Heterogeneous Arrays of Storage Devices: An Approach to Get Linear Output with Maximum Efficiency from Energy Systems

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***Abstract*—There is an increasing interest in using energy storage devices. Storage devices like batteries are used in hybrid vehicles. There is also interest in using batteries and devices like ultra capacitors with windmill and solar panels to mitigate the effect of power fluctuation. The power losses, and subsequently the overall efficiency of practical energy storage devices are highly nonlinear and greatly depend on the rate of charging. In order to maximize efficiency, advance energy systems would utilize heterogeneous arrays of storage devices consisting of multiple power sources combined with multiple control units. This paper proposes such a heterogeneous energy system using PID control which will give linear output with maximum efficiency to the load.**

***Index Terms*—storage devices; ultra capacitors; power fluctuation; heterogeneous arrays of energy system; hierarchical architecture; HierArcHEES.**

I. Introduction

A heterogeneous energy system is such a system where multiple energy sources are used to provide maximum power as output with linearity. The conventional batteries are not equip with all the parameters that is required for a high-quality energy supply system. In recent days new forms of energy/storage systems are coming to overcome the limitation of conventional supply systems. The idea of using a hierarchical architecture of heterogeneous energy supply system combined with a high level architecture was first proposed in [1]. The target is to conquer the limitations of a single energy source since it is unlikely that a single energy supply would simultaneously optimize all the criteria imposed by the load demand. The performance parameters for determining the best storage option includes power, energy, efficiency and density. Depending on the task at hand, an interleaved combination of the heterogeneous energy system could be used which is proposed in[8].

Afterward independently proposed system called hybrid electrical energy storage (HEES) also suggested a block-level system realization for a hybrid network of energy supply options [2]. Recently a hybrid battery super-capacitor power supply system has been proposed in which the hybrid source's charge/discharge policy is made based upon the load profile and supply's state[8]. The work includes a novel algorithm to maximize the supply system's lifetime [3]. A number of limited earlier studies have already shown the benefits of a hybrid super-capacitor and solar energy generation system in optimizing system's efficiency and dynamic response time, in particular for transient loads with a low duty cycle and also for pulsed loads in sensor networks [4], [5], [6].

In this paper, we not only elaborate on the hierarchical energy supply network design suggested in [1] and provide more details for its system macro-architecture but also we will show that this network provide us linear output at load at all conditions. We use the term HierArcHEES to refer to our Hierarchial Architecture of Heterogenous Electrical Energy Supplies. The HierArcHEES system includes different energy supply and storage units along with multiple control units.

II. Performance Parameters

In this part, we talk about a number of key parameters that are usually used to calculate the efficiency of an energy supply/storage system.

A. Power and energy density

Power density often quantifies the average value of rate of energy change (or mean available power) for a unit of volume (weight) of the device. Whereas the energy density quantifies the amount of stored energy in a unit of volume (or weight) of an energy supply/storage device.

B. Charging time and discharging delivery rate

The Charging time is the time required to transmit charges to an energy storage device such that it reaches the full energy capacity. The discharging delivery rate resolves the time required to extract one unit of the stored energy. The discharging time, that is the maximum power discharge duration. It is defined as the ratio of the overall energy capacity to the highest power.

C. Efficiency

A level of performance that describes a process that uses the lowest amount of inputs to create the greatest amount of outputs. Its the ratio between the utilized energy and the stored energy. The cycle efficiency may also be defined as the product of charging efficiency and discharging efficiency. In a highly efficient system, the power transfer system must have small losses due to energy conversion/transfer or self-discharge. The per cycle efficiency of a device is often a complex relationship varying with the operation point such as ambient temperature and notably with the state of charge.

D. Durability (cycle capacity) and aging

This parameter quantifies the number of times an energy storage unit can release the energy level it was designed for (after each recharge). The cycle capacity may be expressed as the maximum number of cycles, where a cycle corresponds to once charging and once discharging the unit. The dura- bility of an energy supply/storage unit often deteriorates with aging of the device. Aging is related to wear by usage (irreversible chemical and physical modifications that occur during operation), and it is also related to state of charge and operation point. Modeling the aging process is often complex and not well defined.[8]

E. Leakage rate

Leakage refers to a gradual loss of energy from a charged devices. The self- discharge rate of a device is important since it determines how long an energy storage device can stay idle. The leakage, which varies a lot across the spectrum of available energy storage options, is a deciding factor for selecting the best energy source to supply the load.

