Application of Cuk converter together with Battery Technologies on the Low Voltage DC supply for Electric Vehicles

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Abstract–Electric vehicles (EVs) have becoming more and more popular, and although there is no doubt that motor is the key part of a functional EV, it is generally accepted that the battery is the critical component and a main obstacle of the development of EVs. In this paper, some advanced research and technology of batteries is presented and compared one by one, especially those adopted by flagship EV automakers. Some emerging batteries which have great potential for future EVs are also discussed. Based on this, the paper studies the application in EV of Cuk converter, which can be regarded as a combination of boost converter and buck converter, on the low voltage side DC supply electric vehicles together with the batteries, and even super-capacitors which have unique characteristics. Further research and design is given regarding to multi-switching of the DC-DC topology.

Keywords–Electric vehicle, Battery technology, EV power system, Cuk converter, super-capacitors.

I. INTRODUCTION

In recent decades, the implementation of Electric Vehicles (EVs) is a fascinating choice for no pollution, zero roadside emission, higher energy efficiency and active participation in load management in future, compared to traditional Internal Combustion Vehicles (ICVs) [1] because of the worldwide acknowledge of energy saving and renewable energy's importance which has great relationship with environment protection. At this moment, however, the main obstacles of the implementation of EVs are battery technology and construction charging stations. Generally it takes long time to charge the batteries for a normal range of EVs. If we implement the fast charging, not only produces greater burden or impact to the grid, but may also shorten the life cycle of batteries. It is widely accepted that battery is the critical component in the development of EVs. [2]

In this paper, some major basic types of batteries and their performance for EVs are presented and compared. The latest batteries that have been adopted by automakers for their flagship electric vehicles are discussed. Some specific emerging batteries that have higher potential for EVs in the future are also presented and discussed, together with some progress and improvement in the battery technology.

This paper also designs the application of Cuk converter on the low voltage side DC supply electric vehicles together with batteries, especially in starting-up and braking state. A well-designed combination topology of DC-DC converter and batteries is important to the whole EV system. Because of many advantages of Cuk converter, its application is very suitable and flexible in electric vehicle system. This paper further studies the effect of energy variation ratio of the Cuk converter in efficiency perspective and provides guidelines for designing a Cuk converter's application in electric vehicles.

II. BASIC TYPES OF BATTERIES AND COMPARISON

An electric vehicle battery can be either a primary battery or a secondary battery rechargeable battery used for the propulsion of EVs. Electric vehicle batteries consist of many sub-categories, including but is not limited to the lighting (especially emerging LED lighting technology), starting-up, and ignition battery, since they are designed to give power over sustained periods of time. Rechargeable batteries are usually the most expensive component of EVs, being about half the retail cost of the car. On an energy basis, the price of electricity to run an EV is a small fraction of the cost of liquid fuel needed to produce an equivalent amount of energy.

2.1. Types of batteries utilized in EVs at present

In the foreseeable future, batteries are the major energy source for EVs, with their better overall performance than other energy sources like ultra-capacitors, ultrahigh-speed wheels, and fuel cells. Major types of batteries that have been developed for EVs are: valve-regulated lead acid (VRLA), nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), zinc/air (Zn/air), sodium/sulfur (Na/S), lithium-ion (Li-ion), vanadium redox, and molten salt battery. [3]

Table 1. Batteries comparison for EVs [3]

Type	Energy density (MJ/kg)	Power density (W/kg)	(Dis-)Charge Efficiency (%)	Life Cycles
Lead-acid	0.11-0.14	180	70-92	400-600
Ni-Cd	0.14-0.22	150-350	70-90	600-1200
NiMH	0.11-0.29	250-1000	66	600-1200
Li-ion	0.58	1800	99.9	1200-2000
Molten	N/A	150-220	69	1500
Zn/air	0.36	105	N/A	2000
Na/S	0.32-0.56	200	89-92	800

VRLA is more commonly known as a sealed battery. It is a lead-acid rechargeable battery. Because of their construction, VRLA batteries do not require regular addition of water to the cells, and vent less gas than flooded lead-acid batteries. [4] The reduced venting is an advantage since they can be used in confined or poorly ventilated spaces. It is widely used in low-cost end EVs.. Vehicles used in auto racing may use AGM batteries due to their vibration resistance.

