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Energy Storage Devices and Its Hybridization for Designing Supply System

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Abstract— Energy sources undergo large momentary changes in power input/output monthly or even annual cycles. Electricity production need not be drastically scaled up and down to meet momentary consumption. Therefore, in order to become these sources completely suitable as primary sources of energy, energy storage is an essential factor. There are storage devices that are used for very large energy storage (i.e. pumped hydro, CAES) or for comparatively smaller storage (i.e. batteries, UC, flywheel, fuel cell). A large range of storage technologies exists with each one possessing different peculiarity and are proposed for different applications. Also, it is highly uneconomical and inefficient to design any energy storage system only based on peak power demand. So, hybrid combination of such devices would lead to availability of a secondary source which in turn will play role in different parts of demand profile and can also work as the primary source for time being.

Keywords— Load profile, Energy storage, hybridization

I. INTRODUCTION

Energy is one of the important key factors of economic growth and plays a big role for the growth of a modern economy. Day-by-day energy demand rate is increasing. Accordingly, future economic sustenance crucially depends on the long-term accessibility of energy from sources that are economical, accessible and recyclable. Energy Consumption rate as shown in figure 1 exposes the changing trends and patterns, that may help framing current energy balance issues and persuade progress towards collectively constructive solutions. Promotion of energy conservation and increased use of renewable energy sources are the leading plans of a sustainable energy supply. The rate of consistency and level of security of energy can be enhanced greatly by employing diversified and distributed generation and energy storage methods.

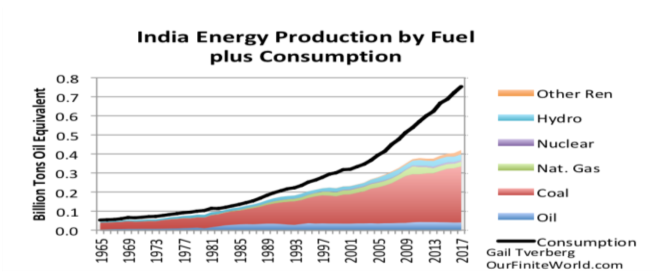

Figure1 Energy Curve[1]

Energy storage can be implemented as a buffer to match the available generation to the variable user demand. Energy storage technology based devices do not represent energy sources; they ultimately enhance the factors like: stability, power quality and security of supply. Although electrical energy cannot be directly stored (cheaply/easily), but it can be easily stored in other forms and converted back to electrical form whenever necessary. As energy demand increases, storage plays multi-functional role, since storage facilities are designed to excel under various dynamic cycles [2].

Energy storage devices can be very useful for an efficient energy or power management. Each technology has its own strengths and operational characteristics. Storage devices are generally characterized to store energy in off-peak hours and deliver energy during peak hours to fulfil energy crises as shown in figure 2.

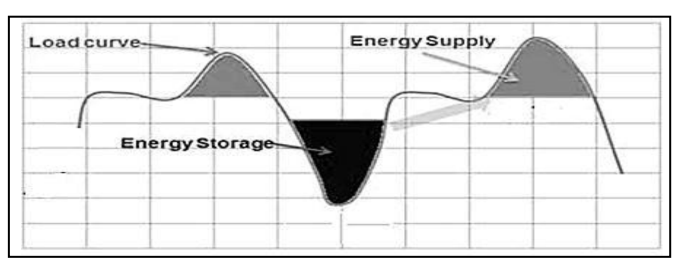

Figure 2 Load Curve [2]

II. APPLICATIONS

- Load management
- Emergency back up
- Renewable system integration
- Power system stabilization
- Transmission upgrades suspension

III. CLASSIFICATION OF ENERGY STORAGE DEVICES

The power capacity and the response time are the key factors that help in categorizing different devices. As per the above factors the classification are as follows

- **Small Power and Storage Capacities**
- Mechanical System: Flywheels.
- Magnetic System: SMES
- Electrical System: Super capacitors.
- **Medium Power And Storage Capacities**
- Electrochemical System: Batteries, fuel cells.
- **Large Power and Storage Capacities**
- Pneumatic System: Air compressors.
- Potential System: Pumped storage.

IV. SMALL STORAGE CAPACITY DEVICES

The energy management of power sources with distinct features in terms of energy and power density are characteristics of modern energy storage devices. This phase is important in order to achieve high efficiency in storing power and to get excel performance of storage device under dynamic load demands.

