CHAPTER 2

LITERATURE REVIEW

This Chapter gives comparative study between Battery and Supercapacitor. Evolution of the Supercapacitor is described here. It also elaborates the study of present possible topologies for their combinations and energy flow. This chapter also describes the classification of DC/DC converters. Various modes of research – Braking and acceleration are also explained here.

2.1 OVERVIEW:

The period 1970s has faced the faced energy crisis and it can be seen that EVs are new area of research. Since then, electric vehicles were considered the domain of automotive and mechanical engineers and hence not a popular topic of research for electrical engineers until the middle of the 1990s. Later on, the innovators has reintroduced all the electrical propulsion system and made the area again open for the electrical engineers to serve the society by modifying the automobile domain to the electrical and power electronics domain. With IEEE section only, there are more than 18000 conference presentation, Journal and Magazine publications of more than 2800 and 6 standards related to EV and HEV up to March, 2016 and still the number is increasing. A histogram taken from the IEEE xplore (Fig. 2.1) shows, "the last decade has shown an increase in publications by the electrical engineering community in this area of research. It does however show those electric vehicles and the associated problems of organizing power and energy in fact growing research interests."

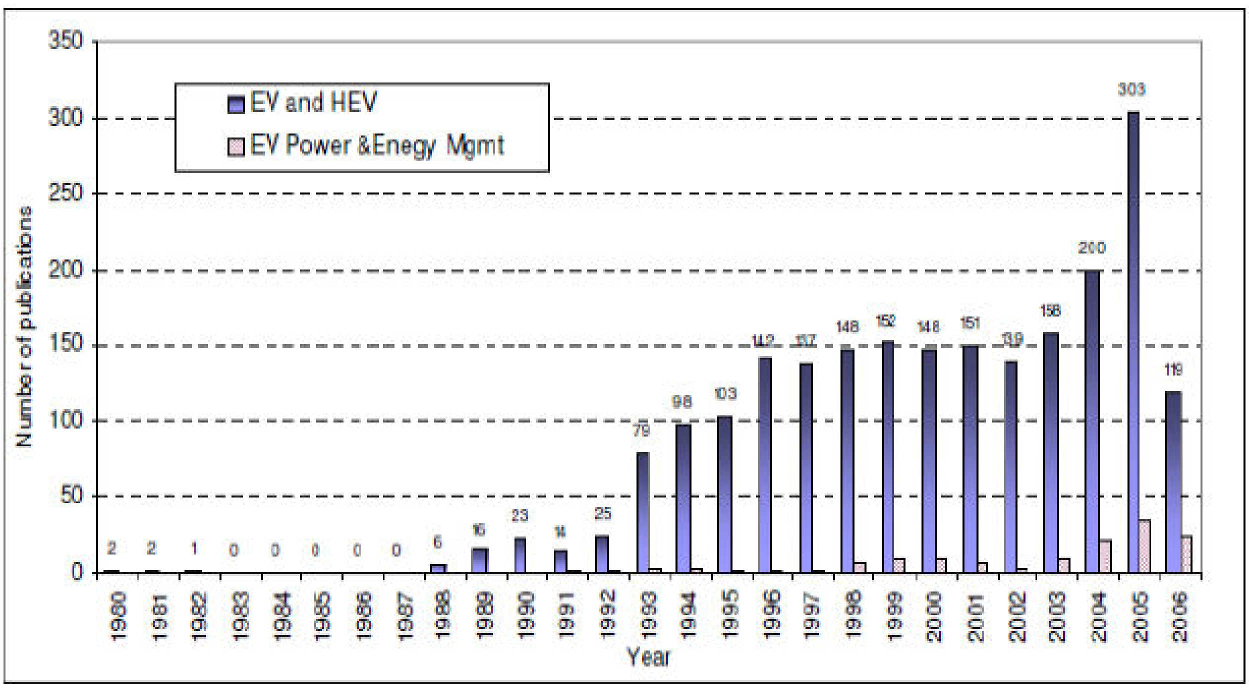

Fig.2. 1 IET / IEEE Publication on Electric Vehicles – Extracted from IEEE Xplore

EV has taken its place as a new category of electrical engineering and automobile engineering with unique features [18]. As such, there are abundant opportunities for research and development offerings in the field of electrical engineering because some industrial standards are being framed now [21]. Firstly the research is focused in providing the electrical source for the mechanical propulsion which has slowly changed in the matter of controlling the facilities and ease of electrical power supply with less maintenance made the excellent over come from the mechanical research. "The electric vehicle power and energy management problem has had a range of definitions. It has been described from the point of view as a purely mathematical optimization problem to an electrical design, configuration and component problem. Consensus of opinions in recent reports indicates that it is a problem that is best approached at a systems level". [23] Evidently, the cost of petroleum products and emission of greenhouse gases made necessity for the invention in electrical depended vehicle to survive the world.

The following section allows understanding the methods and domains of vehicles where research work conducted by a community in the area of vehicular power and energy management as well as electric vehicular technology is reviewed.

2.2 MULTIPLE ENERGY STORAGE SYSTEMS IN AN EV:

Hybridization of multiple energy storage systems requires understanding the main characteristics of each source so that each can be more efficiently utilized. Especially for EVs, it is basically integrating energy systems having high-energy capacity with systems having high power delivery capabilities. By thorough research, energy storage systems capable of supplying continuous power with minimum reduction in their age have greater energy storage capabilities when compared to the pulse power supplying devices. A combinational usage of these energy storage systems in a synergistic configuration exploits the effective use of power whenever necessary whilst maximizing the storage devices operational age. Energy storages systems can be classified according to their total energy storage capacity, energy density, and pulse power deliverability; hence a multi-criteria selection is created based upon the expected power demand profile.