F. Autonomy & cost, volume, and weight

This parameter defines the maximum amount of time the system can continuously release energy once it is charged to its full energy capacity.

The cost is one of the most important metrics for selecting energy sources while devising a system. The most commonly used quantity for the expense metric is cost per unit of energy stored, or the cost per unit of mean output power. The cost per unit of energy supply or storage device may also be characterized versus the unit of pertinent device's volume or its weight. While designing a hybrid energy supply system, the overall cost of the system may be a design constraint to keep the overall electronic system economically viable.

G. Reliability, safety & adaptability

Reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time. While the reliability and safety are more subjective than the parameters defined so far, they constitute an important dimension in selecting the appropriate energy source. For example, in certain scenarios, it may be possible to use energy scavenging and then convert/store the resulting energy in a supercapacitor. However, such an intermittent energy scavenging option may be unreliable for critical applications that need a constant source. Safety dictates another set of subjective concerns. For example, in high temperatures, fuel cells that might explode should be excluded even if they satisfy the other design parameters.

In the context of a specific application load, the adaptability of the energy system is the ability of the energy source to match the application requirements [8].

There are a lot of parameters except those which has been discussed earlier. But those are less important related to the application of this paper. So our emphasis will be on the parameters which majorly involved in the efficiency of energy system.

III. Storage Devices

A. Electrochemical batteries

An electric battery is a device consisting of one or more electrochemical cell that converts stored chemical energy into electrical energy. Examples of commercial electrochemical batteries are Lead-acid batteries, Li-ion batteries, NiMH batteries, and Metal-air batteries.[2]

Lead acid batteries are currently used in most automobiles for starting, lighting, and ignition applications. They have been used in electric vehicles including General Motors' EV-I. Lead acid batteries are very efficient and inexpensive, however, they have low energy densities, [10; 50]Wh=Kg, power densities in the range of [1; 500]W=kg, and poor lifetime.[8]

NiMH batteries can provide high power densities up to 1300W=kg and energy densities up to 110Wh=kg. NiMH batteries have reasonable prices and have enabled commercial HEVs. They have exceptional high temperature capability and long-life under high depth of discharge. Their main disadvantage is that they suffer from memory effect.[8]

Lithium-ion batteries are used in most contemporary con- sumer electronics. High efficiency, long life-cycle and low self-dischargerate are their advantages. Recent advances have enabled production of Lithium-ion batteries with extremely high power densities such as Sony's 1800W=kg batteries and energy densities of up to 250Wh=kg. The main disadvantage of those batteries is their relatively expensive prices.[8]

B. Capacitors

A capacitor is a passive two terminal electronic component used to store energy electro statically in an electric field. It consists of a pair of conductors separated by a dielectric which can store electric energy when disconnected from its charging circuit, so it can be used like a temporary battery. They are commonly used in electronic devices to maintain power supply DC level while batteries are being changed. Capacitors power densities and charge/discharge rates are higher than that of batteries and supercapacitors but their energy densities are low.

C. Supercapacitors

Supercapacitor(SC) are also called Electrochemical Double Layer Capacitor(EDLC). These are electrochemical capacitors that have high capacitance and high energy density compared to common capacitors and higher power densities compared to batteries. Their benefits other than high power and energy density are high cycle efficiency, long cycle life, low maintenance and wide thermal operating range. However supercapacitors energy densities are still lower than batteries or fuel cells. The other shortcoming is the low voltage they can provide comparing to the conventional capacitors. Size of the supercapacitors is not a good one but research is on for using these things as power sources.

D. Fuel cells

A fuel cell is a device that converts chemical energy from a fuel into electricity through a chemical reaction with oxygen and another oxidizing agent. The main advantages of fuel cells are their considerably high energy density, environment-friendly system and low maintenance. A number of currently under development fuel cells such as the polymer electrolyte membrane fuel cells (PEMFC) can be used for stationary, portable, and mobile applications. Some of their disadvantages are cost, low power density, and low cycle efficiency in comparison with batteries and supercapacitors.

Table 1 demonstrates a numerical judgment between the performance parameters of different storage devices. From the table it is quite clear that no single unit does better than others in all the parameters and so a hybrid system is must.