A. Mechanical System

- *Flywheel*

A flywheel is a mechanical battery, which can store energy mechanically in the form of kinetic energy. The amount of energy stored in the flywheel depends upon its rotational velocity and its moment of inertia. This is generally achieved by rotating an electric motor coupled with flywheel when being used in an electrical system. This stored energy can be converted by applying a decelerating torque to slow down the flywheel and then converting back the kinetic energy of the flywheel to drive the electrical motor, which is used as a generator [3] generating the electrical energy. The set up arrangement is shown in figure 3.

The speed at which the flywheel rotates with has a greater impact on energy stored by it as compared to its moment of inertia. The flywheel can be either low speed, with operating speeds ranging around 5000-6000 revolutions per minute, or high-speed with operating speeds ranging about 50,000-60,000 rpm. Low speed flywheels are extensively used in power quality applications. They are usually made of steel rotors and conventional bearings. Specific energy achieved is around 5 Wh/kg.

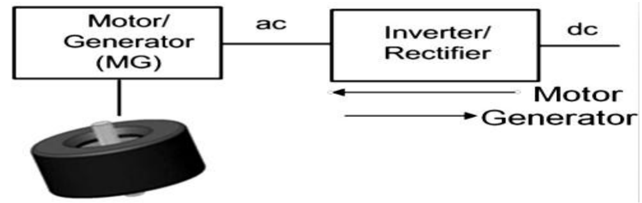

Figure 3 Systems with Flywheel[3]

High-speed flywheels are light-weight and high-strength composite rotors. These flywheels generally used in UPS applications are made up of composite materials for the rotor with ultra-low friction bearing assemblies. They can achieve specific energy of 100 Wh/kg [4]. Also, such flywheels come up to speed in a matter of minutes, rather than the hours needed to recharge a battery.

B. Magnetic System

- *Superconducting Magnetic Energy Storage (SMES)*

An SMES unit is a device that stores energy in the magnetic field created by the direct current flowing through a cooled super-conducting coil. The coil is cryogenically cooled beyond its super-conducting temperature (-269°C). At this temperature, it becomes a super conductor so as the resistance offered to electric currents disappears, and the limited electrical resistance allows high charge-discharge efficiency up to 97%, since the superconducting coil has virtually no Joule losses [5].

An additional advantage is the power management of the device. That is, it implicates instant release of power which makes the system suitable to the consumers requiring extremely high quality power output. This technology, enables obtaining high power peaks within very short period of time (<<1 s).

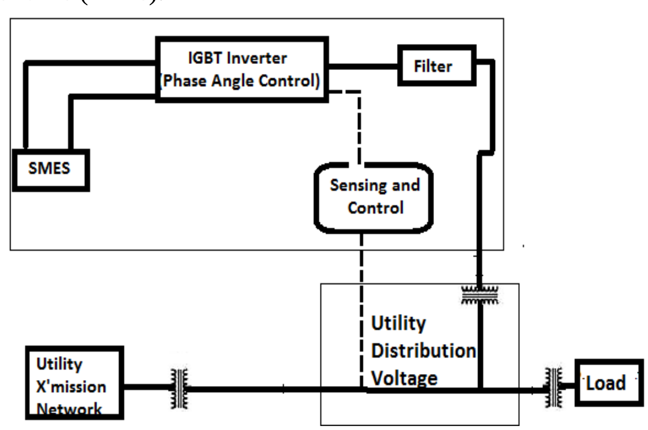

Figure 4 Basic Operation OF SMES [5]

C. Electrical System

- *Supercapacitor*

Supercapacitor/ Ultracapacitor is an electrochemical device which has large pores and it stores energy in form of electrostatic charges in these pores lying on the opposite surfaces of the electric double layer formed between each of the electric and electrolyte as shown in figure 6. This empowers ultra capacitor to store large amount of energy .No chemical reaction occurs during charging and discharging cycle even though it is electrochemical device. UC construction is similar to battery possessing two non reactive porous electrodes immersed in an electrolyte solution which is separated by an electronic layer called separator. Electrodes consists of porous carbon material (activated carbon fiber material) deposited on metal foils having a pores in the nanometer range and very high surface area (1000-2000 cm^2/gm) the properties of the double layer capacitor strongly depends on how porous carbon activated material is and how small the electrolyte ions are. The surface is greatly increased due to the very high porosity of the electrode [6,7].