"In electric vehicles, notching and braking period require peak power to be supplied from and transferred to the energy storage system. For a battery sourced EV, augmenting the battery pack with a high power capacity system results in reduced high power stresses impressed on the battery" represented in [16]. As per the power demand profile expected, an EV needs transient power supplier to accelerate the vehicle. On the contrary, pulse power device with capacity of the storing energy produced during regenerative braking is advantageous. It must have also high current capacity. Essentially, peak power can be generated and stored electro-mechanically via a flywheel system, electrochemically via capacitors or by other forms of peak power buffers. Having multiple energy storage systems in an EV makes compulsion to find a method of integration for power sharing between such energy systems.

2.3 POWER & ENERGY MANAGEMENT OF MULTIPLE ENERGY STORAGE SYSTEMS:

Power management among the various energy storage systems can be precisely described as one of the method here:

"Considering the block diagram of Fig.2.2, the contribution of power to meet a particular load requirement is divided between two energy storage types. W_1 and W_2 represent the weighing factors corresponding to the proportion of energy extracted from the two storage units. Due to the difference in Power to Energy ratios of Type 1 and Type 2 systems, a strategy to coordinate power flow by dynamically varying the weighting factors is required. For successful operation of the vehicle, the power availability must at least meet the power requirement", suggested by Cao and Emadi. This has to be done with further consideration to the system constraints. Fig.2.2 explains a typical power management configuration of Type 1 and Type 2, in this case, battery and SC storage system to fulfill the load demands.

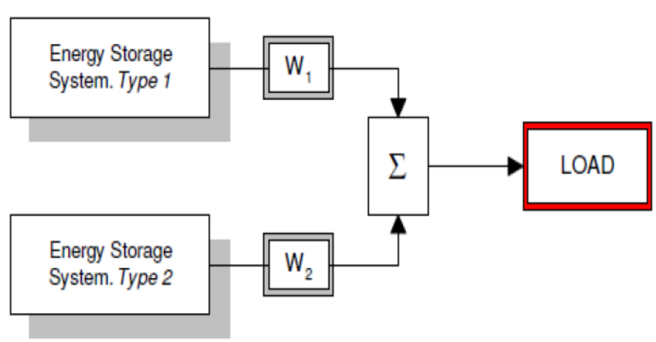

Fig.2. 2 Power Split between two energy sources

Mamadou Bailo Camara says that apart from the main energy source (oil or gas), hybrid vehicle is to add other source combination of reversible energy storage devices like fly-wheels, SC, and batteries [23]. These technologies that associate supercapacitors and batteries, supercapacitors have a power density that is 10-100 times larger than that of batteries. The battery and SC model, buck-boost converter topology, operation inverse model of buck-boost converter and its control strategies are introduced. Different series and parallel connections of battery converter configurations can be designed for HEVs.

Caratozzolo, Sera and Riera [24] also suggested, "An energy management strategy derived from a heuristically composed rule-base. Due to the highly non-linear nature of EV and HEV drivelines, the authors suggested a rule-base approach to provide an employable scheme for intercession of power flow under various operating modes of the vehicle." Phaneendra baboon bobba say that Hybrid energy storage system uses more than one source –in Electrical vehicle, Battery, SCs and Fuel-cell [25].these sources are used under the controlled system in necessary situations. EVs require high power density during acceleration or in starting and high energy density to travel more distance in single charge. Battery and SCs combination provide this facility to the system. HSS connected one side malty input DC-DC converter and other side connected load. For the system design concern the modelling of battery, SCs and its various operating rang with convertor topology is involved.

According to Langari and Won [26], optimal control methods, due to its dependency on the drive cycles used to generate the control actions may not yield optimal power split for misclassified or arbitrary drive cycles. As an alternative, they proposed a concept of a fuzzy logic (FL) based energy management to capture driving situational awareness [27, 28].

2.4 EV ENABLING TECHNOLOGY – THE SUPERCAPACITOR

More commonly referred to as "Supercapacitors", these devices are able to operate at power levels high above that of conventional batteries and can store a considerably high amount of energy above the energy capacity of conventional capacitors. These devices yields one of the latest innovations in the field of electrical energy storage devices [31], and lend itself as a significant technology enabler for future of electric and hybrid electric vehicles. As a relatively new energy storage device, EDLC technology warrants a brief historical introduction. The first high capacity electrochemical capacitor device was patented in 1957 (US Patent 2800616) [32]. In [33], "Developed by Howard Becker of General Electric Company, the device was of a basic construction consisting of porous carbon electrodes. Becker described the large capacitive phenomena of the device but acknowledged that the exact reason for this exceptionally large capacitance was not fully known at the time. Subsequently, in 1966, Robert Rightmire of Standard Oil Company Cleveland Ohio (SOHIO) introduced a double layer capacitor utilizing porous carbon in a non-aqueous electrolyte (US Patent 3288641). Four years later, Donald Boos, also with SOHIO, patented another device that used a carbon paste soaked in an electrolyte (US Patent 3536963), which SOHIO later put into production, thus making them the first company to market high capacitance devices. Between 1975 and 1980, Brian Conway carried out extensive fundamental work on EDLCs and also ruthenium oxide type electrochemical capacitors. A detailed account of this can be found in Conway's scientific monograph", studied by Conway. Conway was also the first to use the term "supercapacitor". However, in 1971, the Nippon Electric Company (NEC) produced the first commercially successful high capacitance device under the same name, "supercapacitor". G. L. Bullard [35] suggested that the SC, developed by Pinnacle Research Institute, Inc. represents a new and vastly improved type of double layer capacitor. Low resistance and extremely low inductance provides the SC very high power density and fast rise time as well. As a double layer capacitor is not constrained by the same limitations as dielectric capacitors. According to Helmholtz model, positive and negative particles at the interface, represented as a simple parallel plate capacitor. It was more than a decade later those EDLC devices found presence in vehicular applications [36]. Interestingly enough, it is the advent of EDLCs in vehicle applications that has created a synergistic effect in terms of technology awareness of EDLCs and fuelled a popularity increase in hybrid and electric vehicle. Some conjectures can be made from Figure 2.3 to support the pervious statement. As the histogram shows, the increasing interests in EVs and HEVs coincide with the decade old introduction of EDLCs in vehicle applications. In retrospect, the increasing attention to EV power and energy management can also be linked to the introduction of this technology enabler to the vehicular application domain. Fig.2.3 explains the progress of EDLCs development since 1957.