At the moment the Li-Ion technology is the most promising for the usage in EVs. Its high specific energy density surmounts the values of all the other technologies known so far. The higher the energy density the lower is the additional weight of the car, which means a higher range. None of the batteries can offer high energy density and high power density at the same time. Thus, a compromise between the two or a combination of two batteries is often needed. Here is a brief table showing how the various electric car batteries compare with each other. The specific energy density of different technologies is shown in the figure below. Another advantage of Lithium batteries is the high potential for an increasing energy density. [5]

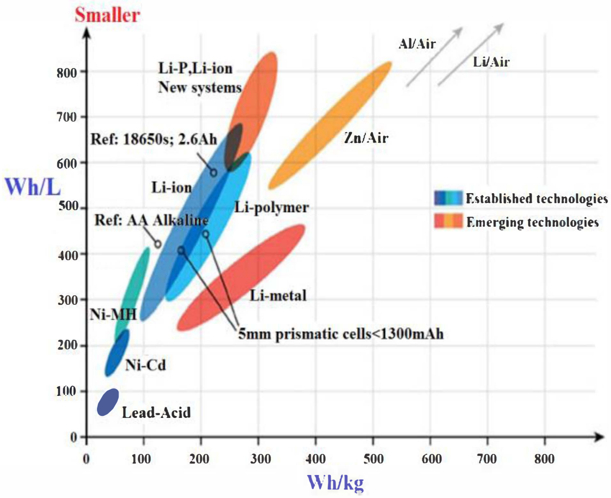

Fig.1: Battery power and energy density [5]

Ni-Cd is a type of rechargeable battery using nickel oxide hydroxide and metallic cadmium as electrodes. Larger flooded cells are used for EVs. Ni-MH is very similar to Ni-Cd. NiMH use positive electrodes of nickel oxyhydroxide (NiOOH), like the NiCd, but the negative electrodes adopts a hydrogen-absorbing alloy rather than cadmium, becoming a practical application of nickel–hydrogen battery chemistry. [6]

Vanadium redox battery is a type of rechargeable flow battery which employs vanadium ions in different oxidation states to store chemical potential energy. [7] The vanadium redox battery exploits the ability of vanadium to exist in solution in four different oxidation states, and uses this property to make a battery that has just one electro active element instead of two.

Li-ion is a member of a family of rechargeable battery types in which lithium ions move from the negative electrode to the positive electrode during discharge, and back when charging. [8] Because of their light weight Li-ion batteries are used for energy storage for many electric vehicles for everything from electric cars to Pedelecs, from hybrid vehicles to advanced electric wheelchairs, from radio-controlled models and model aircraft to the Mars Curiosity rover.

Zn/air is electro-chemical batteries powered by oxidizing zinc with oxygen from the air. These batteries have high energy densities and are relatively inexpensive to produce. Sizes range from very small button cells for hearing aids, larger batteries used in film cameras that previously used mercury batteries, to very large batteries used for electric vehicle propulsion. [10]

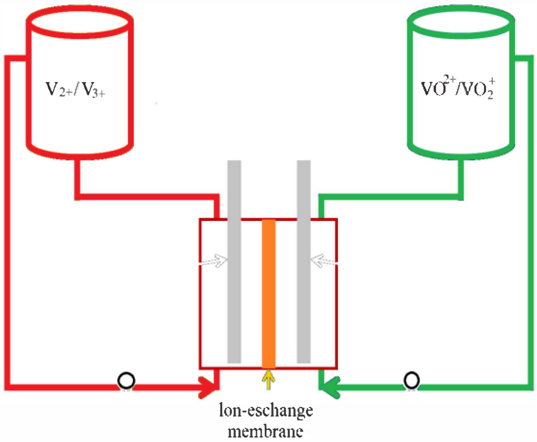

Fig.2: Schematic of a vanadium redox-flow battery. [9]

A sodium–sulfur battery is a type of molten-salt battery constructed from liquid sodium (Na) and sulfur (S). This type of battery has a high energy density, high efficiency of charge/discharge (89–92%) and long cycle life, and is fabricated from inexpensive materials. [11] It needs high temperature to operation.

Molten salt battery is a class of primary cell and secondary cell high-temperature electric battery that uses molten salts as an electrolyte. They offer both a high energy density through the proper selection of reactant pairs as well as a high power density by means of a high-conductivity molten salt electrolyte. [12]

Some researchers have compared many details of various kinds of EV batteries including the size, power and energy density respectively, and life cycle. Which kind of battery is better, however, depends on consumer's criterion and requirement, such as their expected cost and energy density. Some researchers are also considering new type batteries. IBM has declared a research plan to develop various kinds of batteries for EVs [13], including Sodium batteries, Li-O2 batteries, lithium-air batteries, and will adopt nanotechnology.