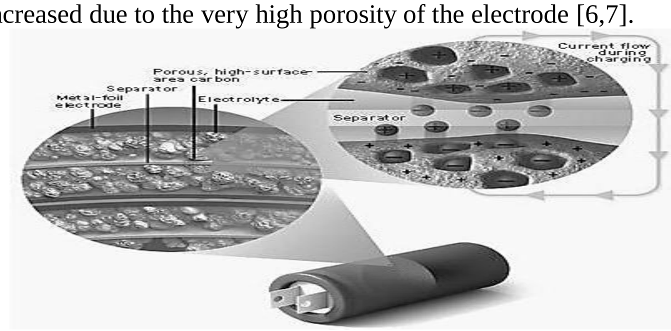

Figure 6 Internal Pores Of UC[7]

During charging the positive and negative ions of electrolyte are drawn to electrodes of opposite polarity where they accumulate into layers inside the activated carbon pores. The penetration of electrolyte ions is governed by pore size of activated carbon. The double layer phenomenon is strongly determined by the activated carbon pore size and electrolyte positive and negative ions diameter. Electrolyte ions diameters are of the order of 1 nanometer. If the average pore diameter is 3 nanometer good capacitance value exists for both organic and aqueous electrolytes when it is less than or equal to 2 nanometer, good capacitance value exist for only aqueous electrolyte and if it is below 1 nanometer no double layer capacitance exists. The specific capacitance for ultra capacitor for aqueous electrolytes is in the range of 75 -175 F/gm and for organic electrolyte 40-100 F/gm. This is because of larger size of ions in organic electrolyte. If larger the ion size less penetration of ions into pores of activated carbon [8]. The cell voltage of the ultra capacitor is dependent on electrolyte used and the maximum voltage is limited by the insulating ability of the electrolytes. For aqueous electrolyte the cell voltage is about 1 V and for the organic electrolyte the same voltage is about 3-3.5 V [9]. This leads to obtaining efficiencies of about 90% in the complete cycle of charging and discharging. UC offered some resistance, as conductivity of organic electrolyte is low it has higher ESR then aqueous electrolytes. They are good means of qualifying an energy storage system and to size the storage system for variety of application [6].

UC main advantage is its power management over energy management. Figure 7 shows the characteristics of UC under different loading conditions (50A,80A,110A,140A) which justifies it's power management capability. 150F ultracapacitor with terminal voltage 48V undergoes various loading conditions as shown in figure 7, which proves that ultracapacitor can satisfy different peak demands adjusting its SOC (state Of Charge) and operating time. It can be observed from the characteristics that higher the peak demand lesser will be the operating time of the device and the discharge rate also increases.

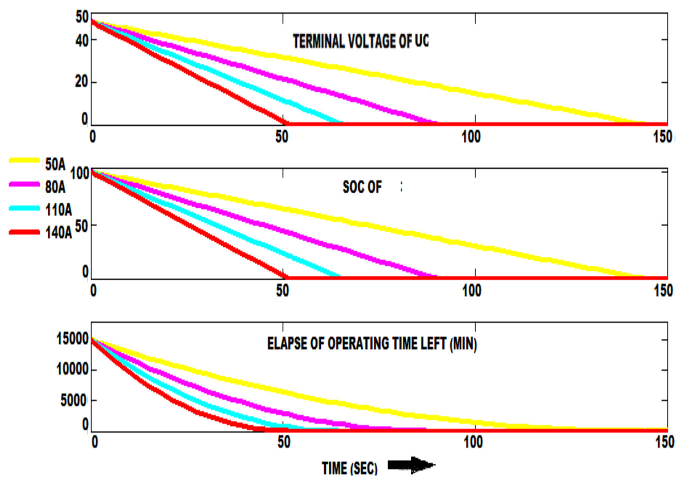

Figure 7 Discharge Curves of 150F, 48V UC

V.MEDIUM STORAGE CAPACITY DEVICES

A. Electrochemical Systems

- *Battery Electric Storage System (BESS)*

Batteries are devices that undergo oxidation and reduction processes to convert chemical energy into electrical energy. They base unit called cell, are combined with each other, in series or parallel, for obtaining the required levels of capacity or voltage [3]. These batteries are characterized by the key features which includes, maintainability, safety, reliability, material, recyclability, abuse tolerance, charging delay, state of charge(SOC),Capacity in AH, open circuit voltage, maximum discharge current, depth of discharge, fuel gauging and charge equalization in the series cells .