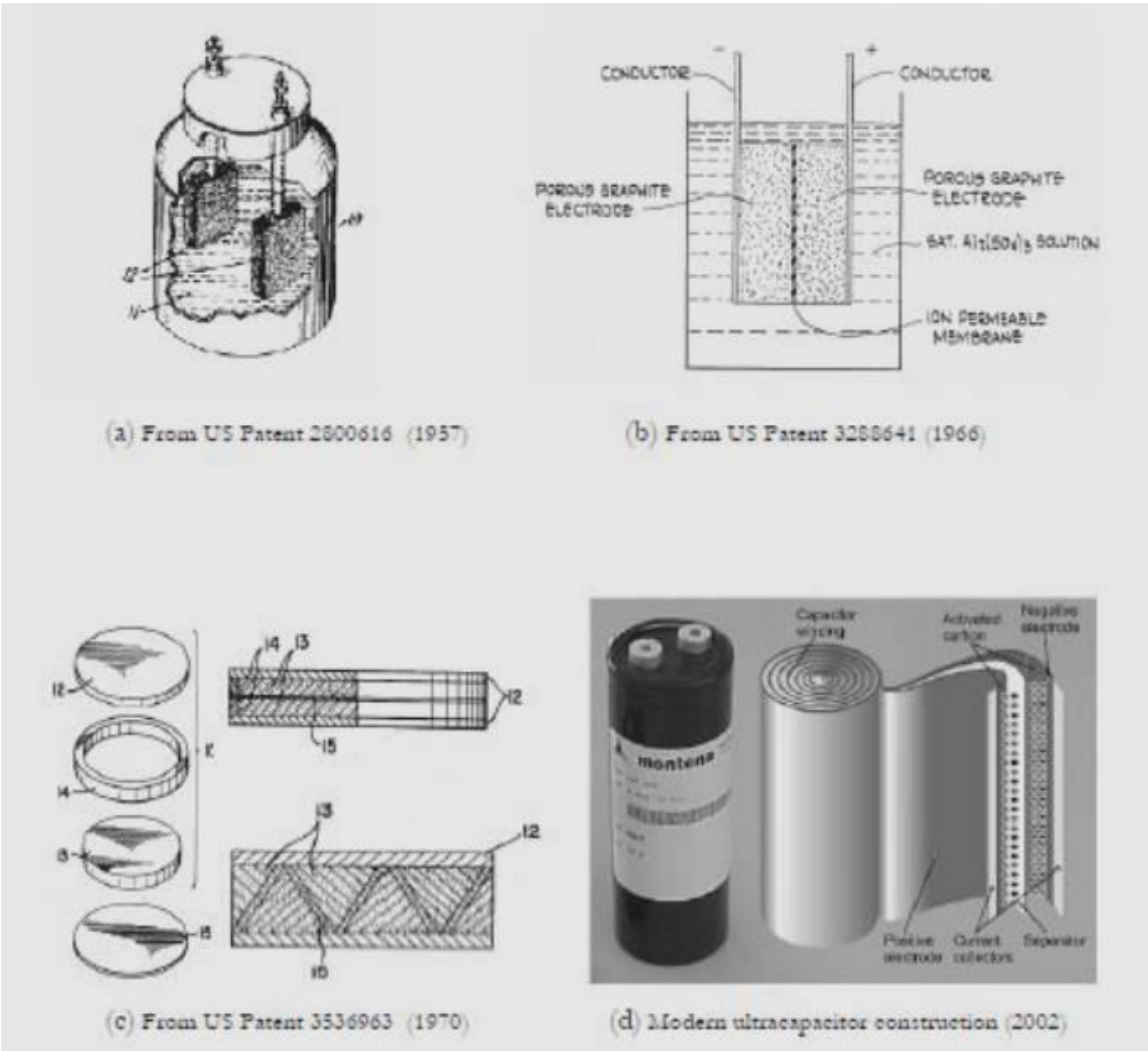

Fig.2.3 Evolution of the EDLC Technology

The terms "Supercapacitor" and "Electrochemical Double Layer Capacitor" have been used indiscriminately in literature in reference to high capacitance devices. Huggins [37] identified, "This uncertainly in terminology and made a distinction between these types of capacitors in terms of their storage methods and redox pseudo-capacitance. However, it is generally recognized that these terms are interchangeable depending on the manufacturer. Throughout the rest of this dissertation, the term

"Supercapacitor" will be adopted for the sole purpose of keeping with consistency when presenting the actual device used in the experimental part of the work." A listing of current manufacturers of these devices and their respective device names are shown in Table 2.1.

