIKACJI TECHNOLOGII ŁADOWANIA AKUMULATORÓW Z PERSPEKTYWY ICH ZASTOSOWAŃ W ŁADOWANIU SUPERKONDENSATORÓW

Streszczenie

W artykule omówiono aktualnie istniejące technologie szybkiego i bezpiecznego ładowania wysokowydajnych akumulatorów do zastosowań motoryzacyjnych. Celem artykułu jest określenie, które z obecnie dostępnych technologii są najbardziej odpowiednie do ładowania superkondensatorów. Określono i opisano obecnie wykorzystywane technologie, które z różnych przyczyn mogą okazać się niekompatybilne z nowymi rozwiązaniami motoryzacyjnymi łączącymi akumulatory z superkondensatorami, zarówno dla pojazdów elektrycznych, jak i hybrydowych. Omówienie to wykonano celem nakreślenia najbardziej prawdopodobnych metod ładowania zasobników energii w przyszłych rozwiązaniach motoryzacyjnych. Kładziono przy tym nacisk na bezpieczeństwo, niezawodność oraz szybkość ładowania, po czym oceniono w perspektywie zastosowań dla pojazdów elektrycznych, hybrydowych i typu plug-in, zakładając, że będą one wykorzystywały hybrydowe układy zasobników energii elektrycznej.

Keywords: superkondensatory, akumulatory, ładowanie, pojazdy elektryczne, BMS