Power batteries of any kind are too much bulky in physical size and heavy weight. Also they must offer high number of cycle life as well as a long calendar life. Main limitation of battery is that the battery can deliver and absorb limited amount of peak power which may be demanded or produced during transient operation of loads. Hence it also affects the load performance. As per mentioned above the basic characteristic of battery under various loading conditions (6A, 12A, 18A, 24A) are as shown in fig.8.

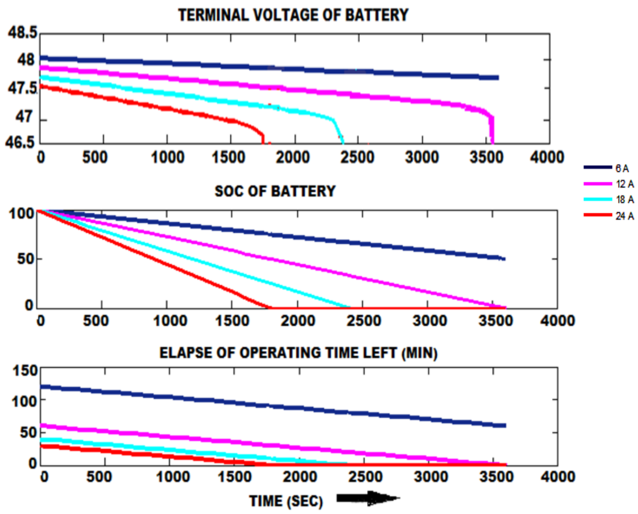

Figure 8 Discharge Curves of Battery 48V, 12 Ah

If the batteries are optimized for its size & mass then normally they are not able to supply huge amount of power as per different loading conditions. Batteries by their application in circuit should not be discharged to voltage lesser than a particular minimum value. Over discharging might make the battery permanently useless. So due to all these limitations generally batteries are loaded with the some constant low power demand applications rather than transient power demanding load. Since, the transient load peak demand is high as in the case of 24 A current demand, the SOC level is reaching zero within very short period of time which can make battery useless.

Many types of electrochemical batteries have been developed, which can be used in electric power systems, including: lead acid, nickel cadmium, flooded type, sodium sulphur, valve regulated, lithium ion, etc. There are three main types of conventional storage batteries that are used extensively today: nickel-based batteries, lead–acid batteries, and lithium-based batteries. Additional to the above mentioned characteristics, the selection of the battery can be done based on some features mentioned in Table 1. The suitable battery for fulfilling the application criteria can thus be selected.

Table 1--Characteristics Of Battery Technologies

Battery type	**η**	**Cost ($/kwh)**	**Life span (cycles)**
Lead acid (flooded)	72-78	50-150	1000-2000
Lead acid	72-78	50-150	200-300
Nickel	72-78	200-600	3000
Lithium ion	100	700-1000	3000

- *Fuel Cell*

A fuel cell is a device that converts the chemical energy directly into electrical energy and heat without combustion. The important feature of the fuel cell is that the fuel and the oxidant are combined in the form of ions rather than neutral molecules. Fuel cells are different from conventional batteries as the chemicals constantly flow into the fuel cell so it never exhausts. In contrast battery the other electrochemical device has all of its chemicals stored inside, and it converts those chemicals into electricity too. It represents a thermodynamically closed system which means that a battery in the long run exhausts and either it is thrown away or recharged [2].

Hydrogen is the most common fuel, but hydrocarbons such as natural gas and alcohols like methanol are sometimes used. that we are all familiar. A battery

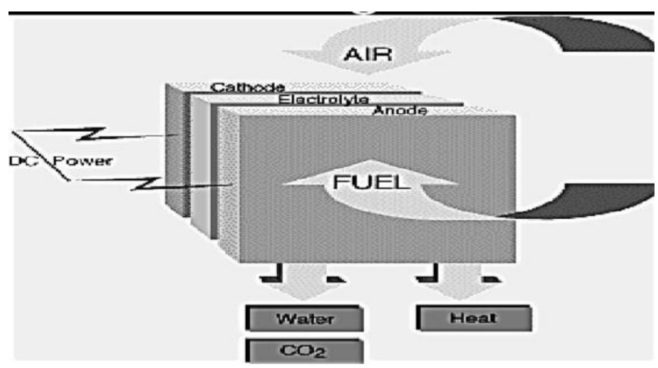

Figure 9 Fuel Cell Working [4]

Fuel cells posses an electrolyte material which is slot in in between two thin electrodes characteristically porous anode and cathode. The input fuel catalytically reacted allowed to pass over the anode (and oxygen over the cathode) where it catalytically splits into ions and electrons. The electrons pass from an external circuit to operate an electrical load while the ions move across the electrolyte and settle at the oppositely charged electrode. According to the type of the input fuel and electrolyte enrolled, different chemical reactions will occur. Generally at the electrode, ions merge to create, primarily water and CO2 as a by-product.