Table 2.1 Manufacturers of High Capacitance Devices [38]

MANUFACTURER	DEVICE NAME	CAPACITANCE (F)
AVX	BESTCAP	0.022 - 0.56
CAP-XX	SUPERCAPACITOR	0.09 - 2.8
COOPER	POWERSTOR	0.47 – 50
ELNA	DYNACAP	0.033 – 100
ESMA	CAPACITOR MODULES	100 – 8000
EPOCS	ULTRACAPACITORS	5 – 5000
EVANS	CAPATTERY	0.01 - 11.5
KOLD BAN	KAPOWER	1000
MAXWELL	ULTRACAPACITORS	1.8 – 2600
NEC	SUPERCAPACITOR	0.01 - 6.5
NESS	EDLC	10 – 3500
PANASONIC	GOLD CAPACITOR	0.1 - 2000
TAVIRMA	SUPERCAPACITOR	0.13 – 160

Research activities supported by the European Community Joule III [29, 32] program specifically titled, "Development of Supercapacitors for Electric Vehicles" began in 1996. There is substantial evidence in literature to support further development in integration technology of supercapacitors in electric vehicle power systems [38 - 39]. However, the obtainable efficiency enhancement has regularly been contested by a cost factor. Andrew C. Baisden explained, "How to reduce the cost of the battery, the current needs to be decreased and stabilized so it is not very erratic [40]. A new model for an energy source is introduced- a battery in parallel with an SC. The SC can supply a large burst of current, but cannot store much energy. Conversely, the battery can store mass amounts of energy without expensive and inefficient unit; a battery cannot provide the current that SC can. By combining the two energy sources in parallel, the result for the storage and peak current characteristics are presented. The results showed that using this model; one can reduce the cost and increase the efficiency of energy source system. In fact, in 2004, both Miller [47] and Barrade [41] reported a significant cost reduction and projected a further fall towards more favorable cost targets.

2.5 HYBRIDIZATION OF BATTERIES AND SUPERCAPACITORS IN EV POWER SYSTEMS:

Luk and his co researchers found, “Although the high capacitance and high power density characteristics of supercapacitors endorses its feasibility in electric vehicle applications, the energy capacity limitation dictates the need for a much higher energy sustainable source, namely a battery bank. The objective of integrating batteries and supercapacitors is to create an energy storage system with the high energy density attributes of a battery and the high power density of a supercapacitor. In essence, the goal is to explore the advantages of both the devices through supercapacitor hybridization of the two technologies in vehicular power system architecture.” Zhang et. all. And Noshirwan, Kusko [48, 49] concisely described the coordination between this two devices by emulating them. An illustration of power density versus energy density of existing electrical storage devices famously known as “Ragone Chart” is shown in Fig.2.4.

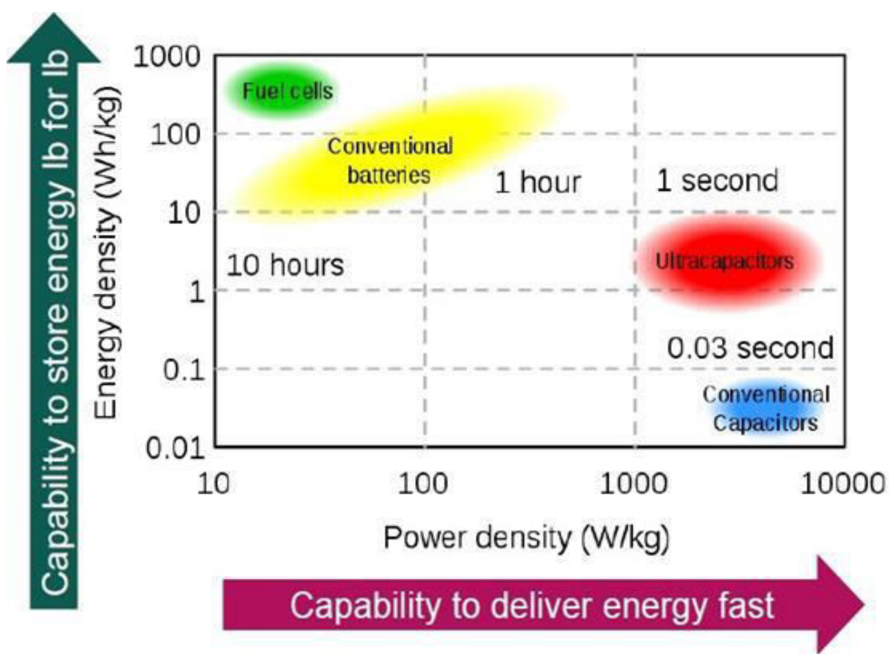

Fig.2.4 Ragone Chart

“The proposition of combining high power density supercapacitors with high energy density batteries was first claimed in 1992. However, the development of supercapacitor systems specifically for vehicular applications only began in recent years.” In 1996, Burke [45] produced a report on the prospective usage of supercapacitors in electric and hybrid electric vehicles. Consequently, the research has developed towards the interaction of the multiple energy storage systems and the method of hybridization to achieve the maximum utilization of each system. This has to be done with particular consideration to the maximum terminal voltage of the supercapacitor system. Side by side, the various models of batteries and SC has supported such researches. Spyker and Nelms [51] looked “At estimated run-time of a SC by clearly showing the simplified model consisting of a battery and supercapacitor configured in such a parallel connection. For the arrangement shown in Fig.2.5, the authors concluded that the supercapacitor is only suitable for low duty cycles, as the battery current surpasses the capacitor current during long pulse durations.”