Table 1: Comparison of Storage Devices [8]

Property	*Supercap*	*Capacitor*	*Battery*	*FuelCell*
Life	> 30*khr*	> 100*k* cycles	[1.5-10]khr	[.15-1.5]k cycles
Cycle	[10 3; 1]s	[10 9; 1]ms	[1,10]hr	[10,300]hr
W eight	1-2g	1g-10kg	1g-10kg	25g-5kg
$=kW hr	[20-50]k	-	[10,2500]	[3.5,10]k
P ; kW=kg	[10,100]	[:25; 104]	[:005; 1:8]	[.001,.1]
E ; W hr=Kg	[1,28]	[.01,.05]	[8,600]	[.3,3]k

IV. Heterogeneous Arrays of Storage Devices

In this part, we will establish heterogeneous arrays of storage devices, a modular architecture for Hybrid energy source system. Our new architecture aims at combining a heterogeneous set for energy supply elements. The reason behind selecting a heterogeneous set is that no one element can provide all the desired performance criteria. Combining the energy resources in a hierarchical way is a viable approach to simultaneously integrate the best properties of all available energy supply and storage elements within one framework. For example we will discuss in this paper about Hierarchial Architecture of Heterogeneous Electrical Energy System(HierArcHEES)[8].

A three-tier hierarchy of energy supply and storage elements is exploited in the HierArcHEES system:

A. External energy supplies

The external energy supplies include the solar power, AC sources, grids, vibration energy scavenging and non rechargeable chemical batteries. Though these are not electronic system but they inject energy to the system.

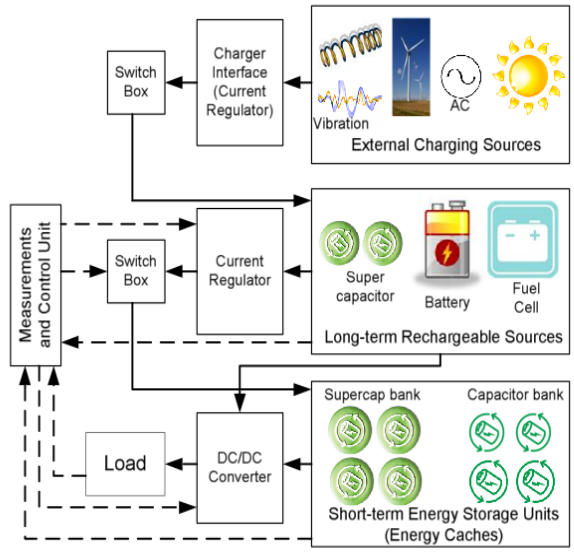

Fig 1- Heterogeneous energy system [8]

B. Long-term rechargeable energy supply and storage elements

It is the second tier of hierarchy. Here elements can be recharged by the external sources. The recharged source can supply energy to the load. The time of the supply of energy depends on technology and application of the device. For a mobile it can be multiple hours and for a camera it can be multiple days.

C. Short-term recycling energy storage elements

This part basically comprises with short term energy storage units like capacitors, supercapacitors. They take less amount of time for charging compared with the conventional long-term rechargeable elements. They can be used for intermediate storage and recycling of charges drawn from the long-term energy elements, while they have a longer life cycle, higher power density, better charge delivery, and better efficiency.

In our energy system, there are a number of control and leveling components needed to ensure the correct functionality of the hybrid energy supply system. Perhaps the most important component in the HierArcHEES system is the control and measurement unit(s). Depending on the application at hand, the control and measurement unit may be centralized or distributed. One important task of the controland measurement unit, is supervising the charge transfer. As shown on the figure 1, connecting the external energy sources to the second tier components and connecting the second tier components to the third tier require charging interfaces controlled by the management. This is because charge transfer to and from each of the heterogeneous energy elements needs specific voltage and current inversion to ensure the cycle life efficiency of the energy source and safety.

The key task of the control and measurement unit(s) is to decide how to serve the load considering the heterogeneous resources in the HierArcHEES system. The control is based on the measurements of the load's shape and its demands, and the performance parameters of the elements of power supply system. While setting the load is the main task, another important role of the energy measurement and control systemis to monitor and supervise charge transfer among the energy supply and storage elements in the three levels of our hierarchy. The control management of transfer charges is shown by switches on the figure1. Since voltage and current adjustment are sensitive tasks and often require feedback to mitigate the impact of instantaneous fluctuations, PIDs and other feedback structures are typically used [8].

V. COMPARISON

Now if we use battery or super capacitor in the energy system alone then output becomes nonlinear. And if we use a heterogeneous energy system(battery, capacitor, super capacitor, fuel cell like in fig 1) then the output becomes linear using PID controller.