Thus, fuel cells are one of the efficient alternatives to generate electricity. Conversely the development costs are very high.

- *Flow Batteries*

"Flow batteries" are categorized as an electrochemical system, which lies in between fuel cells and conventional batteries. As per the construction of the flow batteries it is similar to that of the fuel cells, but unlike fuel cells, they are fed by two tanks of electrolyte. Such electrodes are not affected by charge-discharge cycle leading to long cycle life. The flow battery can be recharged instantly just by swapping the electrodes (tanks of electrolyte) where each tank is pumped by their respective sets of half-cells. The flow battery operation is secure -- the electrical energy is stored in the two electrodes consisting of separate tanks separate tanks, with only a small portion of them reacting in the cell stack at any instant. They are largely applicable due to its cost- affectivity, several times cheaper than lithium batteries and to some extent cheaper than, the sodium-sulphur battery.

VI. Large Power And Storage Capacities

A. *Pneumatic System*

- *CAES (Compressed Air Storage System)*

CAES systems are used on very large scales. Large capacities for a CAES system range around 60–300 MW. CAES plant can provide a fast start-up. A CAES can be used to store energy for more than a year due to its low losses.

During off peak demand periods CAES, takes off-peak power from the grid, which passes via large electric motors driving compressors that store energy in the form of compressed air in the sealed mine called "cavern". The air is cooled down as part of the compression process, prior to the storage into cavern, to make the best possible use of the storage space available. The air is then pressurized to high pressure around 70 bar. The pressurized air is then kept stored underground for peak use. To supply power to the consumers during peak demand periods, compressed air is extracted from the stored area i.e. cavern. Primarily, the air is preheated in the recuperator. The recuperator uses the energy stored by the compressor coolers as an auxiliary power. The preheated air is then added with small amount of oil or gas, which undergoes combustion process in the combustor. The hot gas from the combustor can drive turbines to generate electricity to fulfil energy crises in the demand of consumers at peak hours [4]. The basic view of such system is shown in fig.10.

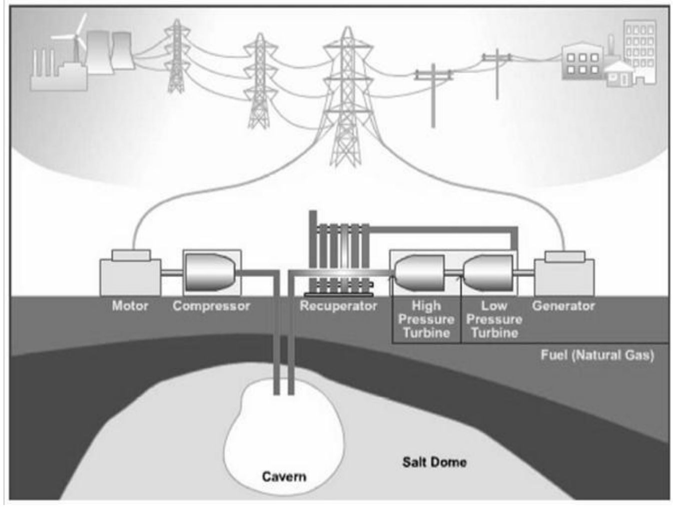

Figure 10 Basic Components For CAES[4]

B. *Potential System*

- *Pumped Storage Technology*

During off peak demand period, excess generated power is used to pump water into the higher reservoir as shown in fig.11. During peak demand period if the shortage of energy arises, water is released back into the lower reservoir via a turbine, generating electricity. Thus, generated power is fed into the grid via the transformer and breaker set as shown in the figure. Reversible turbine/generator assemblies act as pump and turbine [3]. Taking into account various losses, approximately 70–80% of the electrical energy used to pump the water into the elevated reservoir can be obtained. The technique is currently the most cost-effective means of storing large amounts of electrical energy. However, capital costs and the presence of appropriate geographical locations are crucial factors to be considered. The low energy density of this system for power balancing requires either a very large space for water or a large variation in height. The water management is the main art for obtaining optimum efficiency from the storage process.