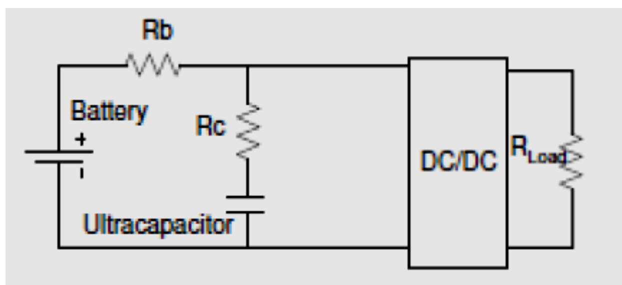

Fig.2.5 Battery- Supercapacitor Supplying a Constant Power Load

In the topology shown in Figure 2.5, the battery potential determines the maximum discharge ability of the supercapacitor. This direct interfacing of the battery and supercapacitor is achieved by initially pre-charging the supercapacitor to a terminal voltage of equal magnitude to the battery open circuit voltage prior to making the parallel connection. For the same configuration, Miller [47] provides, “An analysis for the optimum sizing of the supercapacitor and battery system for a 1610 kg mid-size passenger vehicle. The direct parallel connection of supercapacitors and batteries are said to be in a passive configuration since there is no external intervention of power sharing between the devices.” Fangcheng liu and all say that HSS can improve battery life span and when the battery is charged, the electrons transfer from the anode to cathode through external circuit [42]. The transfer of electrons produces charged particles in the electrolyte. The fast charging system which utilizes the hybrid energy storage system in the vehicle is proposed. The system can realize fast charging process control of battery without any additional devices. The terminal voltage of SC can be controlled in limited range when operation mode switch from charging mode to normal driving mode also introduce basic reflex charger. Fig. 2.7 explains the circuit configurations. Using their Virtual Test Bed (VTB), the authors simulated and experimentally verified an increase of power deliverability with the active configuration. In the passive system, the power sharing capabilities of the devices were dictated by the impedance of the components themselves.

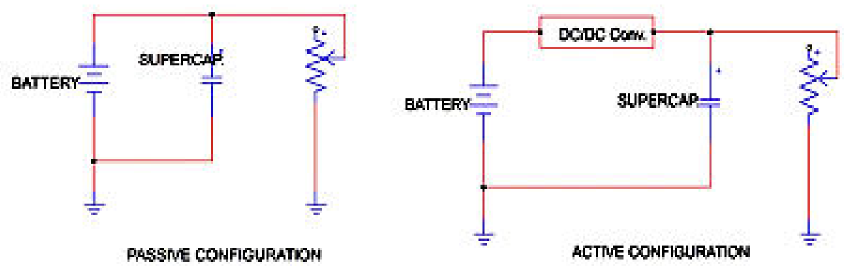

Fig.2.6 Battery-Supercapacitor Systems, Passive and Active Configuration

The active configuration possibilities of batteries and supercapacitors can be classified into two types. The first type has the supercapacitor connected directly across the DC bus and the battery connected through a bi-directional DC-DC converter. The second configuration has the battery on the main DC bus instead. The two configurations are shown in Fig.2.7.

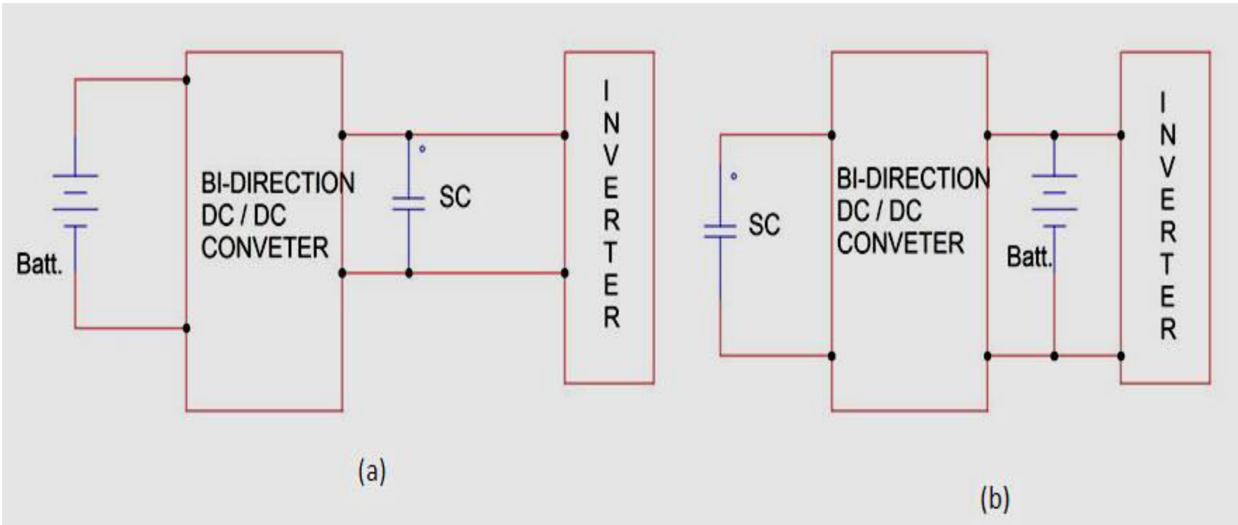

Fig.2.7 Connection Configuration of Supercapacitor to an EV propulsion system

These configurations are examined and stated that having the supercapacitors connected directly to the inverter as shown in Fig.2.7 (a) is likely to produce higher efficiency. Remarkably, in the configuration of Fig.2.7 (a), the overall efficiency of the battery system reduces as the wholesome power from battery is transferred using DC/DC converter. As an initial plan, the authors proposed the following as a simple but idealistic energy management system for EV. Here the buffer unit refers to supercapacitors.

- "The SC unit mainly suffices the peak power"

- "The battery supplies the average power"

- "All the power requirement is directly taken from the battery system in case of DC link achieves a least predicted set level."

- "If the SC unit is fully charged, then regenerative energy is to be diverted to the battery system"

One of the key benefits of integrating supercapacitors with batteries in an electric vehicle propulsion system is the extra ability to harness regenerative energy. It has demonstrated the potential of using supercapacitors as an energy recovery system in larger DC fed applications. By harnessing regenerative energy in a railway vehicle application, the authors expected to increase energy savings by 30%. This gain is possible for vehicles with very large peak to average power ratios and extended regenerative braking events. For road vehicles, the figures are lower and are heavily influenced by vehicle drive cycles and overriding functions such as anti-lock braking, which pre-empts regenerative braking modes [34, 46]. Araujo [47] calculated the number of cells of each source that reduces the overall cost and weight of the vehicle. The filter based approach has been considered to perform the power split among the sources. Linear programming problem to optimize the sizing and non linear programming problem to optimize non causal energy management is introduced for a small EV of the capacity 270 W with a constrained range of operation for EV and SC energy saving upto 7.8% with average observations. Mid-Eum Choi [54] optimized HSS using Multicative-increase-additive-decrease principle with the help of MATLAB simulations. The specification considered are for the renewable smart energy grid upto 2.3 Volt and 5 Amp maximum using Maxwell manufactured BACP series. A simulation study of regenerative energy handling was reported with very promising energy recovery results. The authors proposed connecting a series of supercapacitors through a single Buck-Boost converter, which was then paralleled to a battery pack (see Fig.2.8). As a control scheme, they suggested a primary control loop to establish the supercapacitor current reference and a secondary control loop to generate the required PWM signals for the Buck-Boost converter.