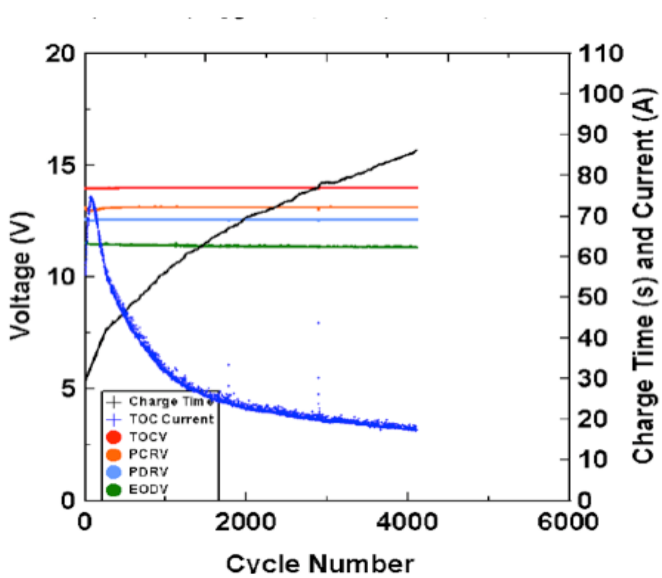

Fig 2: Output of Lead Acid Battery

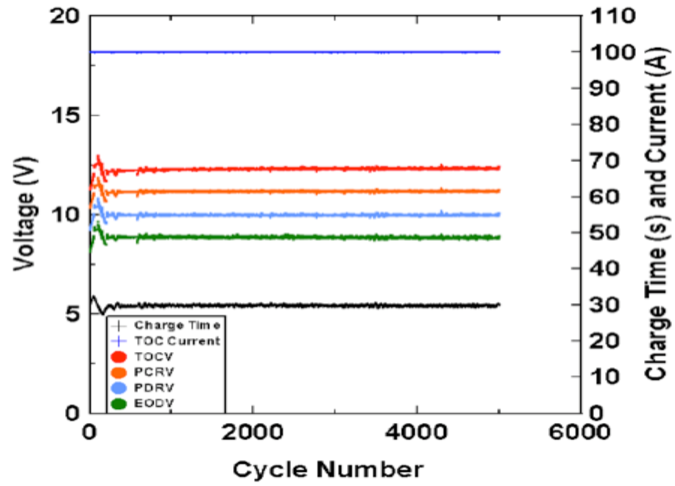

Fig 3: output of a heterogeneous energy system

VI. CONCLUSION

It is clear that all the characteristics those are required for a high-quality energy system, cannot be provided with using one single power source. For this we require to use multiple power sources to meet the demand of the load. This will not only mitigate the power fluctuation but also gives the maximum efficiency to the load. The earlier comparison part of this paper clearly shows that a hybrid energy supply system comprising of heterogeneous energy supply elements with differing performance characteristics provide us with linear output reducing the power fluctuation.

REFERENCES

[1] F. Koushanfar, "Hierarchical hybrid power supply networks," in DAC,2010, pp. 629–630.

[2] M. Pedram, N. Chang, Y. Kim, and Y. Wang, "Hybrid electrical energystorage systems," in ISLPED, 2010, pp. 363–368.

[3] A. Mirhoseini and F. Koushanfar, "Hypoenergy: Hybrid supercapacitorbattery power-supply optimization for energy efficiency," in DATE, 2011.

[4] D. Brunelli, C. Moser, L. Thiele, and L. Benini, "Design of a solarharvestingcircuit for batteryless embedded systems," TCAS I: Regular Papers, vol. 56, no. 11, pp. 2519–2528, 2009.

[5] G. Merrett, A. Weddell, A. Lewis, N. Harris, B. Al-Hashimi, and N. White, "An empirical energy model for supercapacitor powered wireless sensor nodes," in ICCCN, 2008, pp. 1–6.

[6] T. Zhu, Z. Zhong, Y. Gu, T. He, and Z. Zhang, "Leakage-aware energy synchronization for wireless sensor networks," in MobiSys, 2009, pp. 319–332.

[7] Y. Wang, Z. Shi, Y. Huang, Y.Ma, C. Wang, M. Chen, and Y. Chen, "Supercapacitor devices based on graphene materials," American Chemical Society, J. Phys. Chem, pp. 13 103–13 107, 2009

[8] Farinaz Koushanfar, Azalia Mirhhoseini, "Hybrid Energy Supply Networks" ISCES Flagship Conference, Brazil, 2011, pp.2489-2492.