$$P_c = \rho * g * H * Q * \eta p$$

Pc = Capacity in Watts (W)
ρ = Mass density of water in kg / s
g = acceleration du e to gravity in m/s
H = effective head in reservoir in m
Q = discharge through the turbines
Ƞp = pump efficiency

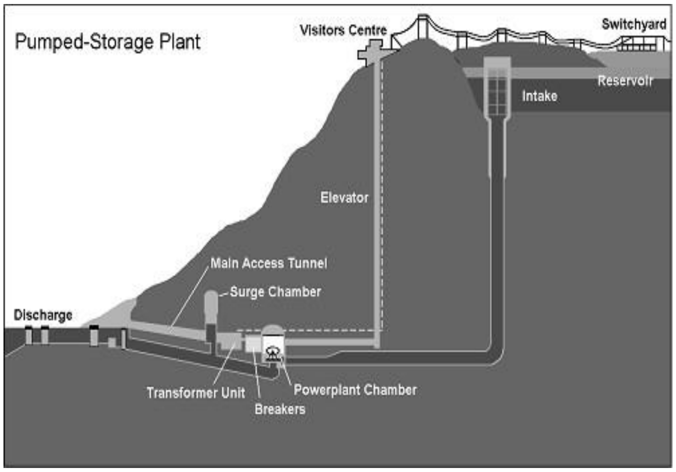

Figure 11 Pumped Hydro Storage System[2]

VII. COMPARISION

Nowadays, researches focus mainly on the design factors like size, weight and competency of energy storage device that is reasonable and even need to have sufficient life cycle. Individual Energy storage unit available possess either high energy density or high power density but both the properties does not belong together. Presently, some key points that need to be kept in mind while selecting any of the different energy storage technologies:

- **Power Capacity measured in kilowatts (kW) or megawatts (MW) :** The instantaneous peak output power that an energy storage device can supply.
- **Energy Storage Capacity kilowatt-hours (kWh) or megawatt-hours (MWh) : T**he quantity of electrical energy the device can store.
- **Efficiency:** The amount of energy recovered as a percentage of the energy used to charge the device.
- **Response Time:** The length of time it takes to release the stored power.
- **Cycle Efficiency:** The total amount of electricity which can be recovered as a fraction of the electricity used to charge and discharge the device.

Figure 12 shows comparative results based on their discharge time against storage capacity. Power quality application require fast responsive devices though the storage capacity can be compromised, on the other hand energy management applications need to be supplied for longer time though they have to compromise in the response time.

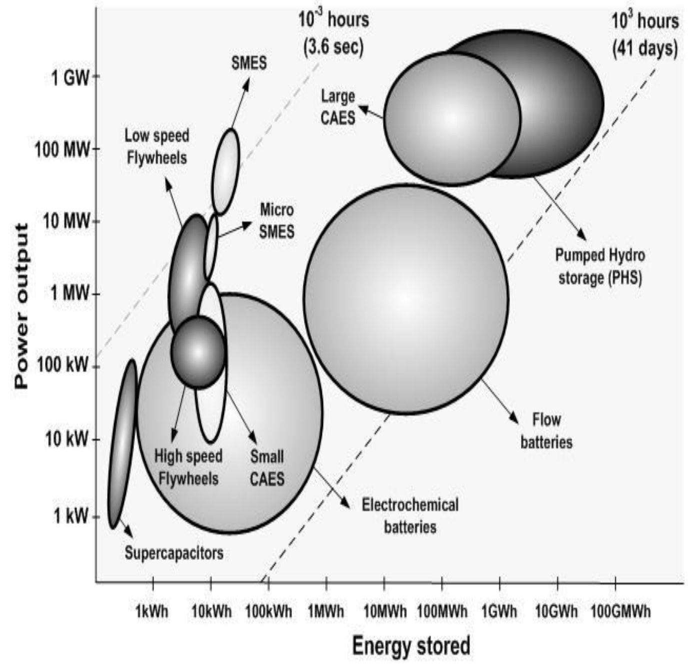

Figure 12 Typical storage capacity versus discharge times[3]