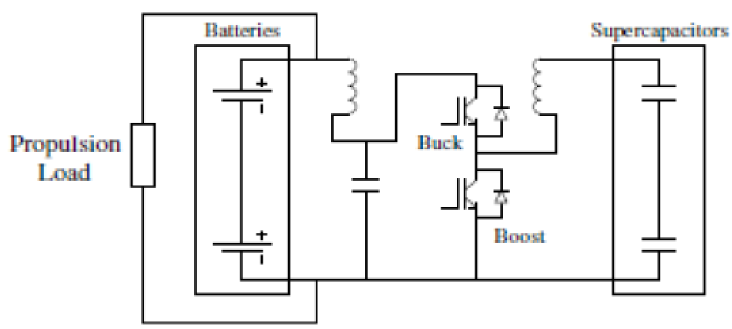

Fig.2.8 Battery-Supercapacitor System with a Buck-Boost Converter

2.6 TYPES OF CONFIGURATIONS :

There are some Schemes which are as follows:

1. ***Cascaded Configuration***
2. ***Battery / Supercapacitor Configuration***

3. ***Supercapacitor/ Battery Configuration***
4. ***Multiple Input Converter Configuration***
5. ***Multiple Converter Configuration***

Proposed Scheme and Various Modes of Operations

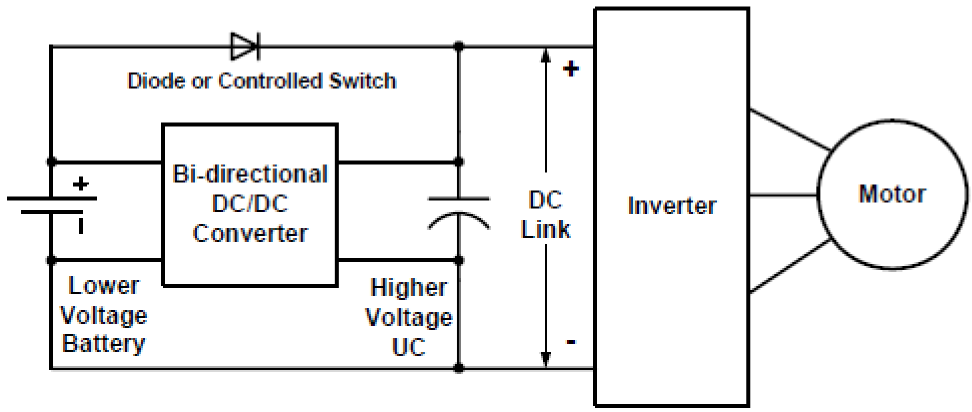

Fig. 2.9 Proposed Scheme Diagram

As suggested by Cao and A. Emadi, "The new battery/SC configuration is proposed and the diagram is illustrated in Fig. 2.9. In this configuration, diverse from the conventional HESS designs, the high voltage DC link is allowed to vary in a predefined ratio. The motor drive is designed to be able to handle the current at the lower voltage. A higher voltage SC bank is always directly connected to the DC link so as to provide peak power demands where as a lower voltage battery is connected to the DC link via a power diode (or a controlled switch). A reduced size bi-directional DC/DC converter is connected between the battery and the SC to convey energy to charge the SC. The DC/DC converter is always controlled to try to maintain the voltage of the SC higher than that of the battery. Therefore in most cases, the diode is reverse biased."

In order to explain the operation of the HESS, an electric vehicle is used here as an example. In an electric vehicle application, the operation of the HESS can be separated into four modes. They are vehicle low and high constant speed operating modes; acceleration mode, and deceleration (regenerative braking) mode.[10] The practical operation of the HESS is complex, but it is a combination of the above four modes. The four operating modes are discussed below in detail.

Mode I: Vehicle Low Constant Speed Operation

The constant speed operation of the vehicle was separated into two modes of operation depending on "If the power of the DC/DC converter (P_{conv}) can cover the power demand (P_{dmd}). If P_{dmd} is equal to or smaller than P_{conv}, we call this operating condition the low constant speed mode. If the vehicle is running at a higher speed and in which P_{dmd} is higher than P_{conv}, we call it the high constant speed mode. Both the low and high constant speed operating modes are ideal modes, since in practical vehicle driving; the power demand is always changing." They are defined here in order to explain the operation of the proposed HESS.

