Indian Journal of Science and Technology, *Vol 8(19), DOI: 10.17485/ijst/2015/v8i19/76707, August 2015*

ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Embedded Control Scheme of Stand-Alone Regenerative Braking System using Supercapacitors

Sneha Mohan Patil and S. R. S. Prabaharan*

School of Electronics Engineering, VIT University, Chennai Campus, Chennai - 600127, Tamil Nadu, India;
snehapatil1822@gmail.com, prabaharan.srs@vit.ac.in

Abstract

The concept of Energy Storage System (ESS) in Electric Vehicle (EV) is the most important challenging part of EV design. Batteries are the main electric ESS which has mostly used for supplying the energy requests and charging the Batteries is a major concern. Supercapacitors based on their specifications are effective for this role. Very high power delivery and fast charging are the most famous parameters of supercapacitors which make them suitable for EVs. This paper describes a novel scheme to manage multiple supercapacitor banks which will assist in continuous storing of braking energy and expend on to the load once fully charged. In the present design, the system monitors the State-Of-Charge (SOC) of each supercapacitor in the bank during each charge/discharge sequence for efficient utilization of produced energy via braking. Supercapacitor bank is designed by connecting the supercapacitor cells in series to increase the rated voltage. Nevertheless, each supercapacitor bank may suffer from the unstable charging consequence due to its inherent characteristic between each supercapacitor in the bank even though all these supercapacitors having the same specification. It is imperative to design a balancing circuit to evenly distribute the stored energy failing which the imbalance will cause some supercapacitors in the bank to reach the overcharging state. The present design prevents the supercapacitor bank from unwanted overcharging and helps protecting other supercapacitors in the bank itself. In this paper, we present a new control scheme which controls and monitors charge/discharge mechanism of supercapacitor bank with a view to incorporate the balancing circuit design for regenerative braking mechanism developed as part of the work.

Keywords: DC-DC Converter, Embedded Control, Nuvoton ARM Cortex M0, Regenerative Braking, Supercapacitors

1. Introduction

At present, urban transportation is primarily dominated by fossil fuels as source of energy for the combustion equipped engines. Increased traffic congestion leads to stop-and-go traffic which consumes more fuel to be burnt releasing toxic pollution. Thus, the electric mobility has been thought as futuristic means of transportation which obviously minimizes pollution from automobile. The increasing demand of the high energy sources is a major concern worldwide and also rapidly increase in the percentage of the emission of hazardous greenhouse gases due to high road traffic transport. These emission of harmful gases could be reduced using Electric Vehicles (EVs). However, there has been some limitation over EVs like energy backup which totally depends on the battery power. But the power management systems involving supercapacitors had found great interest in the power engineering arena and various control schemes and topologies have been proposed recently for numerous supercapacitor augmented applications.

In the context of electric mobility, regenerative braking is a novel technological marvel to harnessing electric energy from braking mechanical energy into usable electric energy which can be stored for later use in the form of battery storage. The limitation on the quick charging ability of Li-Ion batteries commonly found in Electric Vehicles (EVs) of the decade may not be of choice for storing such

**Author for correspondence*

instantaneous electric energy via regenerative braking. This means that instantly generated energy cannot be stored in batteries for obvious reasons as the batteries are meant for programmed charging and they are unsuitable to absorb electric quickly when available.

Alternatively, supercapacitors surpass the obvious demerits of storage limitations centered on batteries. That is, supercapacitors are found to be superior in terms of quick absorption of such instant energy produced by virtue of its inherent technology. In fact, the battery has by far thought to be a high energy storage media. In contrast, supercapacitors offer high power density having quick charging ability and acting as a buffer to absorb instantaneous electric impulse produced during braking

Sang young Park et al.[1] proposed a power electronic interface for supercapacitor-based hybrid energy storage systems and Battery Management for Electric Vehicle. Keeping this in mind, the use of braking energy through regenerative braking mechanism, we have developed a new design protocol using supercapacitors as energy buffer by virtue of its quick electrical energy storage capabilities. Supercapacitors also known as Electric Double-Layer Capacitor (EDLC) has unique characteristics for hundreds thousands of cycles over and over again without degradation unlike batteries offering greater power density. Besides that supercapacitors exhibit fast charging and discharging profile with linear voltage profile with definite SOC. Nevertheless, it suffers from a low rated voltage as working potential.