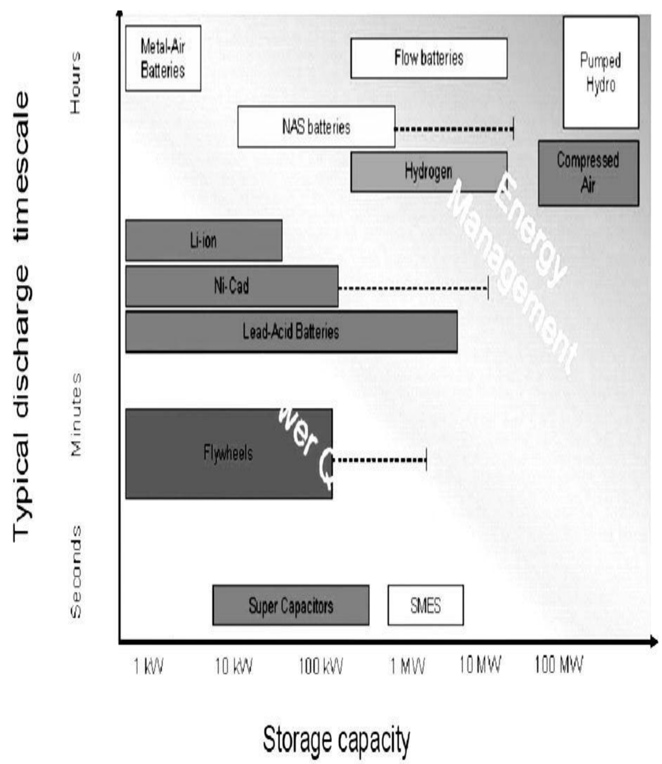

Figure 13 Ranges for application of storage technologies[4]

Figure 13 shows the application range of different energy storage technologies, based on energy stored and power output. This thin line of separation amongst them decides in which system they are best applicable [3].

The future development various applications are highly dependent on the performance and cost of the energy storage technologies available. At present, one of the factors for selection of energy storage devices is transportation, which imposes several limitations. Energy storage units available can be specified as high energy density or high power density. Such criteria help in selecting the device suitable for the application. Thus table 2 shows comparison of different devices.

Based on basic principle of conventional management methodology, hierarchical management concepts will be used for power and energy management of different energy storage devices. Energy management shells handle the long-term decisions of energy usage in relation to the longitudinal dynamics of the loads. Power management shells handle the fast decisions to determine power split ratio between multiple energy sources. In order to achieve the level of performance and competitive cost of energy storage devices based systems designers must use design techniques and tools such as computer modelling and optimization. These tools facilitate development of a virtual prototype that allows the designer to rapidly see the effect of design modifications and precludes the need to manufacture multiple expensive physical prototypes. This research is motivated by the premise that electrical technology integrated with energy storage devices and associated control systems represents an economical, environment friendly and technically feasible option for future electrical system.

Table 2--Comparison of all storage devices [2]

Technology Type	**System Energy Density (Wh/Kg)**	**η of Recovery (%)**	**Suitability for**		
			Energy Management	**Power Quality**	**Transport**
Super Capacitors	0.1—5	85—95	★★	★★★	★★★
Nickel Batteries	20—120	60—91	★★	★★★	★★★
Lithium Batteries	80—150	90—100	★	★★★	★★★
Lead- Acid Batteries	25—45	60—95	★★	★★★	★★★
Zinc- Bromine Flow	37	75	★★★	★★	
Vanadium Flow Batteries		85	★★★	★★	
Metal-Air Batteries	110-420	Upto 50	★★★	★	★
Sodium Sulphur Batteries	150—240	>86	★★★	★★	★
H2 Fuel Cell	N/A	25--58	★★★	★★★	★★★
Flywheels	30-100	90	★★	★★★	★
SMES		97--98	★	★★★	×
Pumped- Hydro	N/A	75--85	★★★	★★	×
CAES	N/A	80	★★★	★★	×

VIII. HYBRIDIZATION OF STORAGE DEVICES

Some applications like EV (electric vehicle) operates with common load profile, described by relatively high peak to average power required. To satisfy such a load condition, high power and high energy density source is essential. Battery which is a high energy device can be combined with ultracapacitor which is a high power device to form a super device having high energy density as well as high power density. Addition of ultracapacitor leads to reduction in battery capacity which ultimately leads to reduction in weight, volume and overall efficiency of the electric vehicle. The interfacing of two devices actively can be seen in figure 14. Also, battery being relieved which ultimately leads to better efficiency and cost reduction [9].