In total, Lithium-ion batteries are still the most attractive among other ones for EVs. Researchers are trying to develop Li-ion batteries with better quality and less cost, and many governments and companies also pay attention to support the development of Li-ion batteries.

III. DESIGN OF CUK CONVERTER'S APPLICATION IN EV

Nowadays Electric vehicles have becoming more and more popular because of the worldwide acknowledge of energy saving and renewable energy's importance which has great relationship with environment protection. An electric vehicle consists of many systems, while the low voltage dc supply part plays key important role, especially in emergency state.

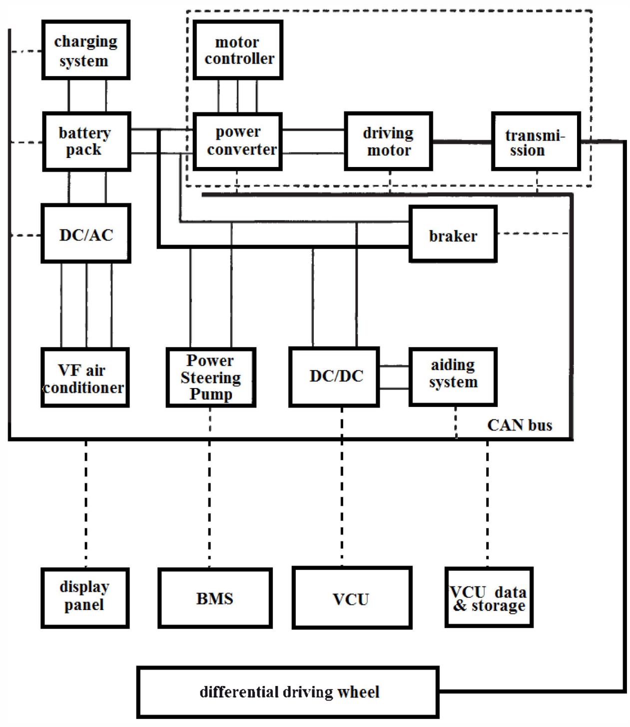

Fig.3: Diagram of EV power flow [14]

Cuk converter is a basic non-isolated DC-DC converter topology which can be regarded as combination of boost converter and buck converter. The output voltage can be adjusted to be larger or smaller than the input voltage, which is very flexible.

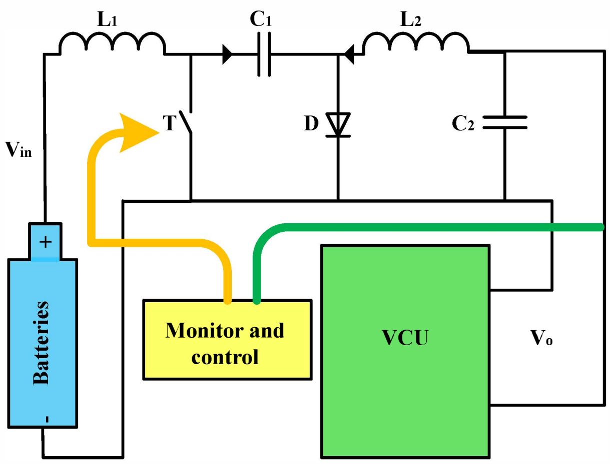

Fig.4: Design of Cuk converter applied on EV

Cuk converter has many advantages among DC-DC topologies. We designed the low voltage side DC power supply by Cuk converter as figure 4 shows. Batteries serve as the input voltage source of the Cuk converter, and the output of the converter is connected to the Vehicle Control Unit (VCU) which normally has a voltage rating of around 20V, and other low-power dc devices. The green line represents feedback and monitoring of the Cuk converter, whereas the yellow line represents the control of the MOSFET of the Cuk converter. No matter what's the value of the battery voltage, Cuk converter can boost or reduce it into an expected voltage level. We select Li-ion battery as the research target since it is the most popular one in current EVs.