Therefore, owing to poor voltage rating of supercapacitors, it is difficult to be employed in high voltage applications and so obviously one has to connect as many supercapacitors in series. This poses several issues while charging all supercapacitors simultaneously. That is, balancing of charging storage is a challenging issue as this becomes mandatory. SCs are used in serial and/or serious/parallel combination. In the present work, we have designed and tested a new control strategy for a supercapacitor for use in regenerative braking system developed. One of the goals of the design is to manage the SC bank via regenerative braking energy. Thus, the energy generated from regenerative braking and quick charge absorbing features of supercapacitors are defined as the novelty of the designed for the first time. The stored energy can be connected to the load for discharging. In recent years, there is numerous power-flow management and control strategies proposed for Hybrid Electric Vehicle (HEV) based applications[2]. Zhang et al.[3,4] researched on active hybrid system control strategies which proposed a charge sharing mechanisms in storage elements involving supercapacitors, while AM Musat et al.[5] presented the dynamic adapting topologies for a hybrid storage systems. To manage the multiple supercapacitors in series, we have devised a charge balancing control scheme to avoid over charging condition. The basic idea of proposed system is illustrated in Figure 1. Figure 1 describes the overall flow of the system.

The braking electrical energy produced from the generator system is shown in Figure 1. The generated energy is stored via DC-DC power converters via a relay switch controls into the supercapacitors. Controller scheme monitors and controls the supercapacitor charge/discharge cycle and also monitors the SOC of the supercapacitor. The stored energy is given to the load for discharge. The primary goal is to develop a supercapacitor based energy storage control system using embedded platform to make intelligent decisions to take advantage of regenerative braking energy.

2. Regenerative Braking System

In recent years, regenerative braking has become a renounced embedded feature of EV's. A regenerative braking system recaptures and stores the kinetic energy in a reusable manner[6]. We present here our success in design fabrication and validation of a proof of concept regenerative braking model with real time energy storage via super capacitor banks. The novelty is that we have devised an embedded protocol to transfer the energy produced during braking into super capacitor via charge balancing system duly controlled by a NUC140 ARM Cortex m0 processor. Further, we discuss the obtained test result with validation parameter such as charge/

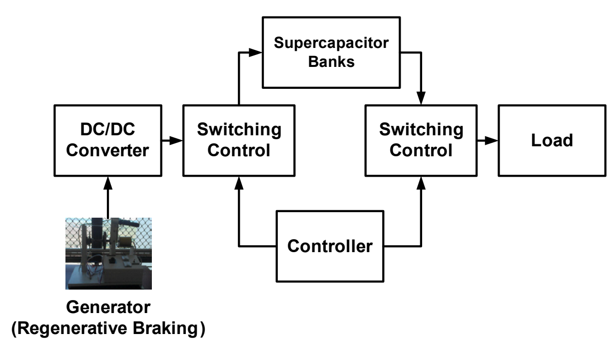

Figure 1. Schematic of a proposed supercapacitor based energy storage system for Regenerative braking system.

discharge state. The design of regenerative braking model is comprised of a DC electric motor and a flywheel with 12V battery powered supply. The braking energy conversion is done by disconnecting the power supply to the motor. Later the momentum in flywheel causes it to continue to rotate at certain reducing velocity in free rotation. Then after, braking model connects to the super capacitors while being isolated from the battery supply through the dc-dc converter and current regulator. When the brake is released, it reconnects the flywheel to the motor. This isolation is provided by the relay switch and is explained in further section.