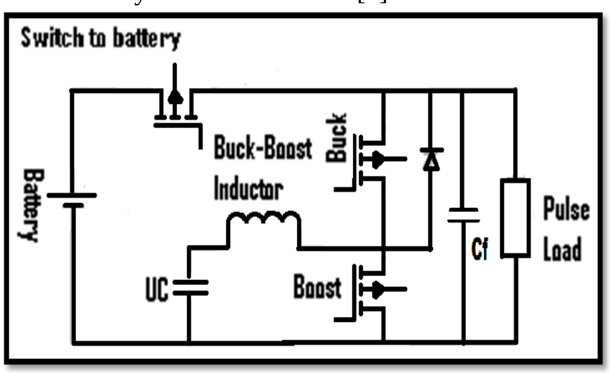

Figure 14 Active Connection of UC

Simulation results of the current waveform and voltage waveforms of the active hybrid are shown in figure 15 and figure 16.

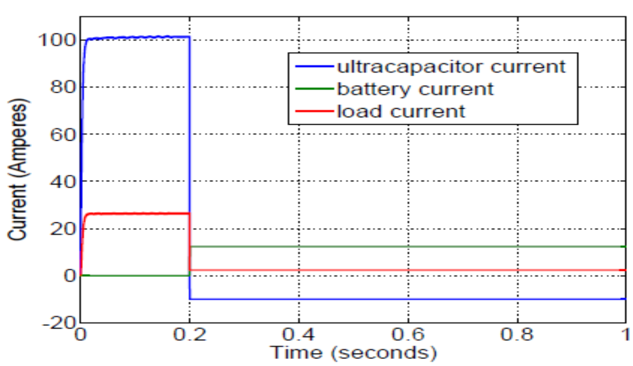

Figure 15 Simulation results of the current waveforms of the active hybrid

Under the peak load condition, the load is supplied only by ultra capacitor through boost converter & battery is in idle state. As UC discharges, its voltage reduces from its fully charged state under constant power operation. DC bus is always operating under constant DC voltage. So boost converter will adjust its duty cycle to maintain DC bus voltage constant & to provide required current under constant power condition. The UC is allowed for its maximum discharge up to half maximum voltage of UC bank, so that at least ¾ of the total stored energy can be utilized. Switching of UC is controlled by boost converter by adjusting its duty cycle through PI control algorithm. PI algorithm is implemented based on reference voltage set inside is compared with output dc bus voltage. When the load current becomes nominal & UC voltage has dropped to certain value, the UC is charged from battery through buck converter. Maximum charging current and voltage level of UC is controlled by adjusting the duty ratio of buck converter.

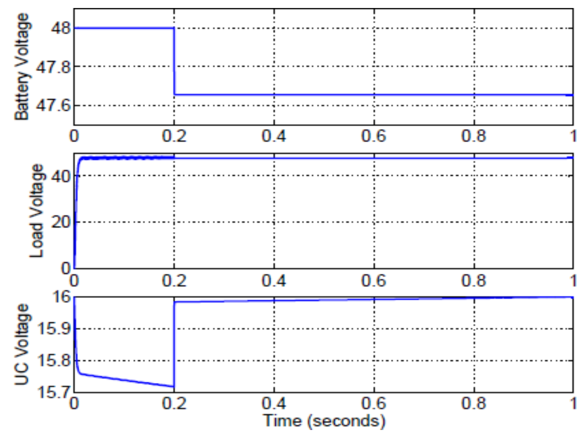

Figure16 Simulation results of the voltage waveforms of the active hybrid

IX. CONCLUSION

According to the above analysis, it is clear that various storage technologies exist, each one possessing different features and applicable for different applications. Also, it is highly uneconomical and inefficient to design any energy storage supply system only based on peak power demand. The better solution is to use energy storage devices of different nature for supplying different parts of the power demand profile. To satisfy such a transient load condition, high power and high energy density possessing source is essential. Battery which is a high energy density device can be combined with ultracapacitor which is a high power device to form a compatible device having high energy density as well as high power density. The capability and benefits of using Ultracapacitor as a battery peak power suppression system is clearly demonstrated. Addition of ultracapacitor leads to reduction in battery capacity which ultimately leads to reduction in weight, volume and overall efficiency of the electric vehicle. Although these supercapacitors are capable enough to store and release energy at instantaneous high rates (i.e. high power), but extracting the energy for use in an electric propulsion system requires a power electronic interface in order to balance working voltage requirements.

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