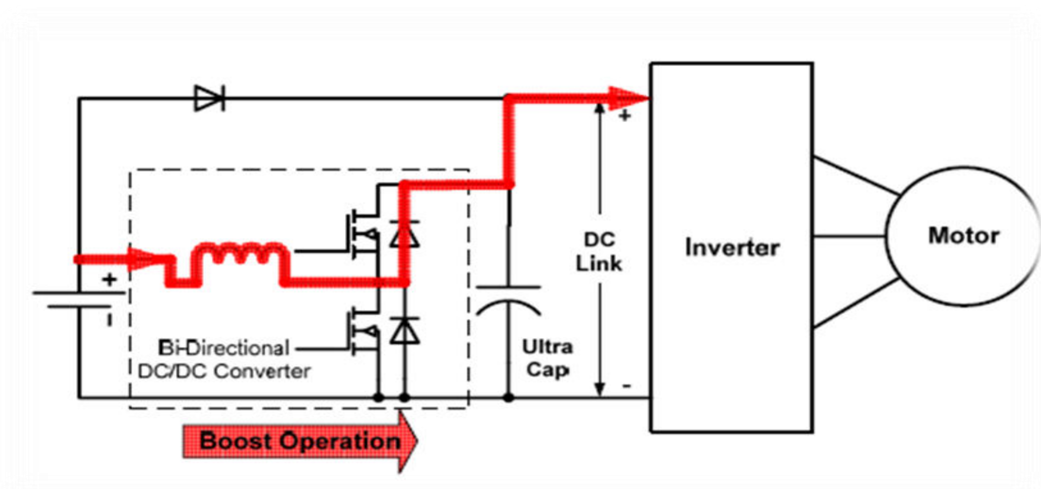

Fig.2.10 Low Constant Speed Operation Energy Flow

Mode II: Vehicle High Constant Speed Operation

In the high constant speed operating mode, "P_{dmd} > P_{conv}, $_{UC}$ V can no longer be maintained higher than V_{Batt}. Therefore, the main power diode is forward biased. The battery is providing energy directly to the motor inverter. In this mode, the DC/DC converter will be turned off" [10]. Fig. 2.11 shows the energy flow of the high constant speed operating mode.

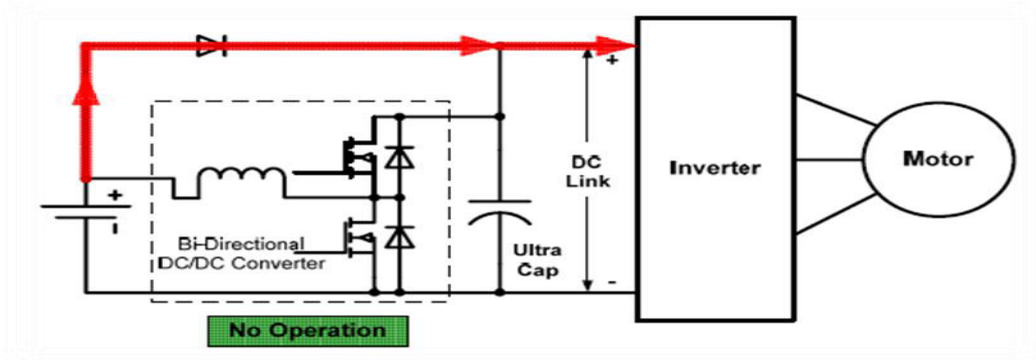

Fig.2.11 High Constant Speed Operation Energy Flow

Mode III: Acceleration

At the beginning of the acceleration mode, "By assumption $_{SC}V > Batt\ V$. Since $P_{conv} < P_{dmd}$, $_{SC}V$ will keep decreasing. Energy from the SC and the DC/DC converter are both supporting the vehicle acceleration." Fig.2.12 explains the energy flow of the acceleration mode phase I.

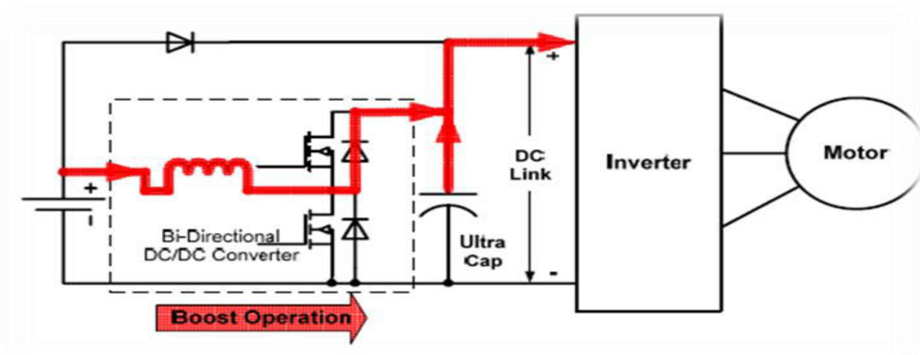

Fig.2.12 Acceleration Mode Phase I Energy Flow

It is to be clearly understood that "With the decreasing of V_{UC}, V_{UC} will drop to the same level as V_{Batt}. When $V_{UC} = Batt\ V$, the battery and SC become directly paralleled through the diode. The system enters the high constant speed operating mode. In the high constant speed operating mode, if P_{dmd} becomes less than P_{conv}, the power difference between P_{conv} and P_{dmd} will be used to charge the SC." [10] The energy flow is illustrated in Figure 2.13.

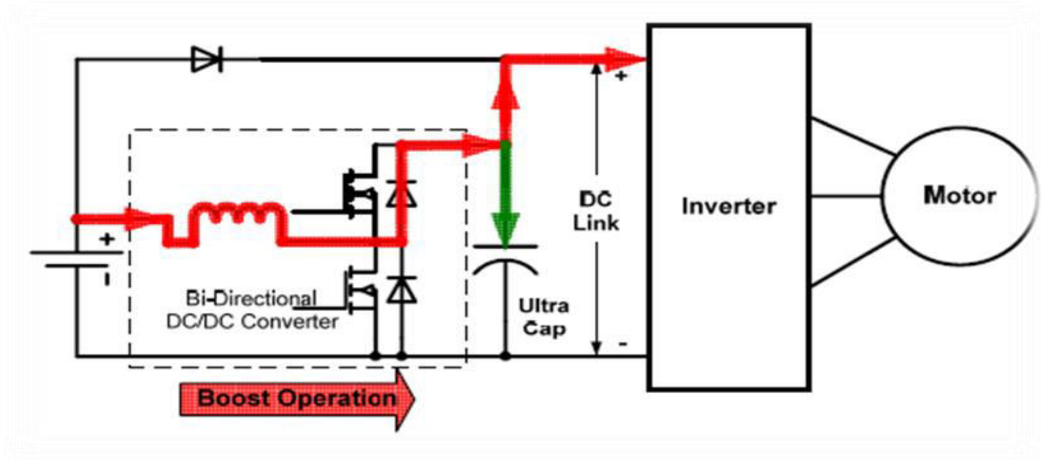

Fig.2.13 Acceleration Mode Phase II Energy Flow

Mode IV: Deceleration (Regenerative Braking)

In the deceleration mode, "For detailing, there are two phases. In phase I, the regenerative power will be injected into the SC only. In phase I, the DC/DC converter might be in boost operation or no operation depending on if V_{sc} is less than the target ultracapacitor voltage S*C* $V_{sc\ tgt}$." The energy flow diagrams for the two conditions are shown in Figures 2.14 and 2.15, respectively.