The circuit schematic of the electric model of regenerative braking is shown in Figure 2. In the schematic shown in Figure 2, when the main switch and the limit switch is closed, the relay coil it successively gets magnetized. An energized relay coil will force the normally open switch to close circuit and vice-versa. In the braking situation, where the brake lever is pressed to trigger the limit switch, then the limit switch will become an open connection that will cause the current to flow to the supercapacitor bank (see arrow in Figure 2).

3. DC-DC Converter

An energy harvesting circuit is essential to deliver the available input braking energy to supercapacitors. DC-DC converters are a specific type of energy transfer circuits that adjust the amount of energy taken from the input in order to keep their output voltage level at a certain value. The purpose of a DC-DC converter ensures continuous flow of charge from the flywheel to the super capacitor bank during regenerative braking period. The DC-DC boost converter circuit schematic is shown in Figure 3. The sense resistor works as reference input for the controller. A 10mH inductor serves as tool to boost the output voltage at OFF state of the converter. The diode is connected to cease the flow of the charge from the supercapacitor to back into the circuit and duty cycle for the converter controlled by MOSFET.

The DC-DC converter is able to produce a different level of boosting since the output of the controller produces square wave in varying duty cycle and has been used as a switch to control the converter. The controller circuit schematic is shown in Figure 4 designed in combination of a differentiator, an integrator and a Pulse Width Modulator (PWM) generator. This will ensure the output of the DC-DC converter is always higher than the supercapacitor bank.

4. Supercapacitor Energy Storage

The super capacitor is an optimized standard for the energy storage[7-10]. They are suitable for variety of areas

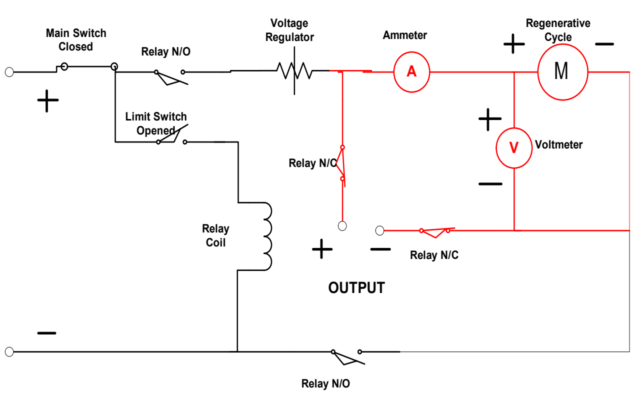

Figure 2. Electrical circuit schematic of a Regenerative braking system.

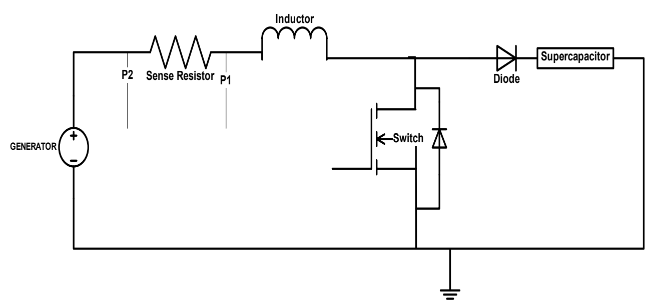

Figure 3. The implementation of DC-DC boost converter ensuring the proper flow of the voltage.