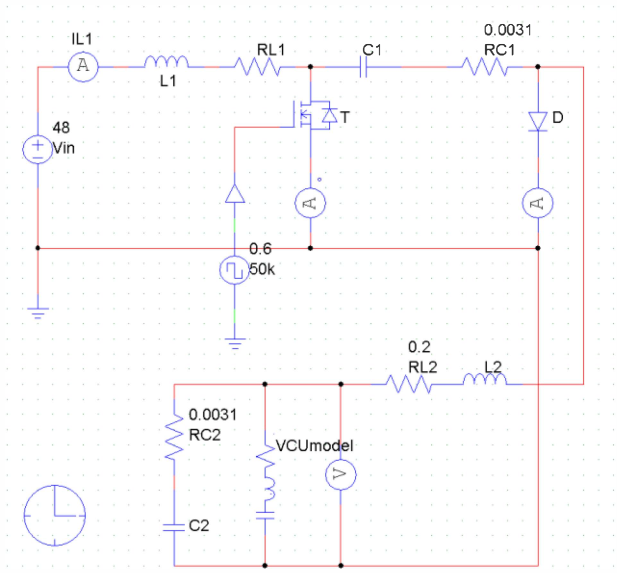

Fig.5: Simulation diagram in PSIM

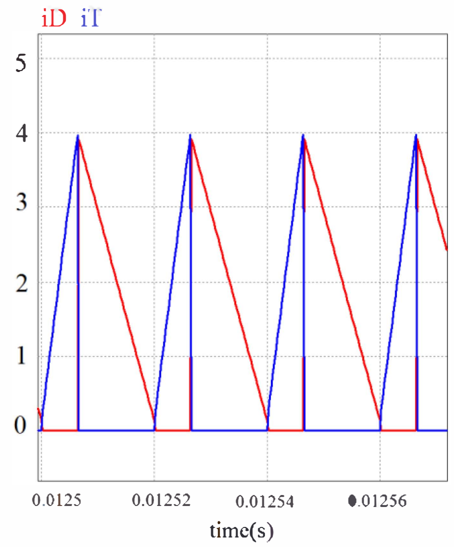

Fig.6: Waveform of diode and transistor current

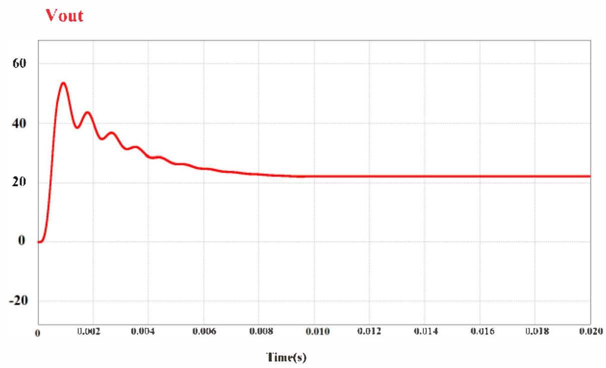

Fig.7: Waveform of the output voltage at the beginning

Simulation of the Cuk converter together with battery and VCU model is conducted in PSIM platform. The diagram is shown in the above figures. The input voltage is set at 48V while the goal of output voltage is 20V. Calculation of the parameters of each device of the Cuk converter is a bit complicated because of the VCU and other devices' model. Combining the simulation result and calculation analysis, we set the inductor at 200uH level, capacitor C1 at 10uF level and C2 at 1mF level, which could bring ideal output. Simulation result is shown as figure XX and XX, and we can see the Cuk converter operates at good condition.

IV. Further Research of Multi-switching and Supercapacitors

The staring-up and braking state during the EV's operation is very important and requires more stable power supply. The instantaneous larger current of the machine would have influence on the battery and the low-voltage DC side's state. In this way, a Cuk converter with multi-switching is proposed to balance this problem.