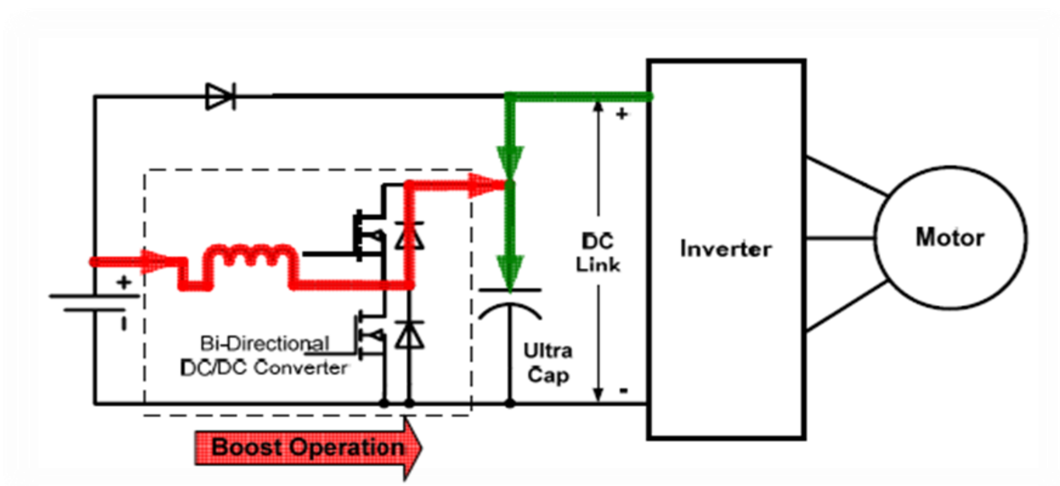

Fig.2.14 Regenerative Braking Phase I Energy Flow {V_{sc} < V_{sc_tgt}}

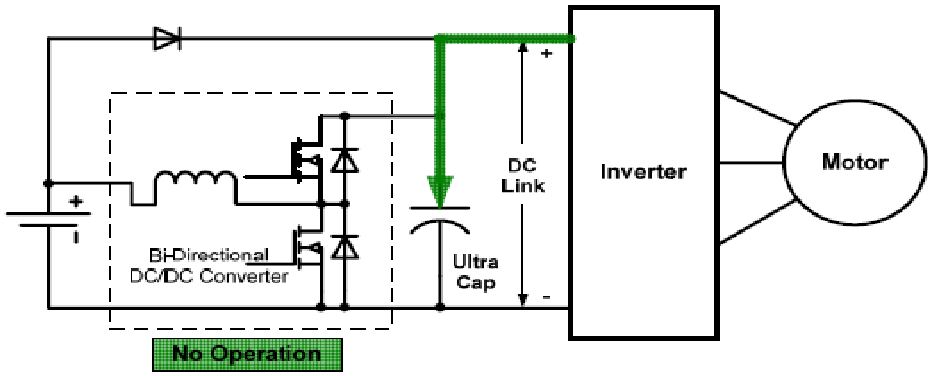

Fig.2.15 Regenerative Braking Phase I Energy Flow when {V_{sc} >=V_{uc_tgt}}

Figure 2.16 shows "The energy flow of the regenerative braking phase II. Phase II describes the working conditions of the continuous regenerative braking. If continuous regenerative braking is needed, in order to make sure $_{SC}$ V is within the safe operating range, the DC/DC converter will work in buck mode to convey the energy from the SC to the battery. When designing the proposed HESS, the ESS components can be properly sized that regenerative braking phase II uses as large as possible. This will extend the life of the battery as well as increase the accuracy of battery SoC estimation." [10, 58, 59]

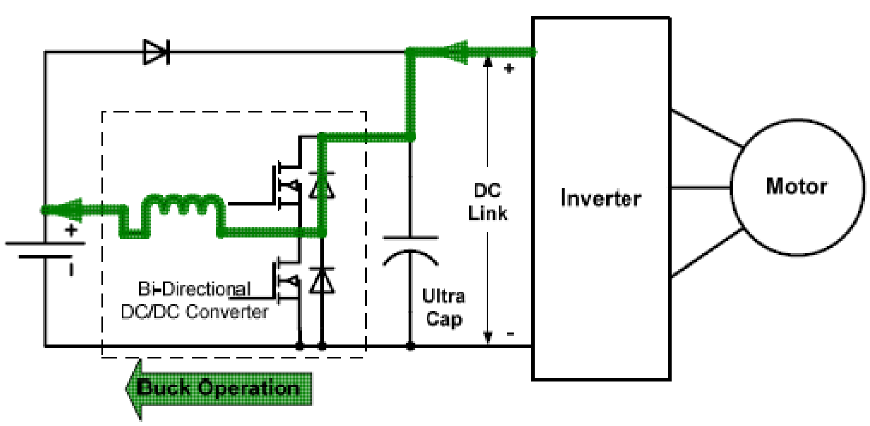

Fig.2.16 Regenerative Braking Phase II Energy Flow