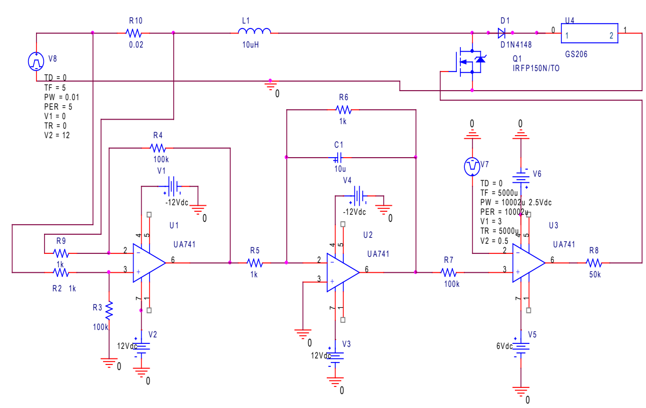

Figure 4. The implementation of the DC-DC boost converter along with embedded controller.

such as industrial equipment, wind energy solar energy, electrical vehicles, hybrid cars and consumer electronics. The supercapacitors are available in a various range of capacitance having a long lifespan. The supercapacitors are very highly efficient due to its low Equivalent Series Resistance (ESR), high current capability, wide temperature range, long life cycle, ease of maintenance. The fast charge/discharge rate makes supercapacitor more attractive in energy recovery systems as buffer.

5. Intelligent Control Algorithm Design

The proposed algorithm of the system in this paper is illustrated in Figure 5. It should be expected that at all times all supercapacitors cannot be simultaneously charged and discharged. According to algorithm only one bank will be charged and another bank will be in discharged state. As shown in Figure 6, the State of Charge (SOC) of the supercapacitor is monitored and controlled by an algorithm specifically designed for the purpose. The designed algorithm works according to SOC of the supercapacitor. The continuous monitoring of the SOC through the ADC channel for finding the supercapacitor charge/discharge state. With respect to the supercapacitor state, it will be connected to charge/discharge module circuitry. The decisions made by embedded processor ARM Cortex M0 controller, having five GPIO ports each of 16 bits length, advanced timers, serial and parallel communication protocols etc. This state of the

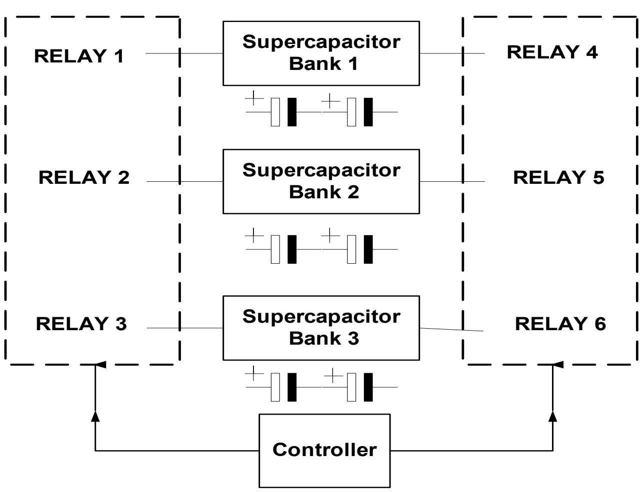

Figure 5. The schematic of the proposed algorithm to capture the electrical energy from regenerative braking.