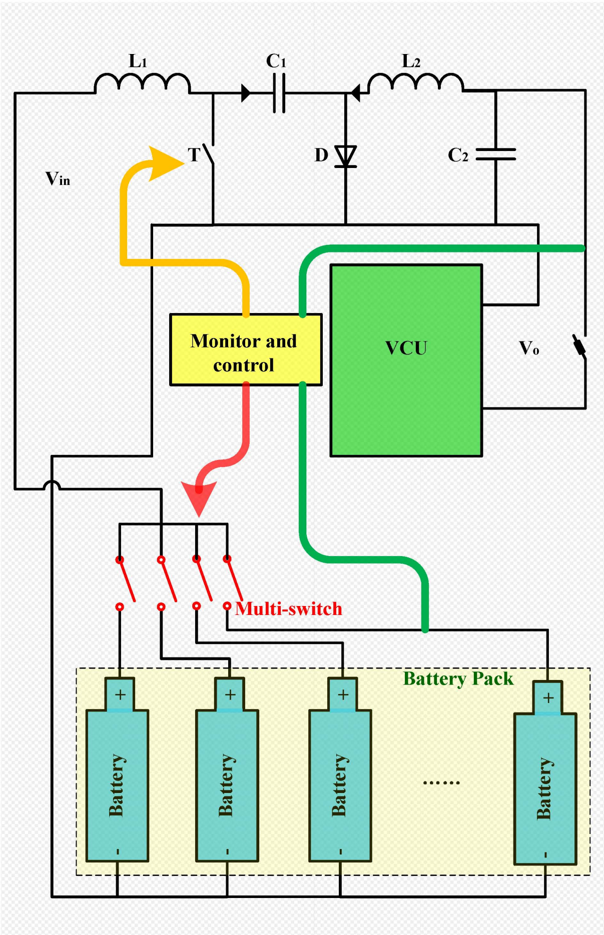

Fig.8: Cuk converter's application with multi-switch

Figure 8 shows the topology diagram of this design. A battery pack is composed of many battery cells. They can be in series with each other and divided into several groups where the voltage of each group is 20-50V. A multi-switch is connected to each group as the figure shows. Also, the green line represents the feedback and monitoring of the condition of output voltage of the Cuk converter and the battery's charging or discharging current and State of Charge (SoC). The red line represents its control over the multi-switch, which plays an important role in the whole design.

During normal driving state of the EV, the multi-switch is connected to one battery at a time. It would switches to another battery after a certain period. During special condition, the multi-switch would follow rules to handle the connection. For example, during the starting-up and braking state, the multi-switch would connect more than one battery, to avoid unstable power flow. If the SoC of one battery is too low, the multi-switch would not connect it until being charged.

Now researchers are trying to apply super-capacitors to replace part of the EV battery as the power source and storage. Generally one single super-capacitor could only provide 1-5V voltage, thus it must be used in series to improve the output voltage. Cuk converter has the advantage of boosting or reducing DC voltage freely, so it is a good method that combines Cuk converter and super capacitors together. Whereas the disadvantage is the whole system becomes more complicated and the design of multi-switch is a bit harder with higher cost.

V. Conclusion

This paper represents some advanced research and technology of batteries and compares them one by one, especially those adopted by flagship EV automakers. Besides, the paper studies the application in EV of Cuk converter, which can be regarded as a combination of boost converter and buck converter, on the low voltage side DC supply electric vehicles together with the batteries, and even super-capacitors which have unique characteristics. Simulation of the Cuk converter is conducted which shows stable operation. Further research of multi-switching together with Cuk converter is given which solve the problem of start-up and braking pulse together with the interrupt of battery state. There is great potential for the application of Cuk converter in EV platform because of a series of unique advantages and feature.

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BIOGRAPHY

Wenzheng Xu received his B.E.E. degree from the Department of Electrical Engineering , Beijing Jiaotong University, Beijing, China, in 2012, and received the M.Sc. degree from Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong, in 2013. He is currently working toward the Ph.D. degree in the Department of Electrical Engineering, the Hong Kong Polytechnic University.

From April to September in 2013, he was a part-time research assistant in Department of Electrical and Electronic Engineering in the University of Hong Kong, where he was involved in researches about smart grid development in China. From September 2013 to June 2015, he was a full-time research associate in Department of Electrical Engineering in the Hong Kong Polytechnic University, where he was the team leader for a silicon-carbide power devices based dc-dc converter project. His research interest includes power electronics topologies and control for switch mode converters.

K.W.E.Cheng obtained his BSc and PhD degrees both from the University of Bath in 1987 and 1990 respectively. Before he joined the Hong Kong Polytechnic University in 1997, he was with Lucas Aerospace, United Kingdom as a Principal Engineer.

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Dr K.W. Chan received his BSc(Hons) and PhD Degrees in Electronic and Electrical Engineering from the University of Bath (UK) in 1988 and 1992, respectively. His doctoral research study was in the area of real-time power system transient stability simulation using parallel processing techniques.

From 1993 to 1997 Dr Chan was with the Power System and Energy Group at the University of Bath as a research officer. A number of industrial strength real-time power system simulators were developed and applied in the National Grid Control Centre, UK for daily monitoring and protection of the UK National Grid. Dr Chan joined the department of Electrical Engineering of the Hong Kong Polytechnic University in 1998 as a lecturer and subsequently promoted to Assistant Professor in 2005. So far, Dr Chan has secured over 37 research projects, including 6 RGC-ERG, 2 RGC-Large Equipment, and 2 NSF projects with total funding over $15.4M.