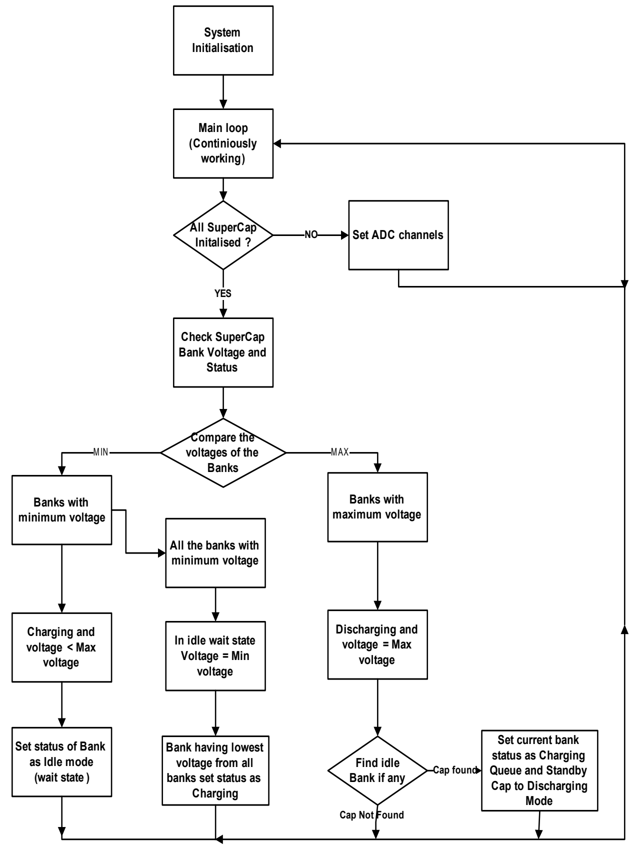

Figure 6. The Flowchart of the control algorithm employed for the implementation.

supercapacitor changes according to voltage level of the supercapacitor bank named as Bank 0, Bank 1, and Bank 2 and this structure created in software to define current state of the supercapacitor banks. The flowchart of the control algorithm which implemented to prove the proposed idea depicted in Figure 6. If at all the banks will have minimum or below minimum threshold, then the first bank will be charged and other two banks will be in idle state. Then second will be charged and the first will begin to discharge while the third will continue to remain in idle state itself. The control algorithm works based on states of the supercapacitor as shown in Table 1.

Table 1. The Supercapacitor Bank Status (Figure 8)

Bank 1	Bank 2	Bank 3
Charging	Discharging	Idle
Discharging	Idle	Charging
Idle	Charging	Discharging

6. Experimental Results

The designed regenerative model setup illustrated in Figure 7 which exactly works as expected. After applying the brake the system generates voltage around 2-3 V. The hardware setup shown in Figure 7, shows that controller system produces the square wave once the integrated signal i.e. input from braking modulated with the triangular wave is recorded on DSO. The system setup connected to Nuvoton controller with the supercapacitor along with relay switch. The fully charged voltage of the supercapacitor bank around 2.1 V to 2.5 V is set in the programming as preset limit. After initialization according to voltage level relay switches are getting on and off for connecting respective bank to the respective module for charge/discharge cycle. In a developed system every time a bank will be in an idle mode meaning that it will not be connected to either of charge/discharge module. The system configuration results recorded and examined. In the shown in Figure 8 for example, one condition represented as the bank 1 and the bank 2 was fully charged and the bank 3 was not fully charged. According to the control strategy bank 3 showed in charging mode connected to charging model by respective relay and bank 2 was maximum among all the bank started to discharge. The bank status is displayed on LCD is shown in Figure 8. In the present design, we have employed Maxwell 10F 2.5V supercapacitors as energy buffer. In the system setup after comparing the voltage of each bank is shown on LCD indicating the states. The intelligent embedded system is programmed using C language.

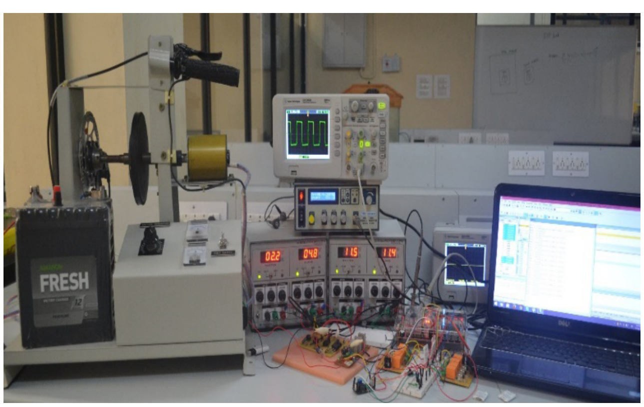

Figure 7. The working prototype model of Regenerative braking system designed to replicate the brake system (as in EVs) integrated with controller board and supercapacitors.

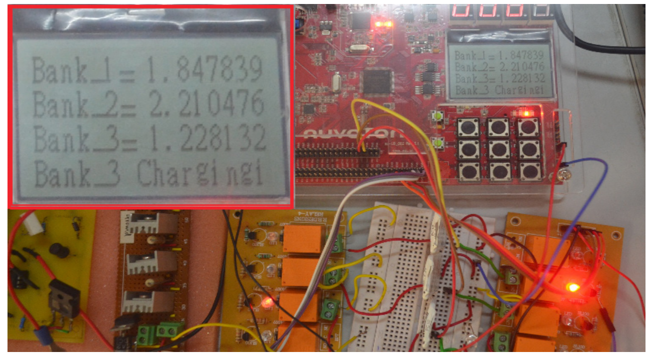

Figure 8. The control algorithm setup combining Nuvoton NUC140 cortex controller, relay and the supercapacitor (Insert shows the bank status).

7. Conclusion and Future Work

In this paper, it is demonstrated that supercapacitor augmented regenerative braking system in which supercapacitors were regarded as energy buffers. To enable the energy storage across supercapacitors, an embedded management system employing a switch control unit and ARM processor was designed and validated. An algorithm was successfully designed which monitors the SOC of supercapacitors in a bank in turn to provide stored electrical energy to the load. Further, the proof of concept of managing the supercapacitor bank in regenerative braking environment is verified in a prototype model adapted and designed. Further work is underway to expend energy stored in the supercapacitor bank to the batteries and will be reported elsewhere.

8. References

1. Park S, Kim Y, Chang N. Hybrid energy storage and battery management for electric vehicles. The 50th Annual Design Automation Conference; 2013 May 29-Jun 07; Austin, TX, USA. p. 1–6.
2. Brabetz L, Ayeb M, Tellmann D. Efficient vehicle power supply by adaptive energy, charge and heat management of an alternator - super capacitor system. SAE Int J Passeng Cars – Electron Electr Syst. 2009 Apr; 2(1):359–66.
3. Zhang Y, Jiang Z, Yu X. Control strategies for battery/supercapacitor hybrid energy storage systems. IEEE Energy 2030 Conference; 2008 Nov 17-18; Atlanta, GA. p. 1–6.
4. Carter R, Cruden A. Strategies for control of a battery/supercapacitor system in an electric vehicle. International SPEEDAM Symposium; 2008 Jun 11-13; Ischia. p. 727–32.

5. Musat AM, Carp M, Borza P, Musat R, Sojref D. Hybrid storage systems and dynamic adapting topologies for vehicle applications. 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), Brasov; 2012 May 24–26; IEEE; p. 1559–66.
6. Paredes MGSP, Pomilio JA, Santos AA. Combined regenerative and mechanical braking in Electric Vehicle. 2013 Brazilian Power Electronics Conference (COBEP); 2013 Oct 27-31; Gramado. p. 935–41.
7. Farcas C, Petreus D, Ciocan I, Palaghita N. Modeling and simulation of supercapacitors. 15th International Symposium on Design and Technology of Electronics Packages (SIITME); 2009 Sept 17-20; Gyula. p. 195–200.
8. Choi M, Kim S, Seo S. Energy management optimization in a battery/supercapacitor hybrid energy storage system. IEEE Transactions on Smart Grid. 2012 Mar; 3(1):463–72.
9. Wangsupphapholl A, Idris NRN, Jusoh A, Muhamad ND, Yao LW. The Energy Management Control Strategy for Electric Vehicle Applications. 2014 International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE 2014); 2014 Mar 19-21; Pattaya, Thailand. p. 1–5.
10. Zandi M, Payman A, Martin JP, Pierfederici S, Davat B, Meibody-Tabar F. Energy management of a fuel cell/supercapacitor/battery power source for electric vehicular applications. IEEE Transactions on Vehicular Technology. 2011 Feb; 60(2):433–7.